AstroMHD@HZDR

Frank Stefani

Two (interrelated) reasons to initiate „AstroMHD“…

New projects with new PhD students (…and 2 Postdocs)

1. ERC project LEMAP (Federico, Jude, N.N., N.N., George,…)
2. Helmholtz-Russian Science Foundation project „Magnetohydrodynamic instabilities…“ (Peter, Sebastian)
3. André´s DFG project on precession with blades (N.N.)
4. Rayleigh-Bénard activities…

POF 4 (2021-2027): Transfer of activities from research field „Energy“ into research field „Matter“, Program „From matter to materials and live (MML)“

1. DRESDYN precession dynamo
2. DRESDYN MRI/TI experiment
3. Rayleigh-Bénard activities ???

…first draft until 19 March 2019!!!,

strategic evaluation: 27-39 January 2020

DRESDEN concept HZDR

AstroMHD is intended…

- …to be an open forum for project discussions with focus on the projects with geo- and astrophysical relevance
- …for detailed discussion of data from the related experiments and/or numerical models, or technical challenges that are crucial for the configurations of experimental and numerical setups
- …in rare cases (as today) for lectures

AstroMHD is not intended…

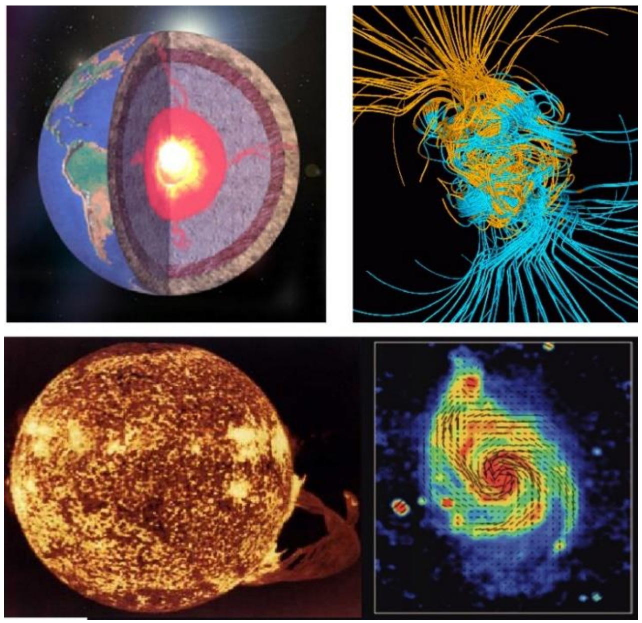
- …to replace the Coffee Meetings
- …as a series of lectures on basic MHD

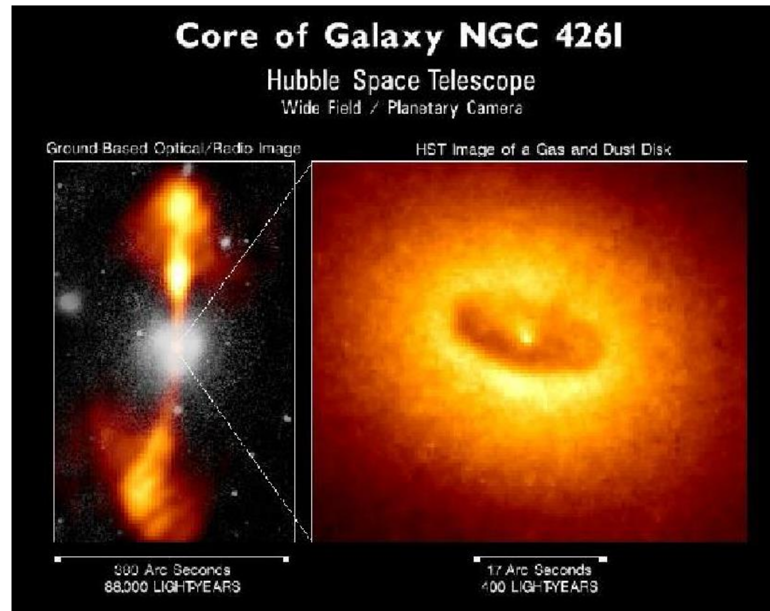
Astrophysical MHD: Motivation

Cosmic magnetic fields…

…are produced by the homogeneous dynamo effect

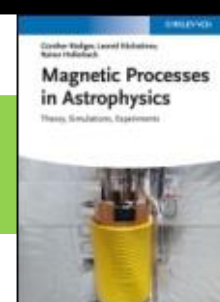
…play a key role in cosmic structure formation by virtue of the magnetorotational instability





Rüdiger, Kitchatinov, Hollerbach:

Magnetic Processes in Astrophysics (2013)



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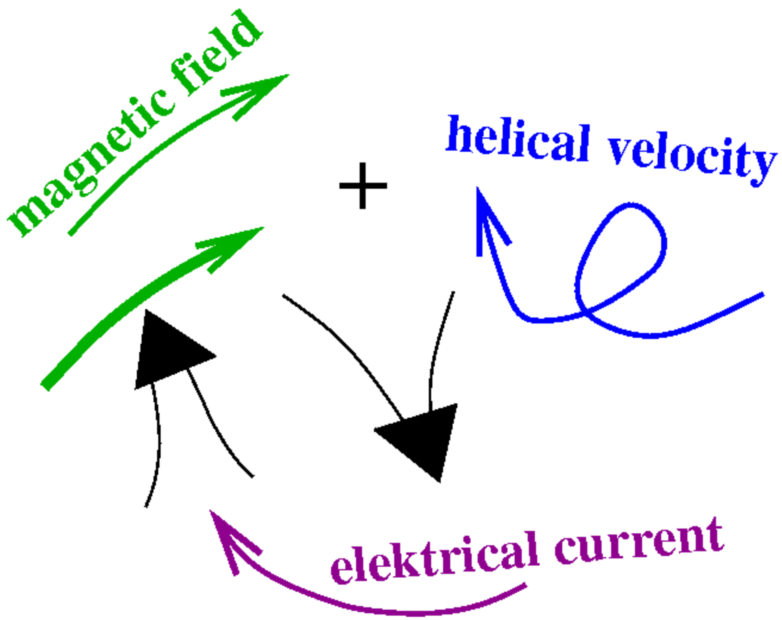
Astrophysical MHD: Basic mechanisms

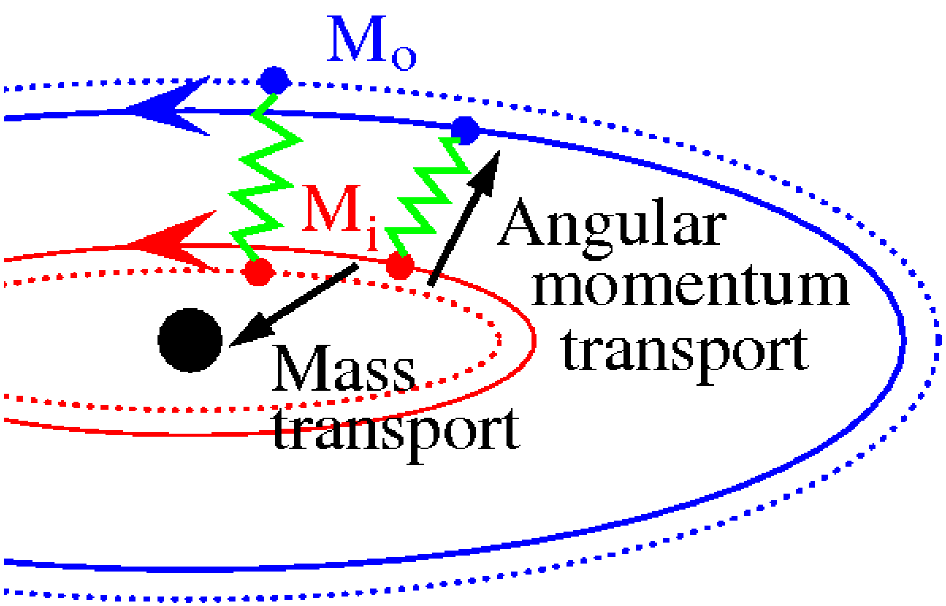
Homogeneous dynamo effect:

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



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Astrophysical MHD: Underlying theory

Navier-Stokes equation:

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

Governing parameters:
(Reynolds, Hartmann)

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

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

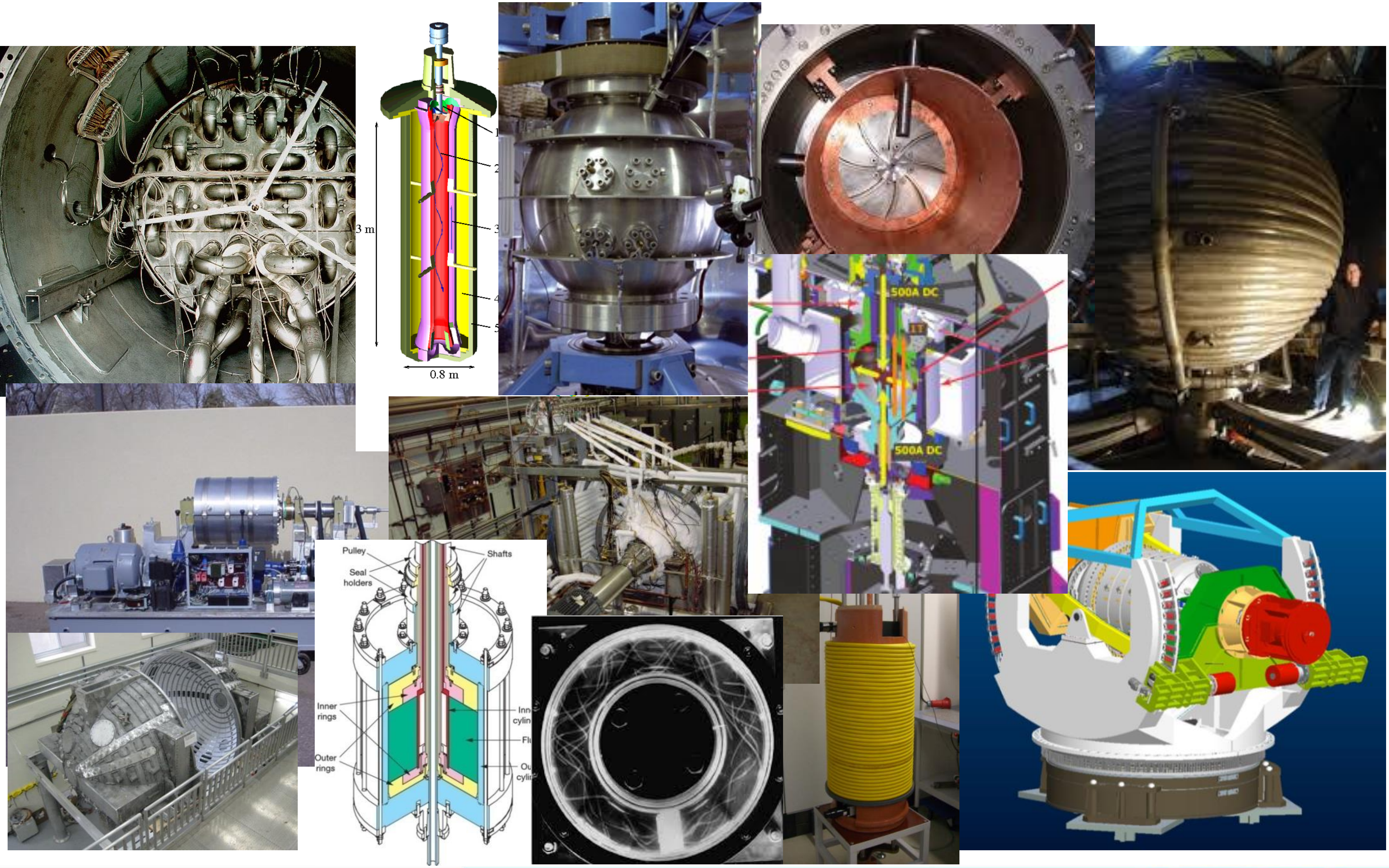
Induction equation:

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

Governing parameter:
(magnetic Reynolds)

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

Astrophysical MHD: Previous, present, and future experiments



DREsden sodium facility for DYNamo and thermohydraulic studies

- DRESDYN building ~500 m^2
- Total sodium inventory: 12 tons
- Precession driven dynamo experiment with separate strong basement and containment for Argon flooding
- Large experimental hall for MRI/TI experiment, sodium loop, liquid metal batteries, Rayleigh-Bénard experiment

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

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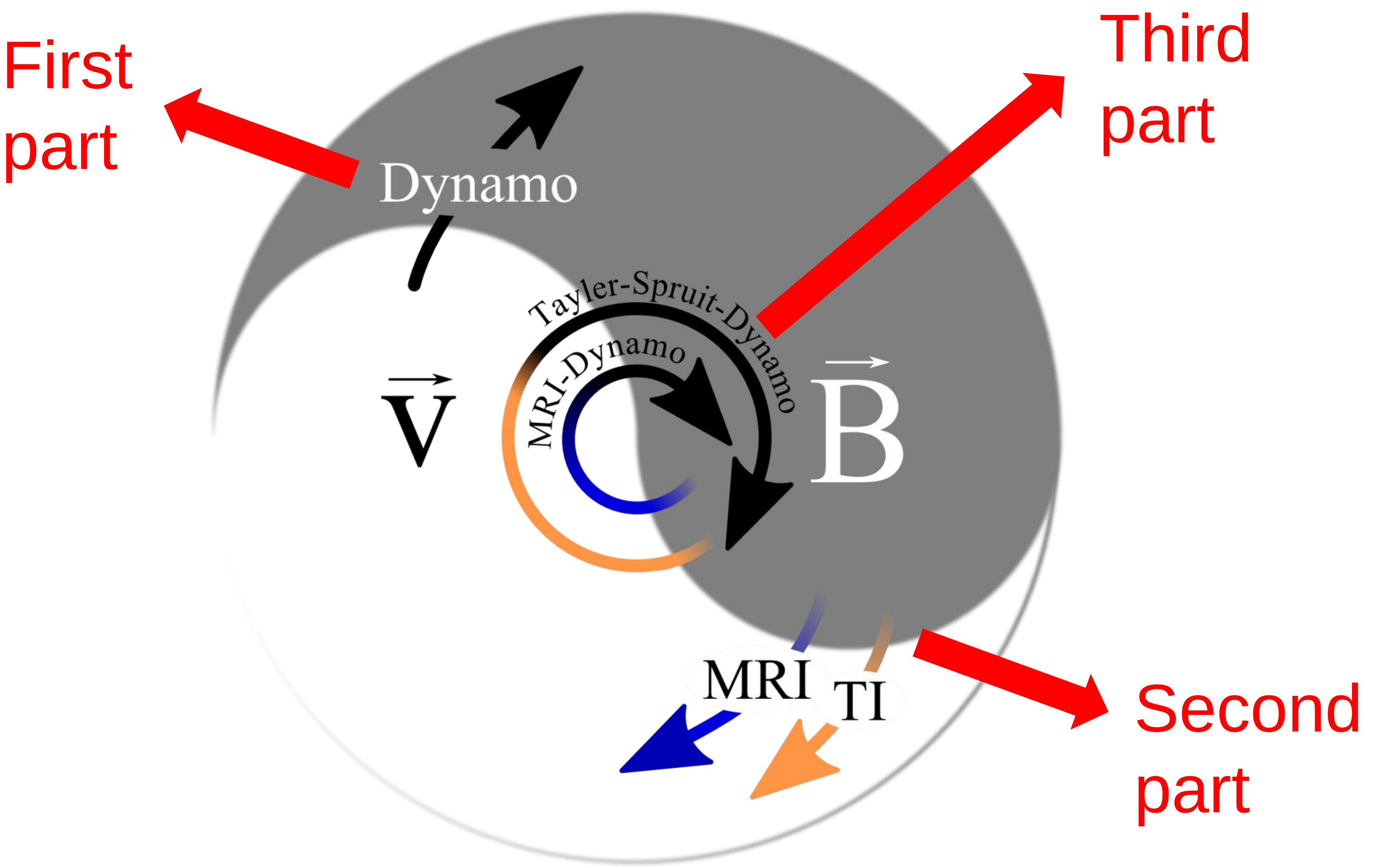
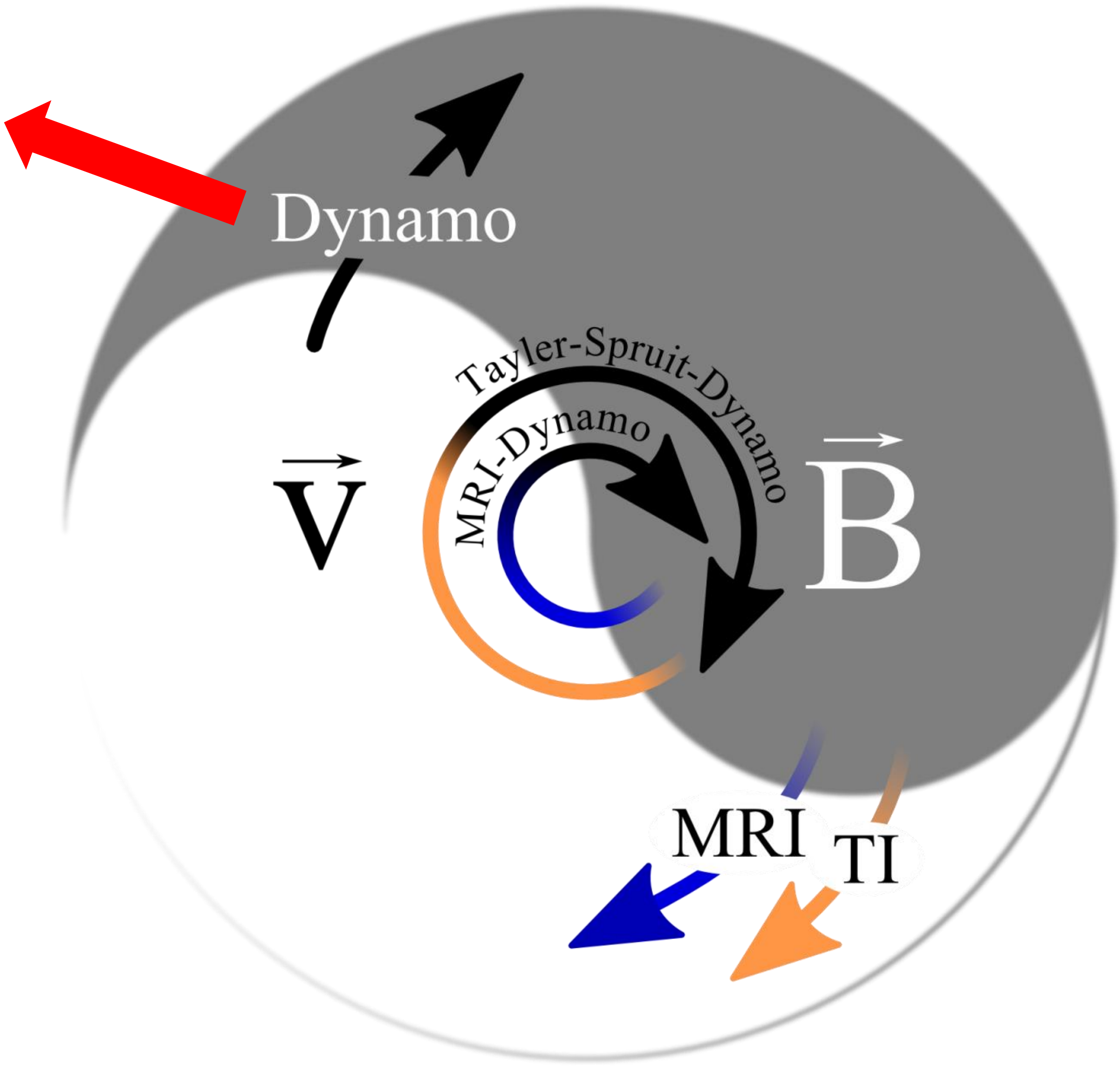
The Yin-Yang of astrophysical MHD



Design by M. Seilmayer

Dynamos

First part



Matter under extreme conditions → Requires large sodium facilities

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

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

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

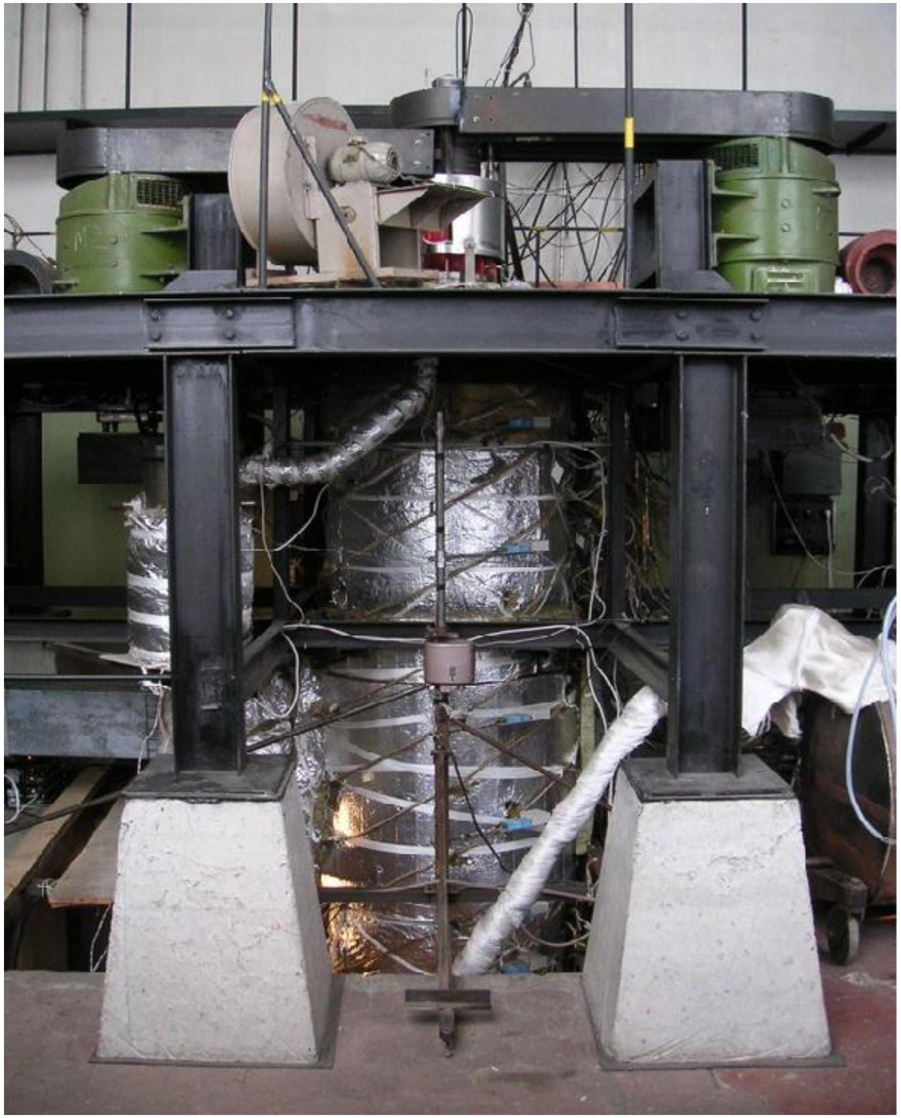
Sodium is the best liquid conductor with $\sigma \sim 10^7$ S/m → UL~1 m^2/s

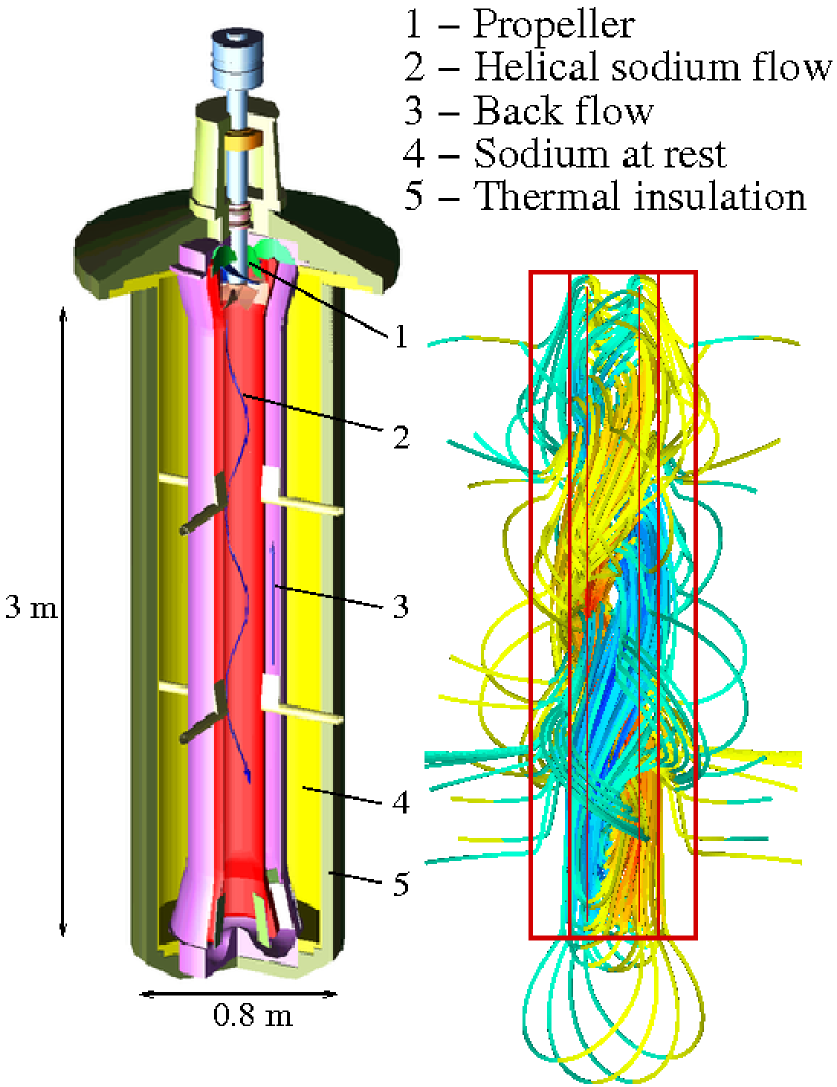
Why so large? Necessary power scales with 1/L:

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

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

Some history: Riga dynamo experiment



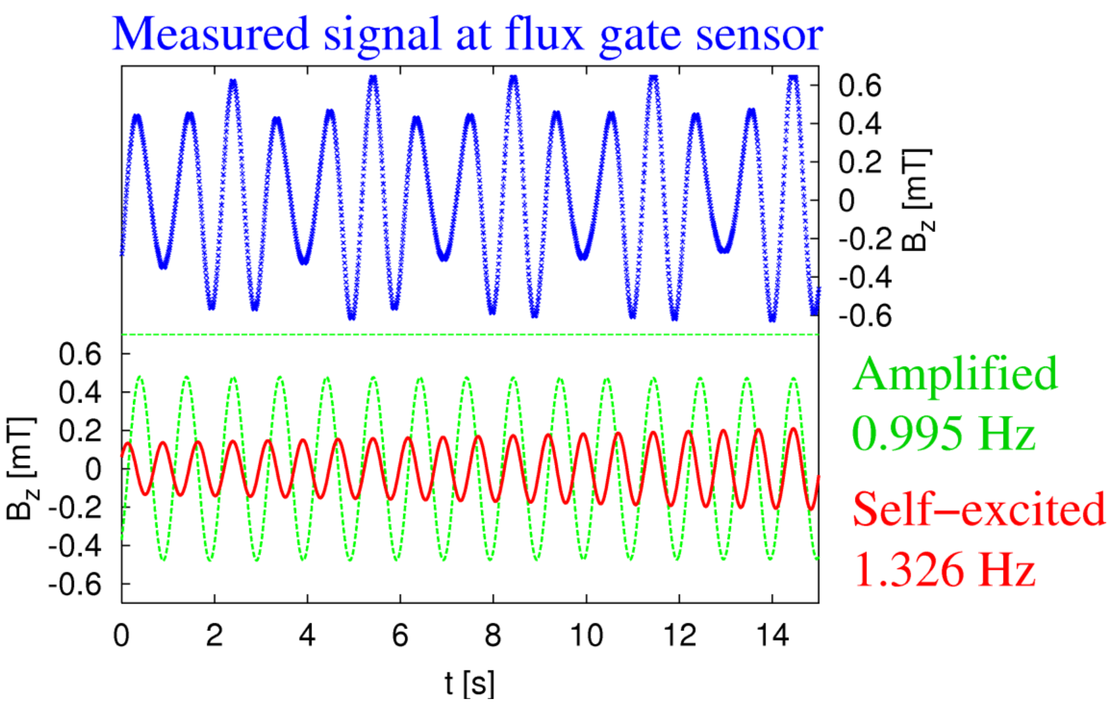


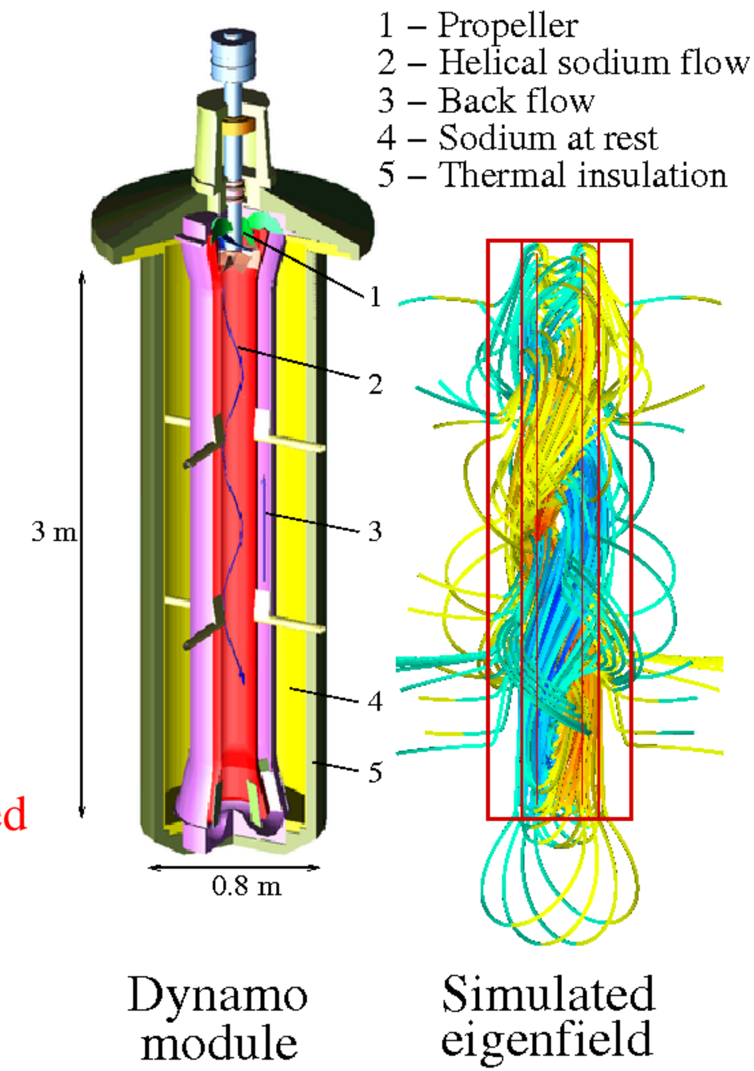
Dynamo module

Simulated eigenfield

Riga dynamo experiment

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

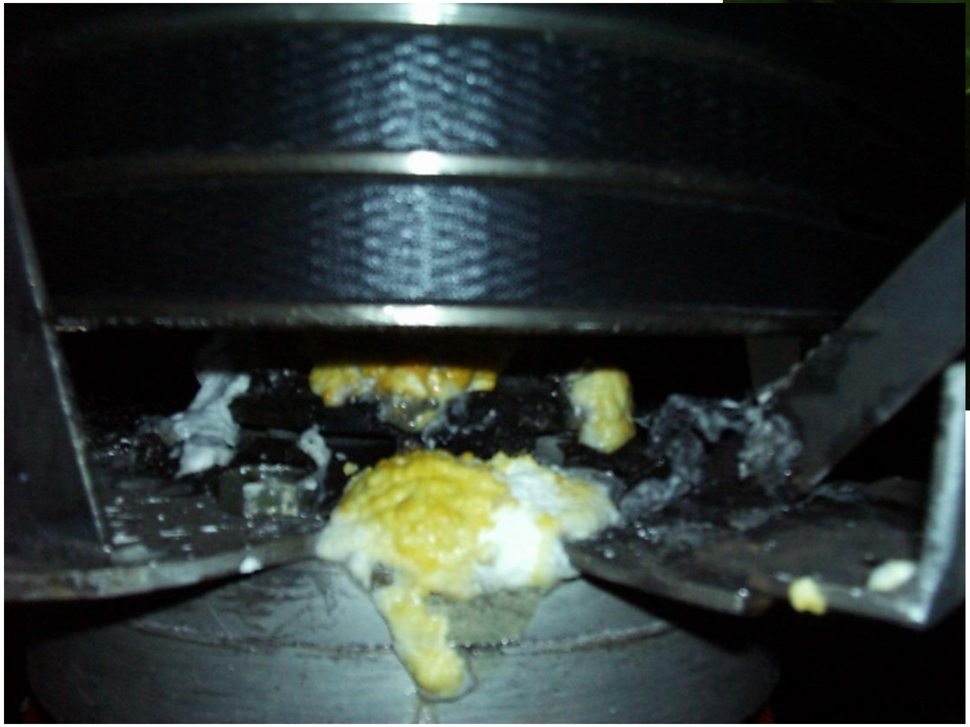




Gailitis et al., Phys. Rev. Lett. 84 (2000) 4365; Phys. Rev. Lett. 86 (2001) 3024; Rev. Mod. Phys. 74 (2002) 973 ; Phys. Plasmas 11 (2004) 2838; Compt. Rend. Phys. 9 (2008), 721

Riga dynamo – Attention: Sodium!

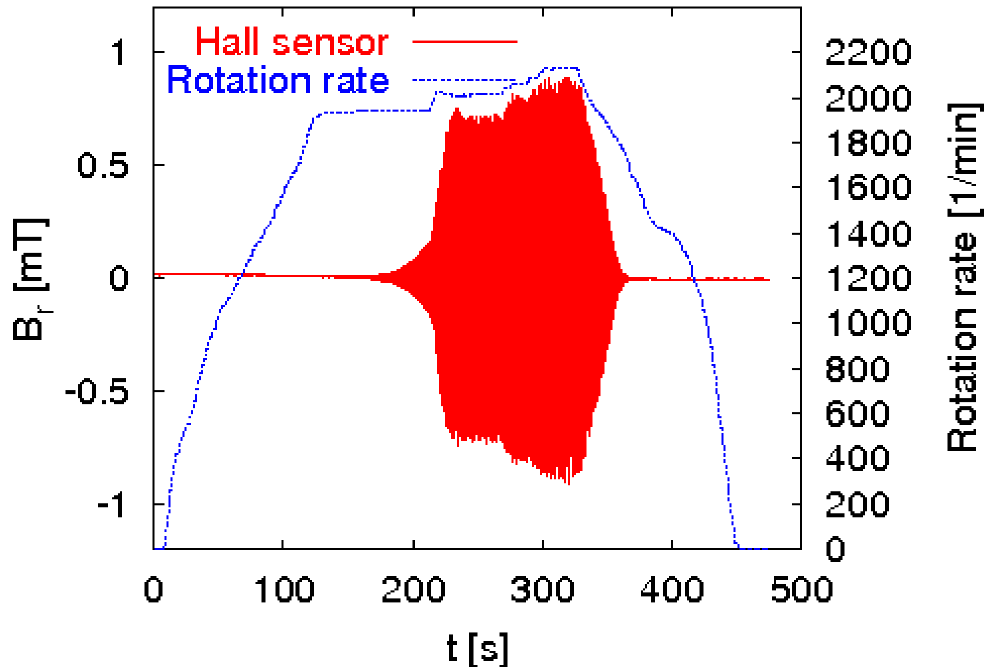
Evening of 11th November 1999...

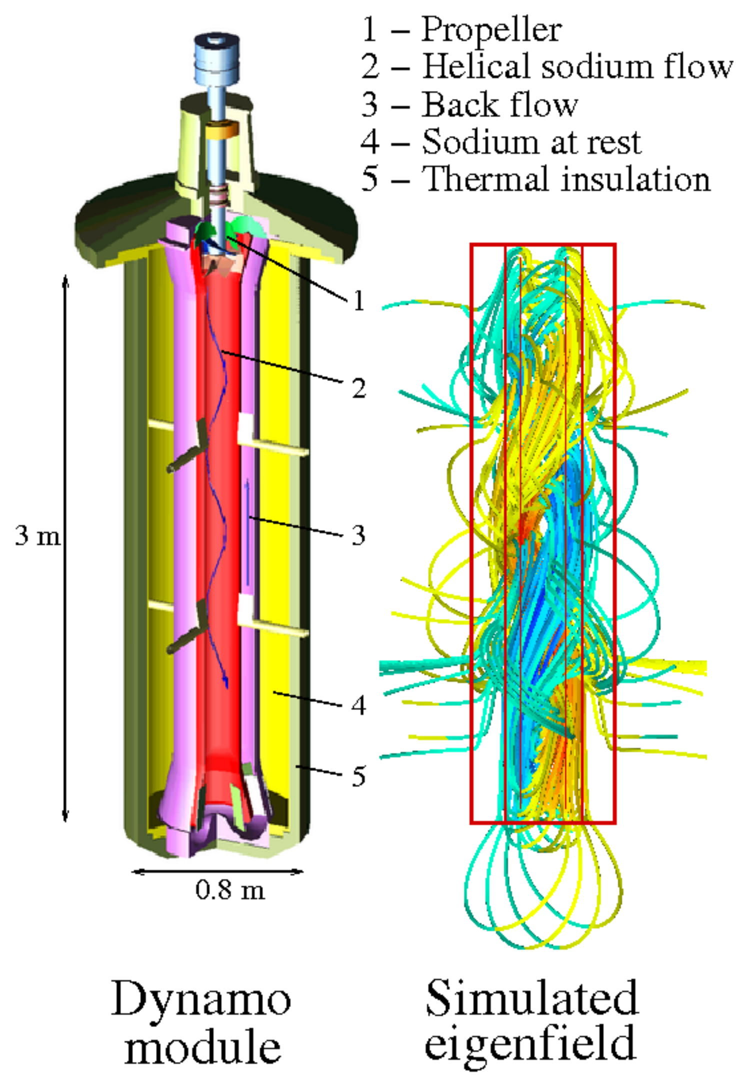


…and the day after...

Riga dynamo experiment

From the kinematic to the saturated regime (July 2000)





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

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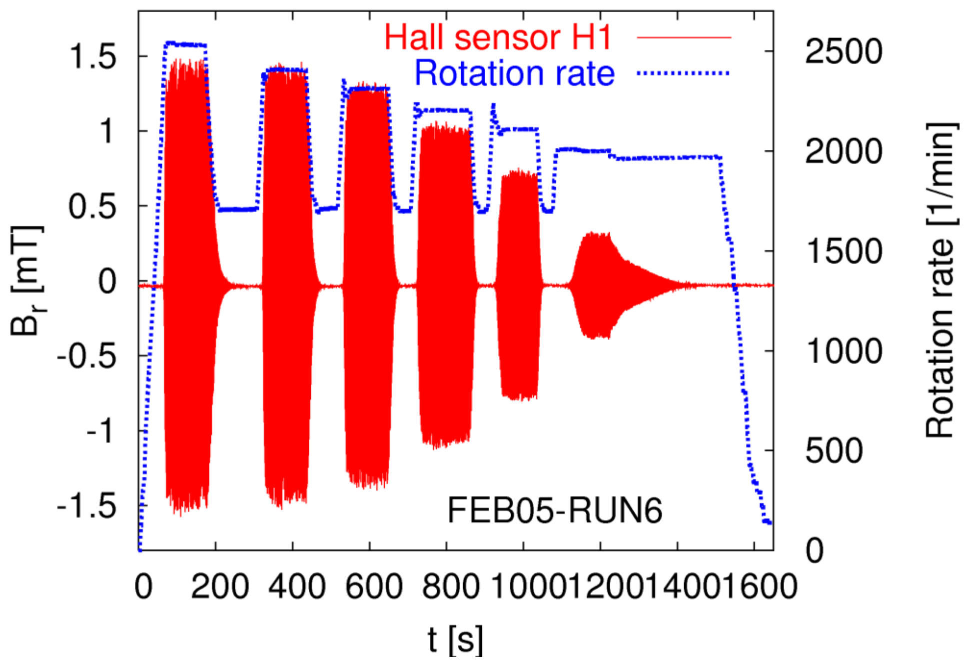
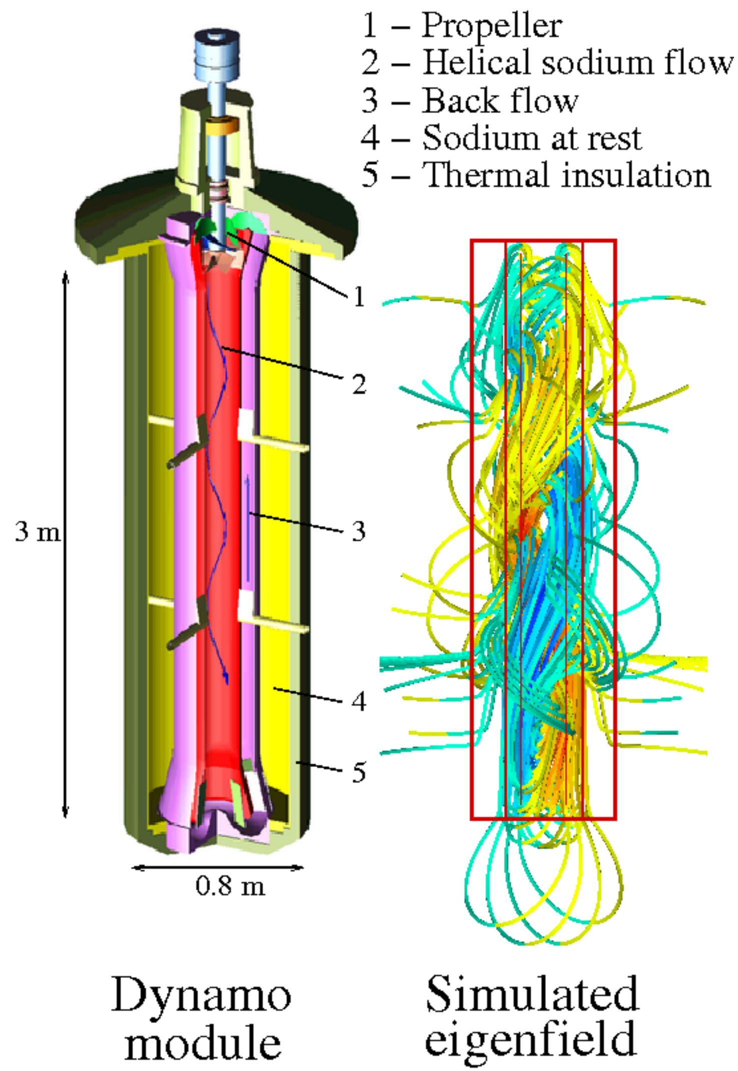
Riga dynamo experiment

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

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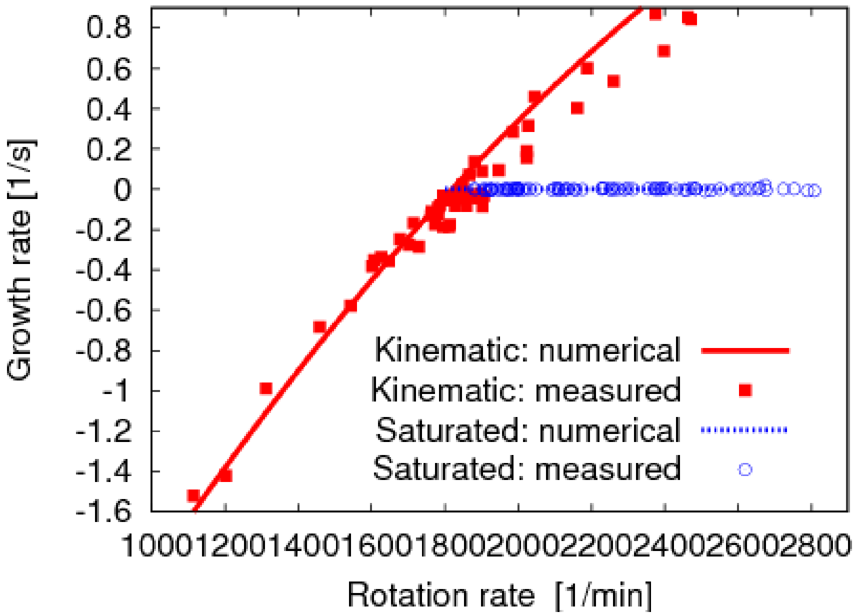
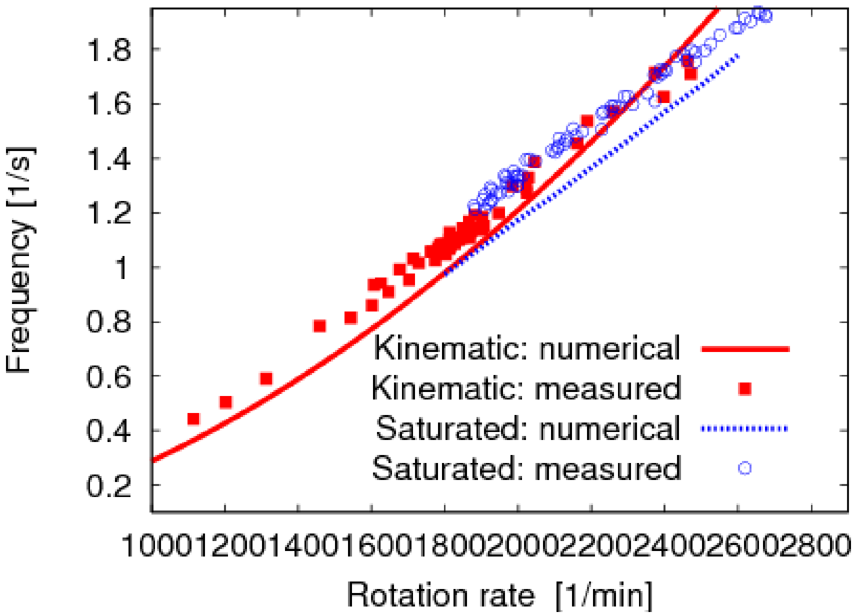
Riga dynamo experiment: Growth rates and frequencies





Numerical predictions (with correct vacuum boundary conditions) of the kinematic dynamo were accurate to some 5-10 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., C. R. Physique 9 (2008), 721;

J. Plasma Phys. 84, 735840301 (2018)

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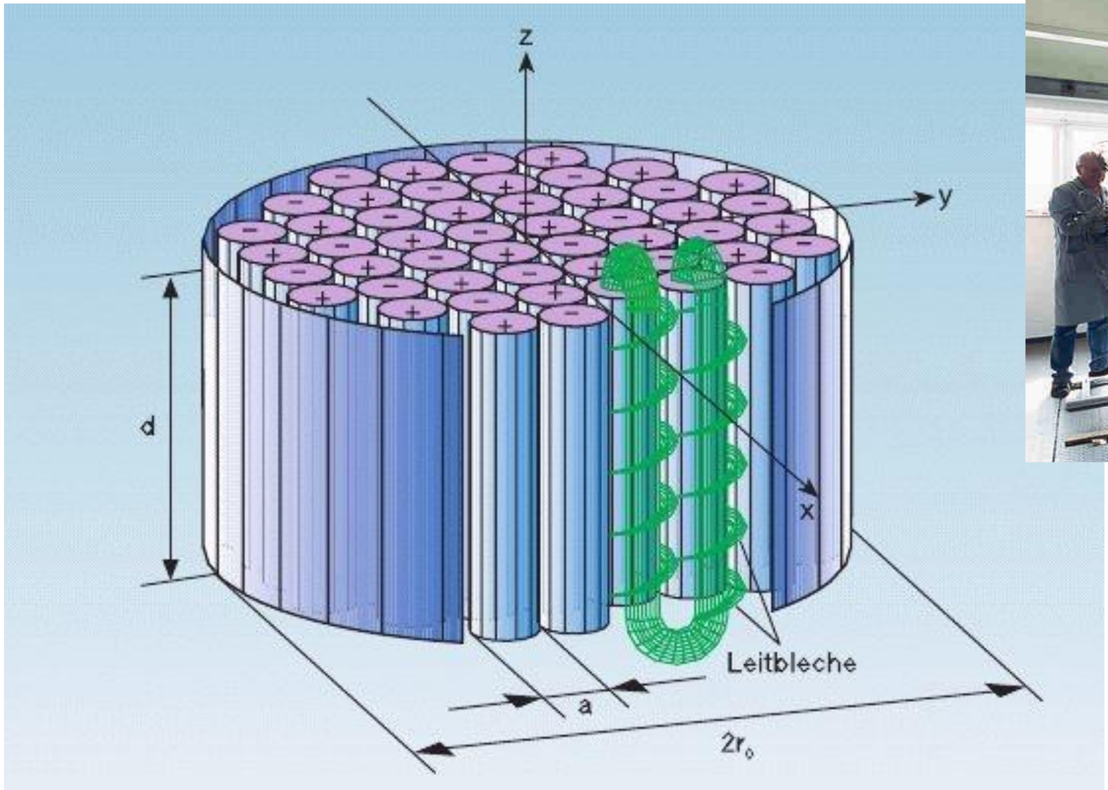
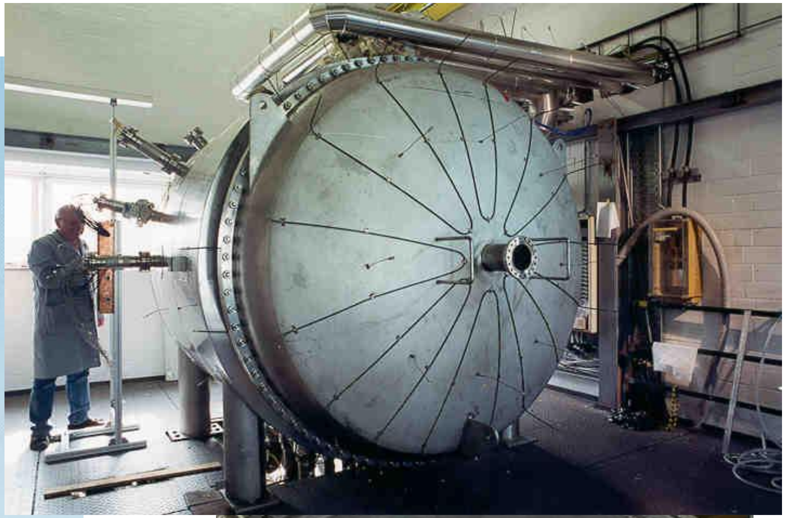
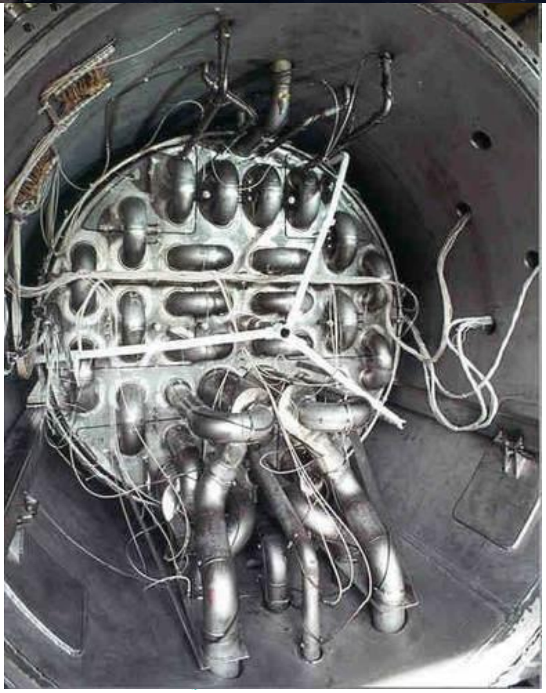
Some history: Karlsruhe Dynamo Experiment



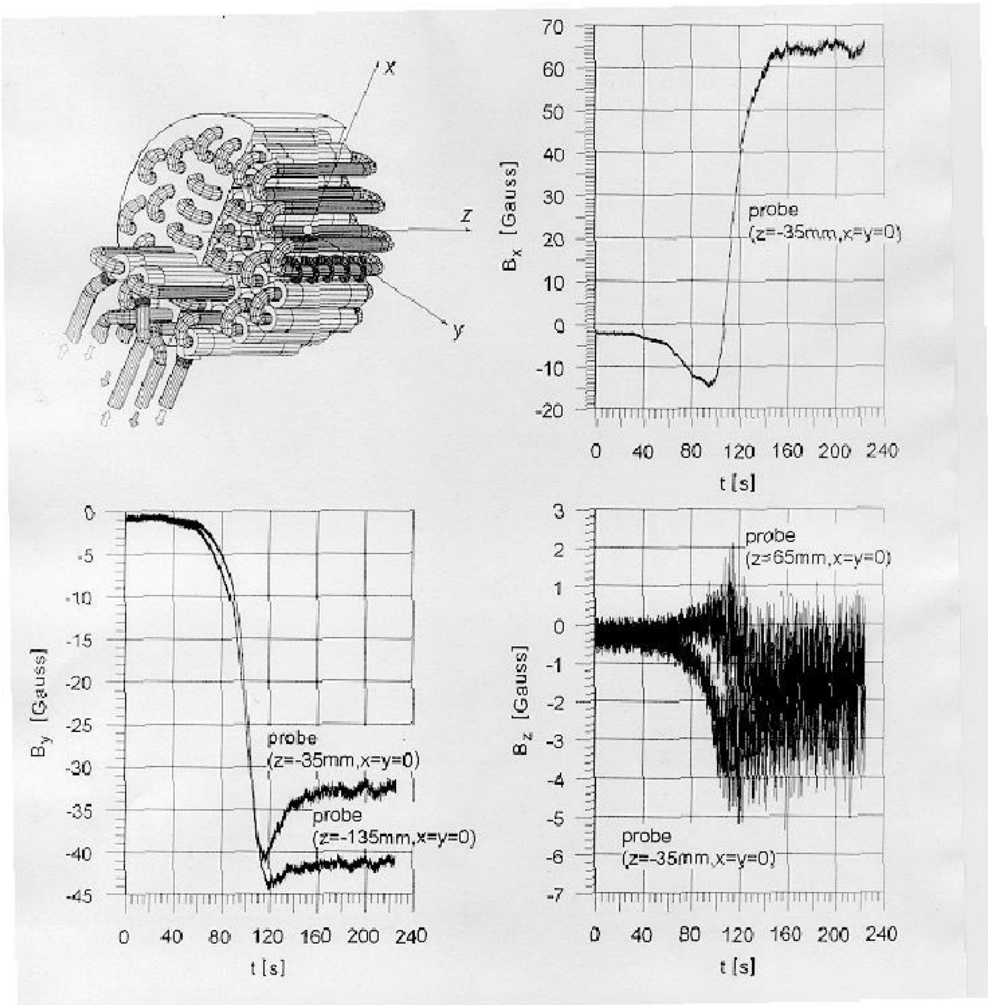




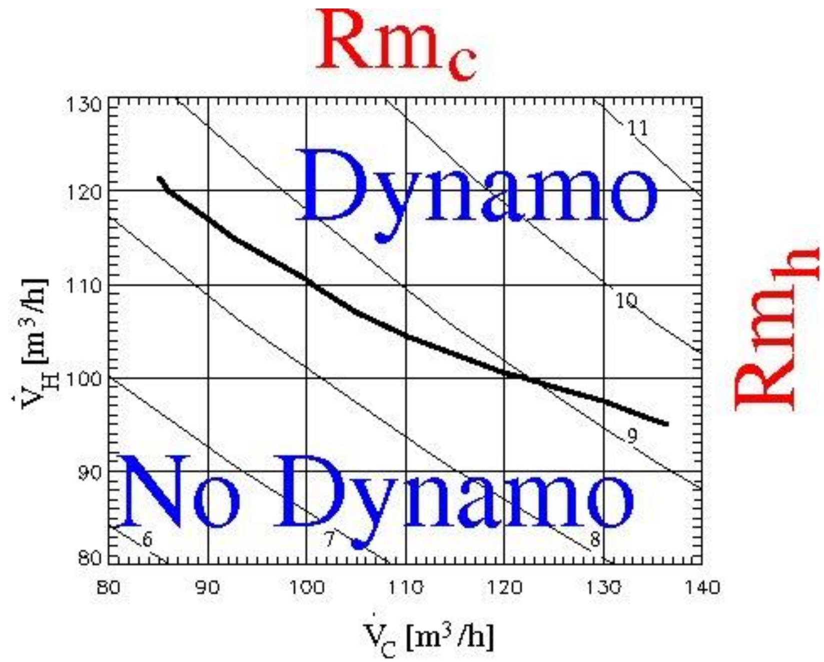
A two-scale, α^2 type dynamo, realized by 52 spin-generators

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

Karlsruhe Dynamo Experiment



„Secret Fax" of 19 December 1999



Again, very good agreement with numerical predictions

Rädler et al. Nonl. Proc. Geophys. 9, (2002), 171

„Dynamo Riga“ versus „Dynamo Karlsruhe“

BZ 2.2.2000

Zwei Forschergruppen streiten sich um einen ersten Platz

Der Ursprung des Magnetfelds der Erde wurde nahezu zeitgleich in Riga und Karlsruhe simuliert und jedes Team will das erste ge

KÜNSTLICHES MAGNETFELD

Bild der Wissenschaft 5/2000

ERDMAGNETFELD

Streit um den Erdkern

Zwei konkurrierende Forschergruppen haben erstmals das Erdmagnetfeld im Labor simuliert. Damit steht fest, dass Erdrotation und der äußere flüssige Erdkern ein stabiles Magnetfeld erzeugen. Jetzt geht es um die Entdeckerehre.

Nature, 29 June 2000

news and views

Critical time for fluid dynamos

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 ... Despite some progress on the ... attempts to recreate this ... until recently.

Frankfurter Allgemeine Zeitung

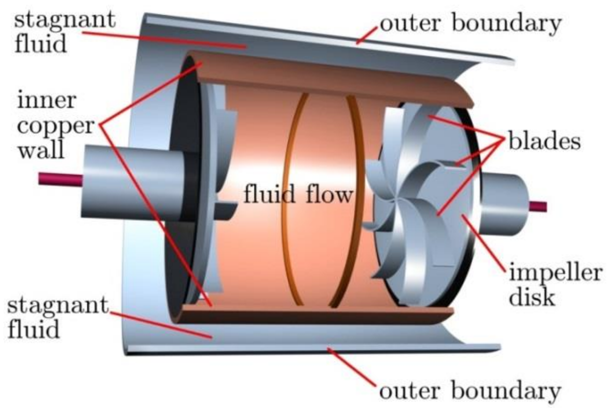
FAZ 2.2.2000

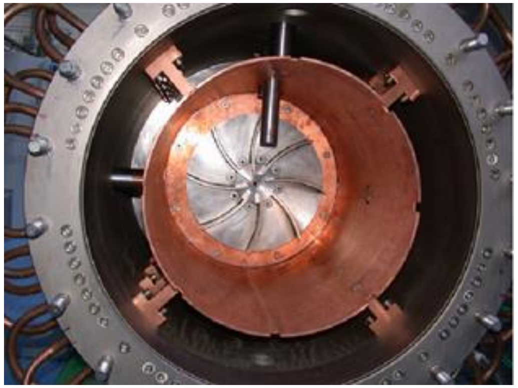
Streit um das Magnetfeld der Erde

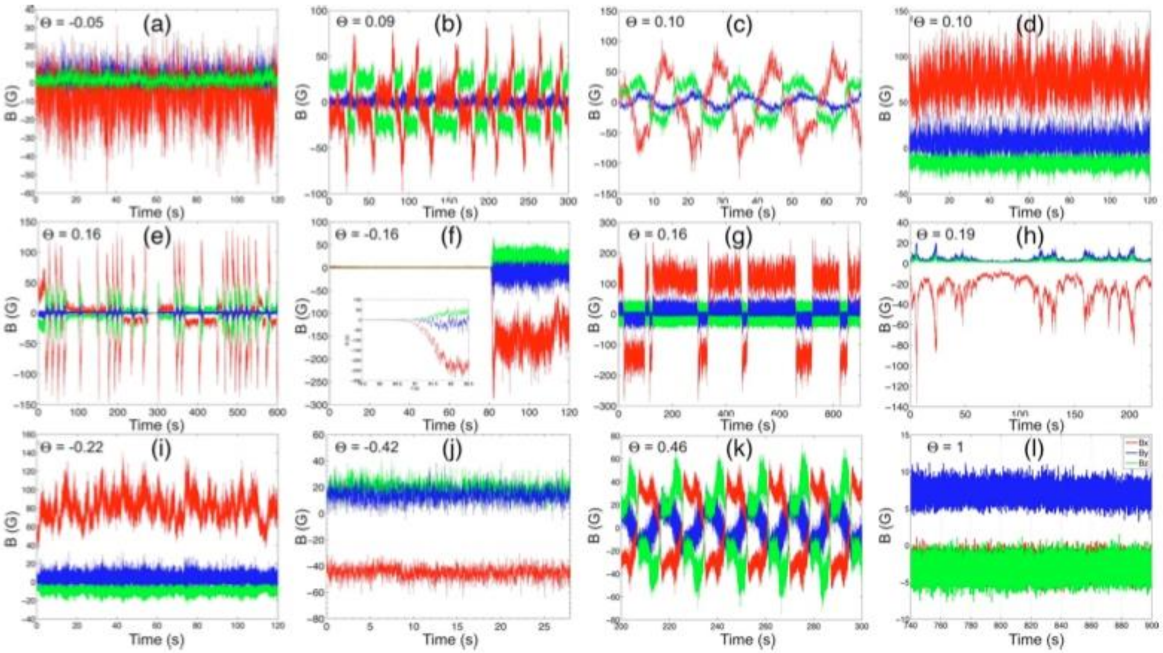
Zwei Forschergruppen beanspruchen die erste Simulation für sich / Strömendes

Some history: von-Karman-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

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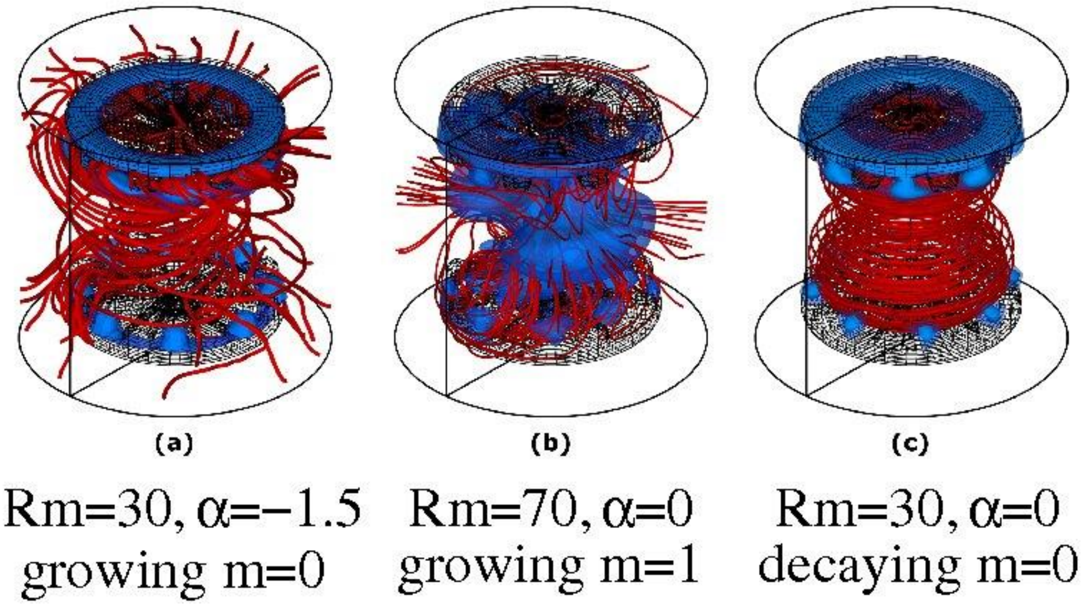
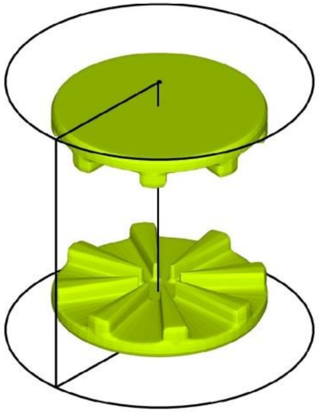
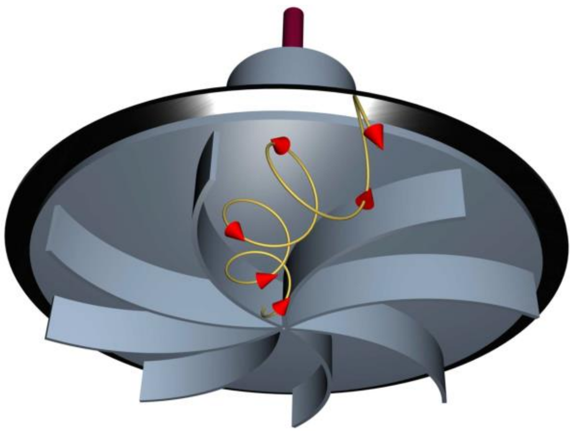
VKS-Dynamo: Role of high μ impellers?







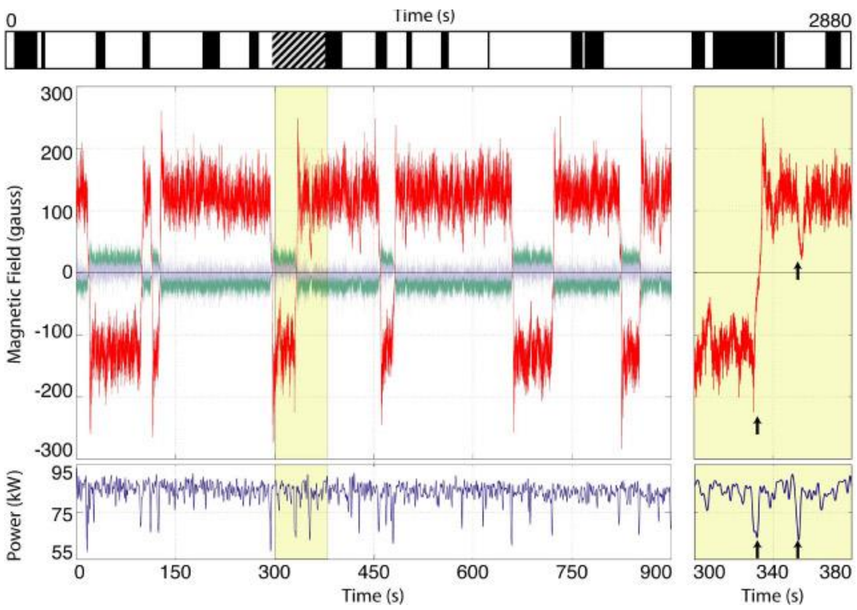
…on the basis of the dominant toroidal mode, some small-scale helicity between the blades (α-effect) is sufficient to ignite the dynamo

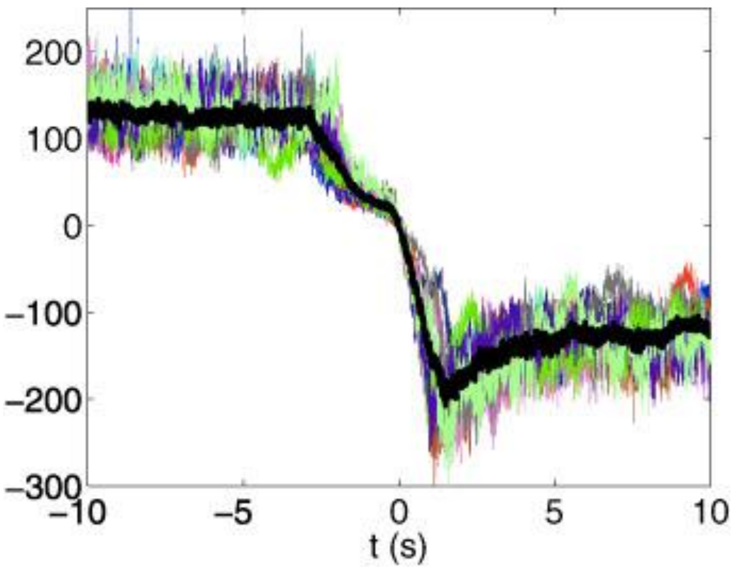
Giesecke et al., Phys. Rev. Lett. 104 (2010); New J. Phys. 14 (2012), 053005

Nore et al., Europhys. Lett. 114 (2016), 65002

Kreuzahler et al, Phys. Rev. Lett. 119 (2017), 234501

Reversals of the geomagnetic field and the VKS dynamo field

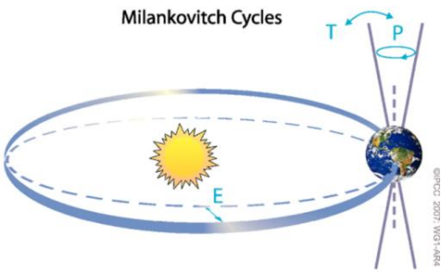


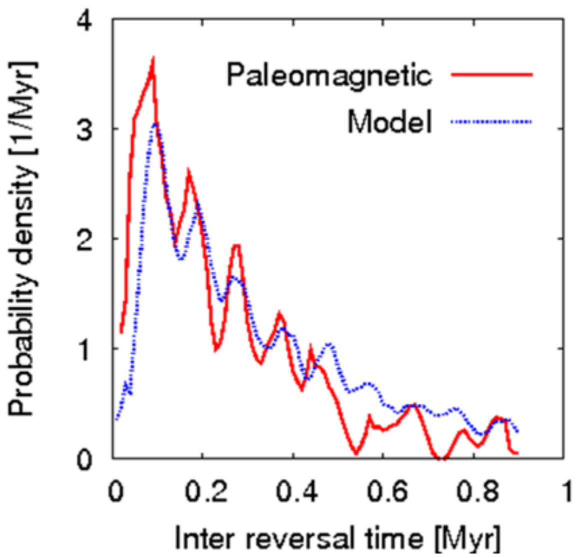


Berhanu et al., EPL 77 (2007), 59001

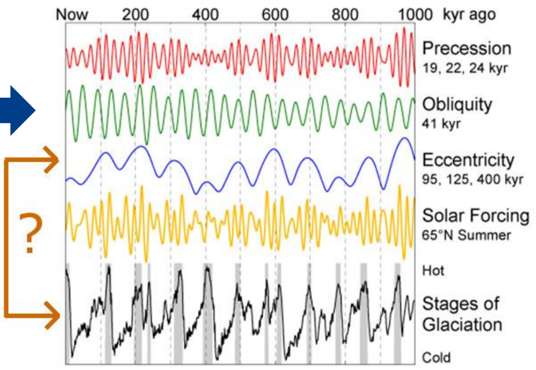
The DRESDYN precession dynamo: Geo/astrophysical motivation

Strong indication for influence of variations of Earth's orbit parameters on the **geodynamo**





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



Doake, Nature 267 (1977), 415

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

Recent discussion of the **lunar dynamo** in terms of precession or impacts

Dwyer et al., Nature 479 (2011), 212; Le Bars et al., Nature 479 (2011), 215

Evidence for ancient core **dynamo in asteroid Vesta**

Fu et al., Science 338 (2012), 238

Precession driven dynamo experiment within the DRESDYN project

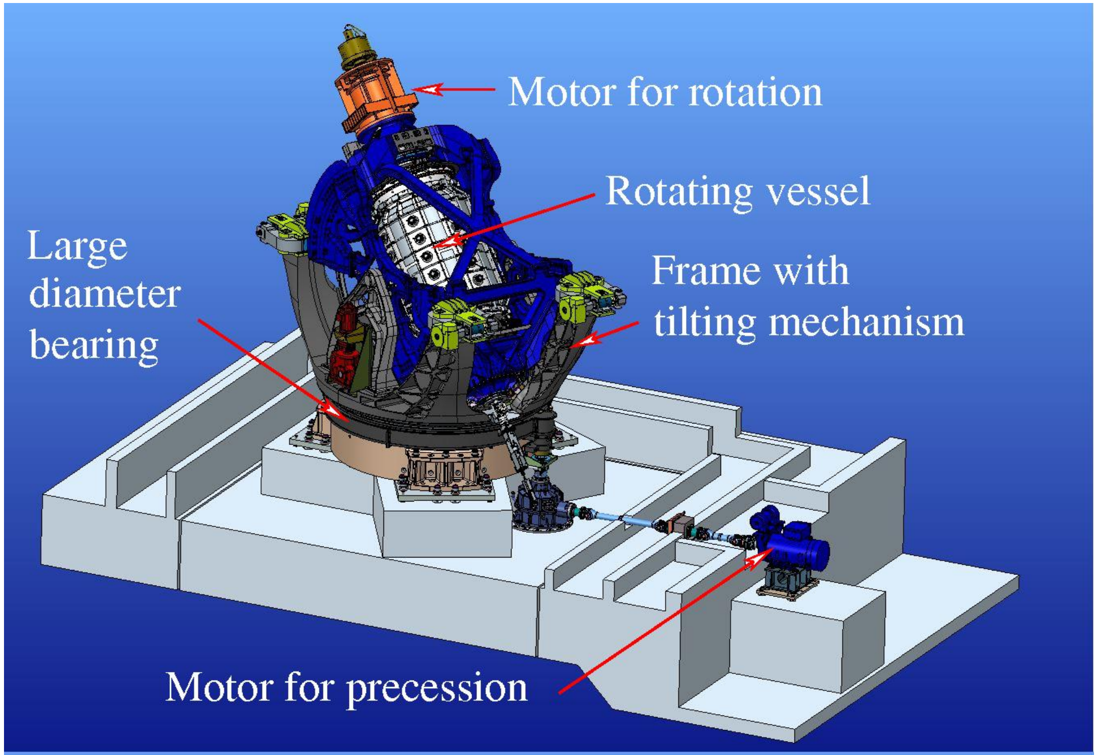
Key parameters:

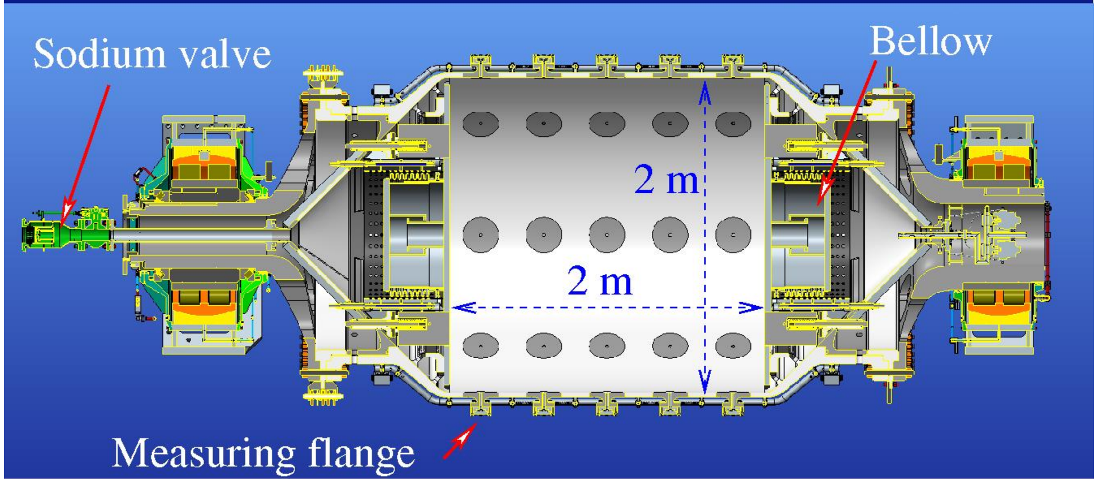
- Cylinder with 2 m diameter and 2 m height, 8 tons of liquid sodium

- 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”)

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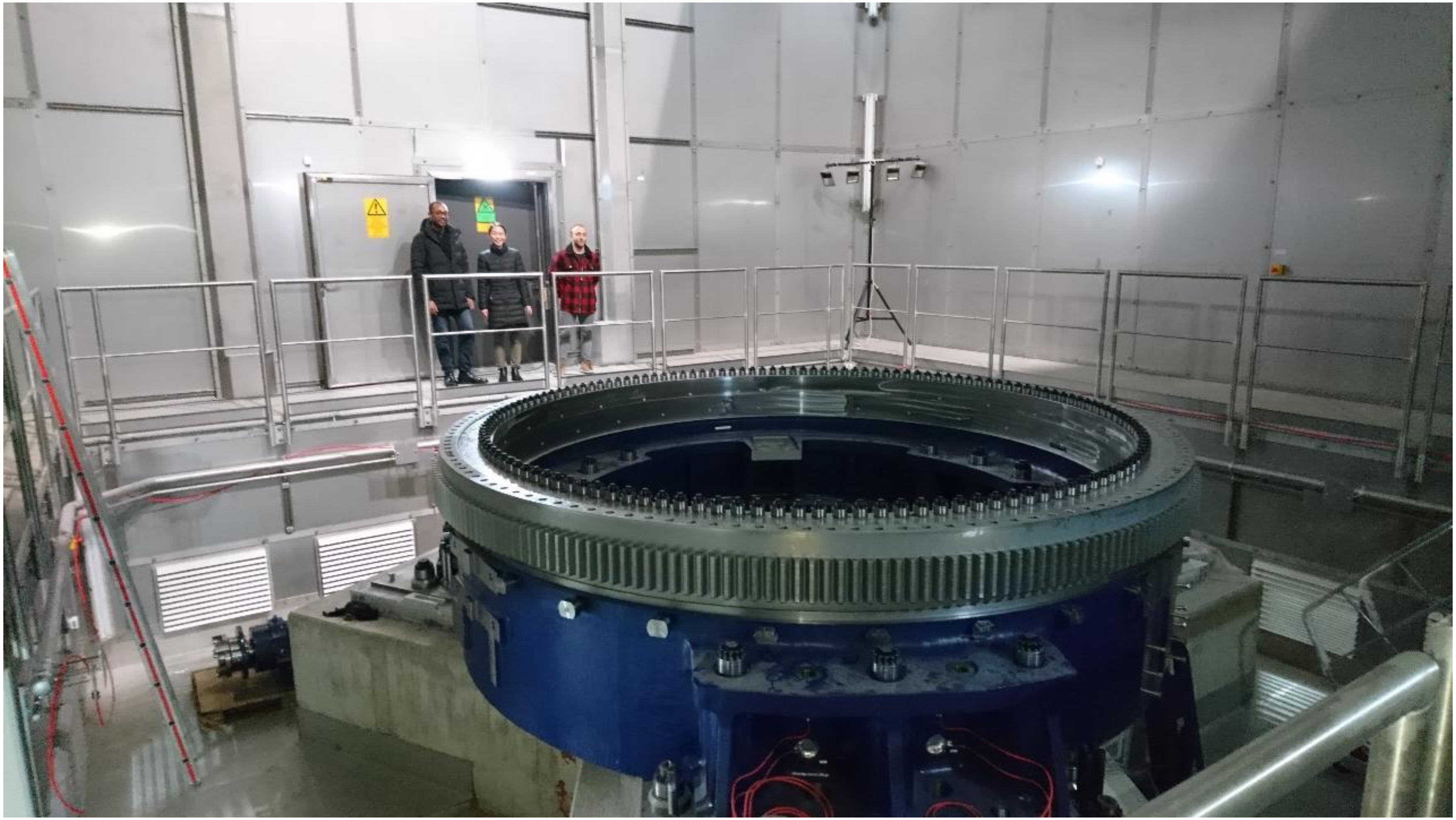
Precession driven dynamo: Underframe mounted on tripod (3/2018)

DRESDEN concept

HZDR

Precession driven dynamo: Large ball bearing installed (12/2018)



DRESDEN concept

HZDR

Precession driven dynamo: Traverse and pylons (01/2019)

DRESDEN concept
HZDR

Precession driven dynamo: Central vessel welded

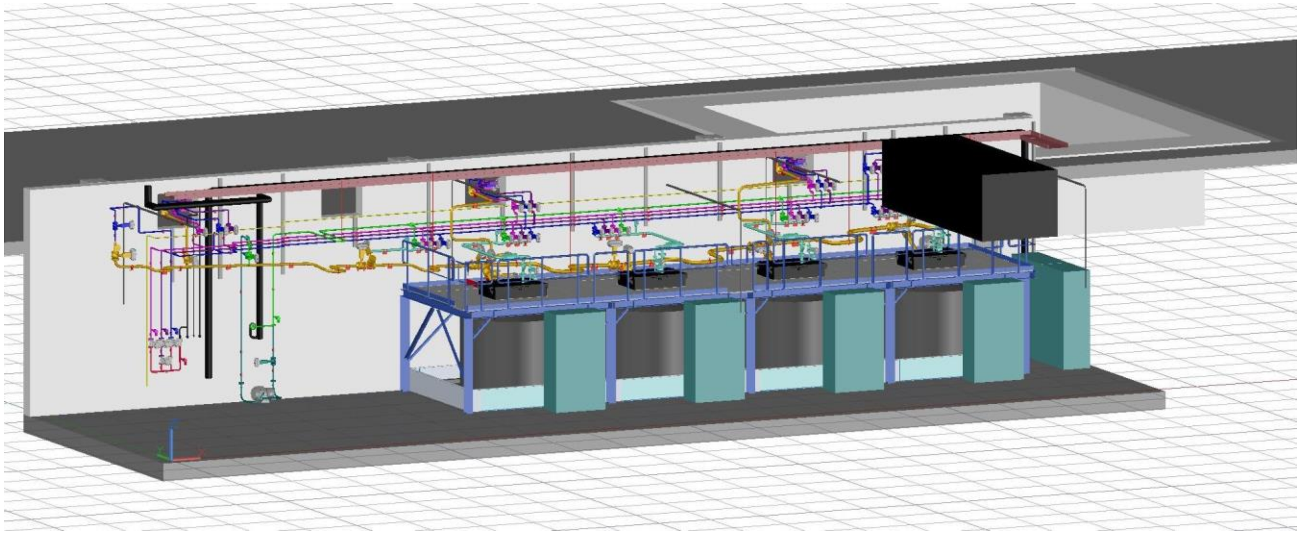
Precession driven dynamo: Motor for rotation is tested

DRESDEN concept HZDR

Precession driven dynamo: Oil station for ball bearings (12/2018)

Precession driven dynamo: Motor for turntable rotation (01/2019)

Precession driven dynamo: Sodium tanks; piping system is designed



DRESDEN concept

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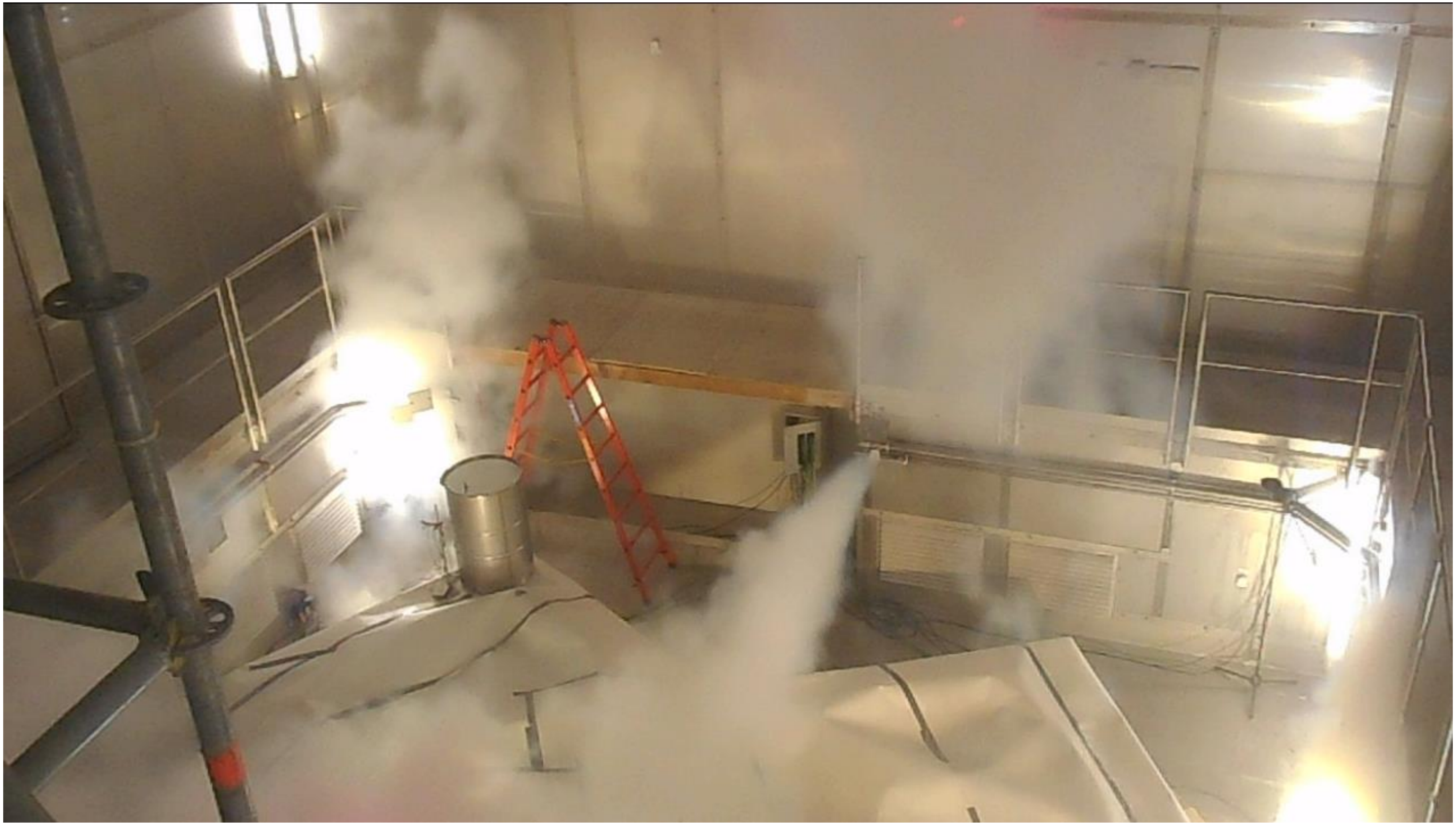
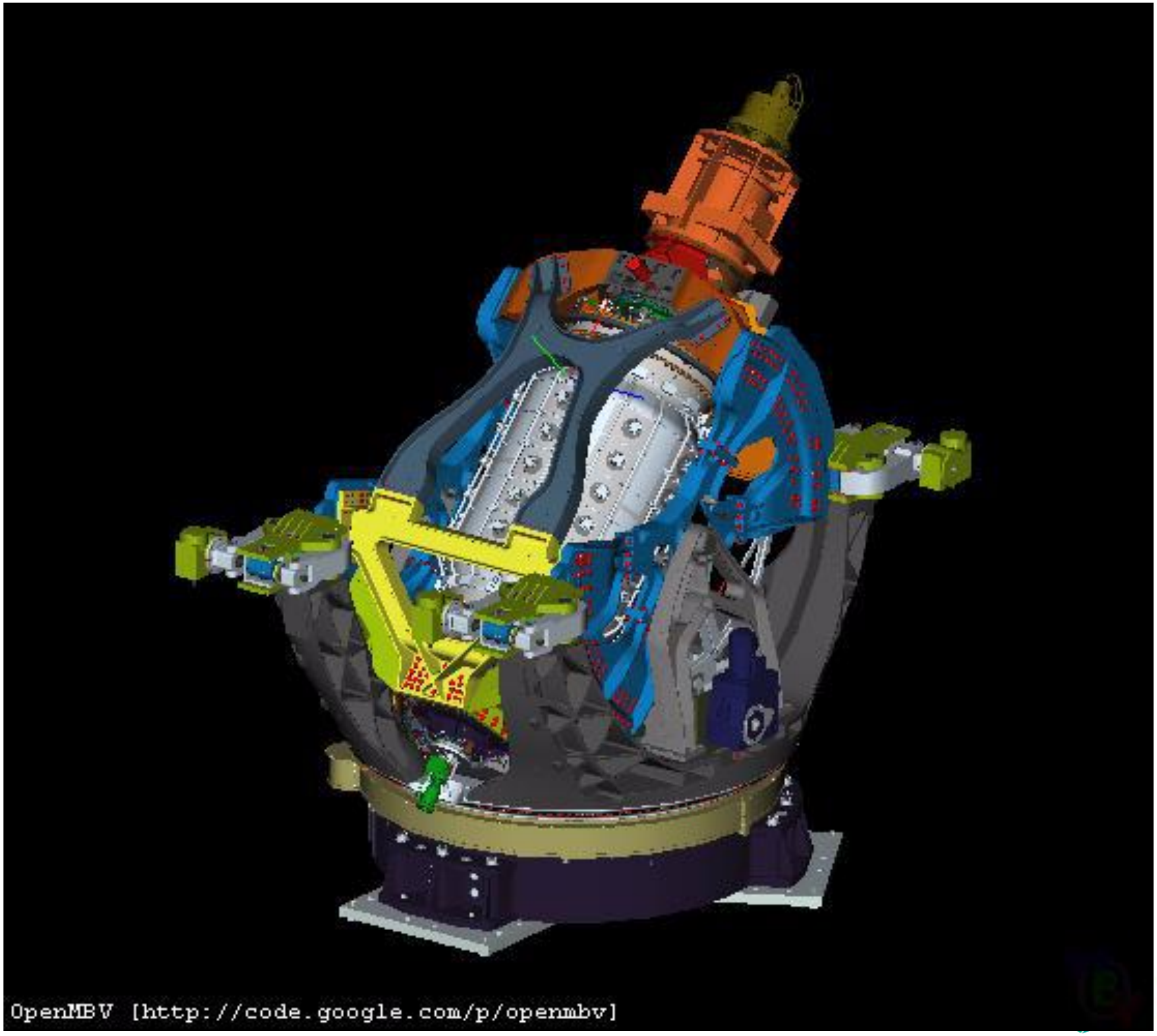
Test of the fire extinguishing facility with liquid argon (01/2016)



Precession driven dynamo experiment: our plan for 2019...



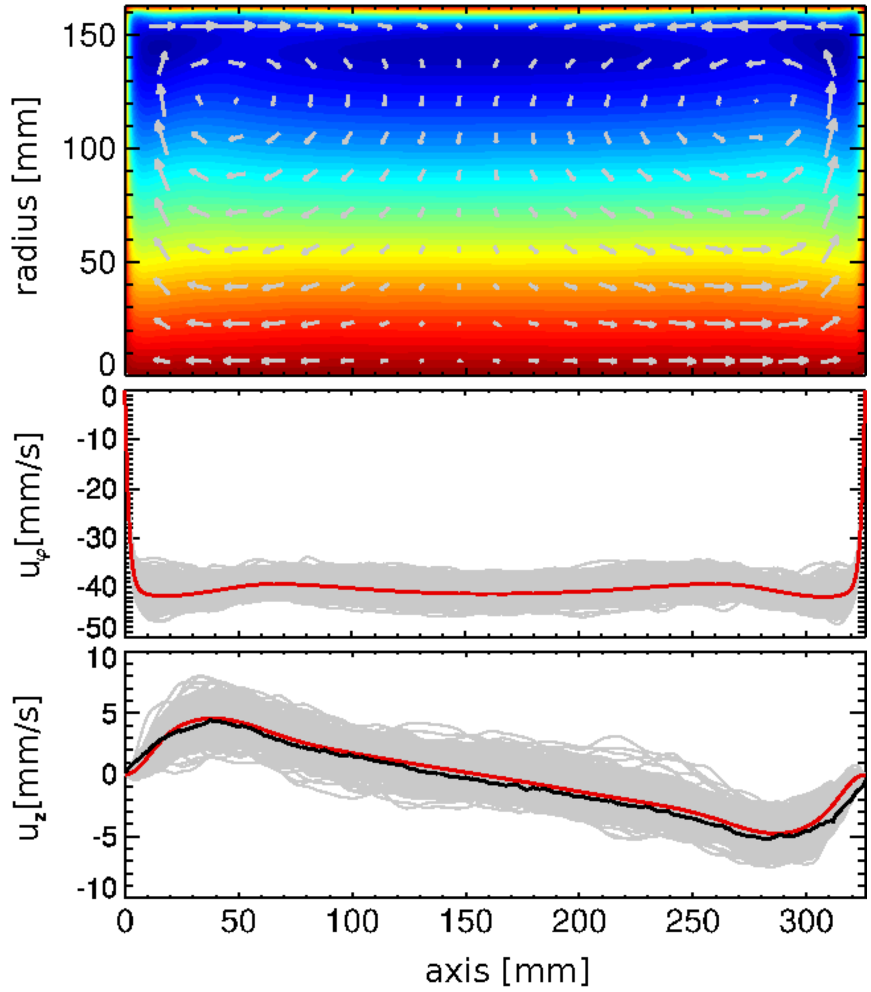
Precession driven flow: Will it really be a dynamo?

<u>New encouraging result:</u>

Axisymmetric double-roll flow (s2t1) emerges in the nonlinear regime from the forced m=1 Kelvin mode in a (narrow) region of the precession ratio.

Possible explanation: The modified rotational profile becomes Rayleigh-unstable and develops 2 Taylor vortices.

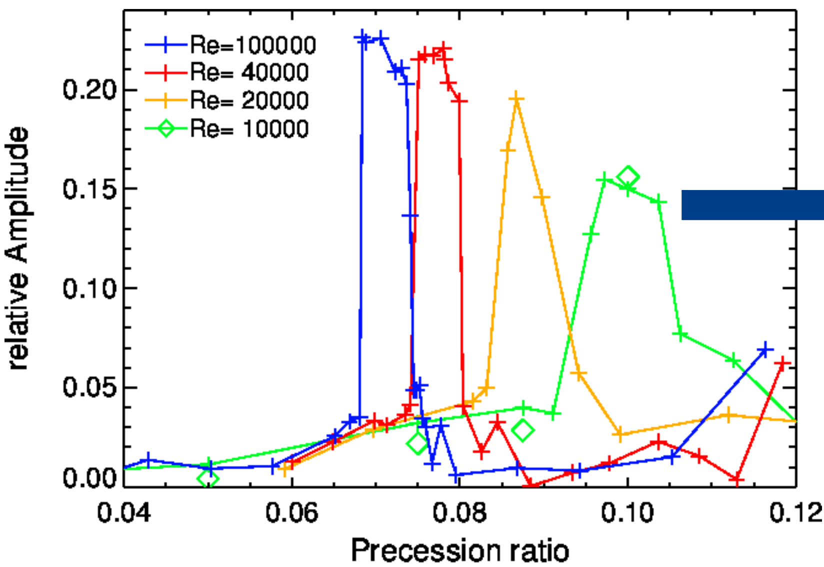
Shortly beyond that, the flow becomes turbulent

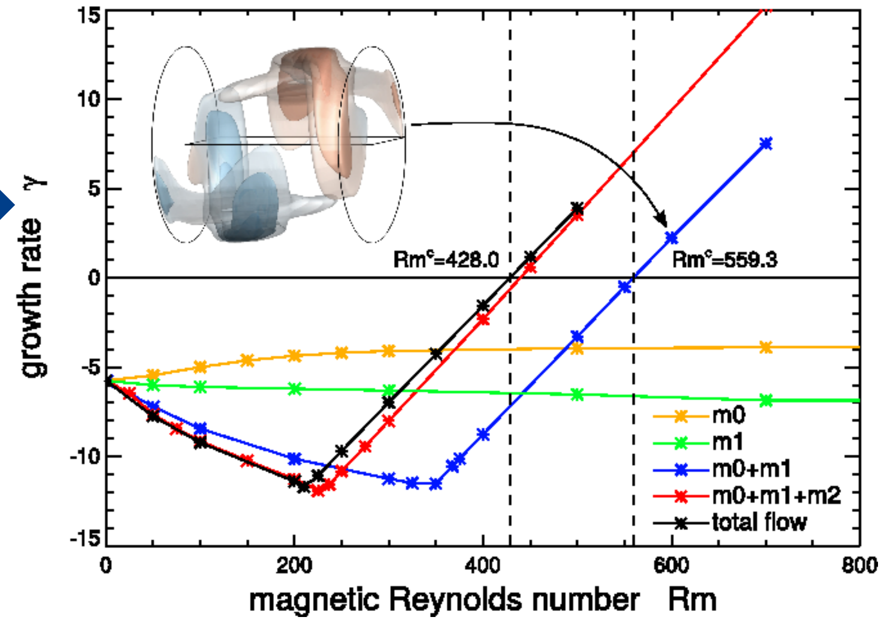


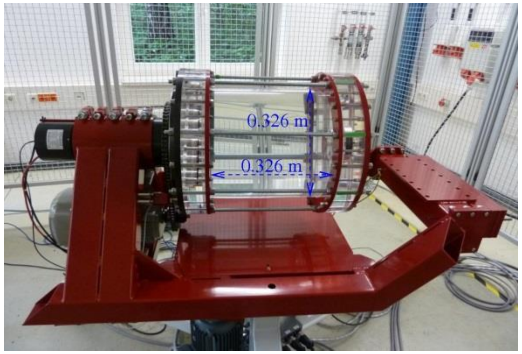
Giesecke et al., Phys. Rev. Lett. 120 (2018), 024502

Precession driven dynamo: Realistic prospects for self-excitation

- Remarkable agreement of numerics and experiment for Re=10000
- Experiment shows: double-roll flow remains robust for higher Re
- In a narrow range of the precession ratio, **dynamo is predicted for Rm~430** (Rm=700 is technically feasible)







Giesecke et al., Phys. Rev. Lett. 120 (2018), 024502

DRESDEN concept

HZDR

Schedule for precession experiment

- 14 March: pressure test of the rotation vessel (with 35 bars)
- 5 June: delivery of rotation vessel to HZDR
- 26 August: large slip-ring installed
- 7 November: rotation vessel mounted on the platform

After that:

- test of all systems
- dry rotation (also for calibrating strain gauges)
- 2020: water experiments
- 2021…: sodium experiments

Next steps for us…

1. Preparing the first water-experiments (to start in early 2020): André, Thomas, Tobias, Matthias, N.N. → next meeting 19 March

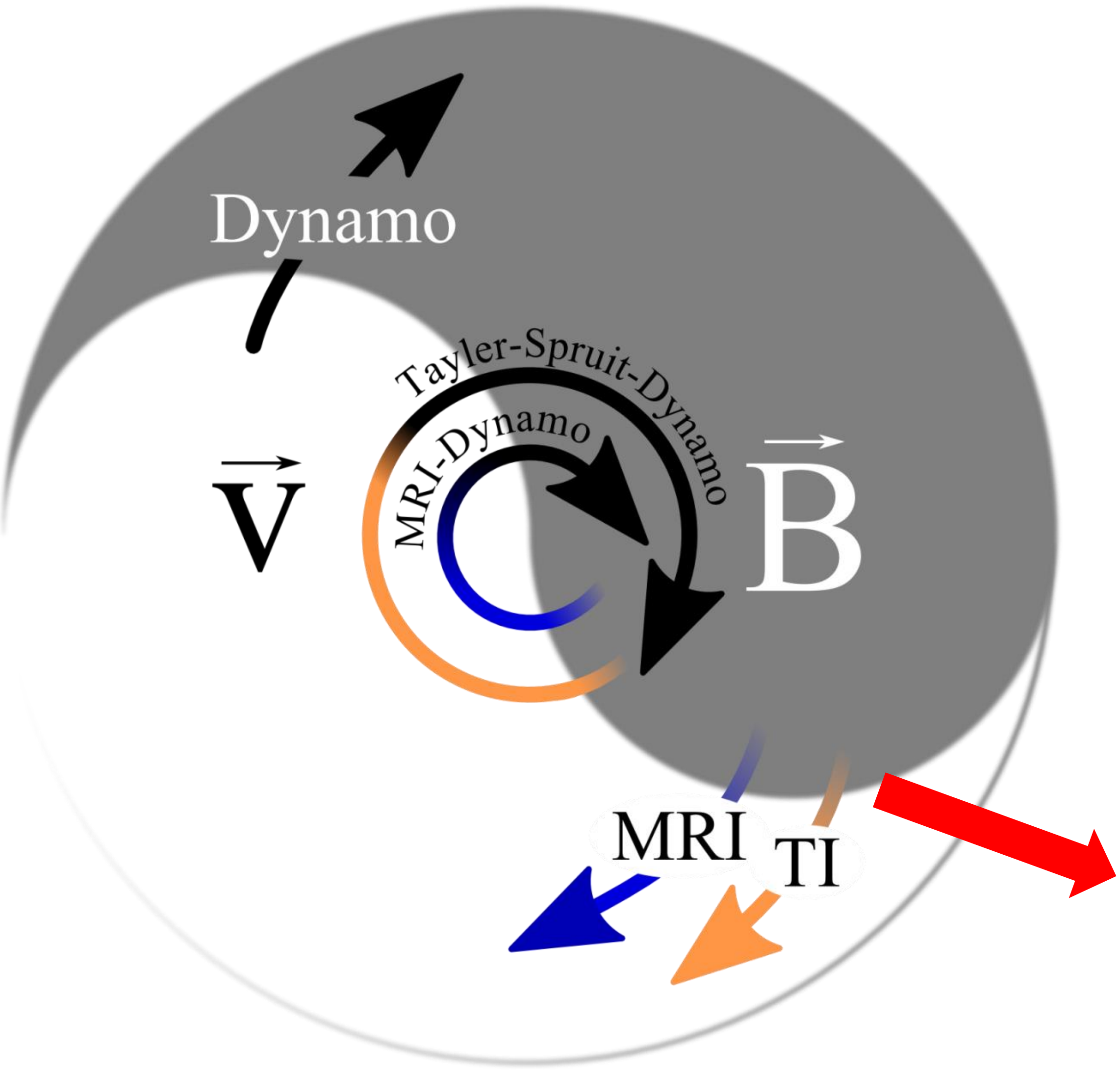
2. Simulations for different nutation angles: Federico, Jan Simkanin

3. Experiments and simulations for the case with inserted blades (André´s DFG project)

4. Securing the dynamo predictions by simulations with vacuum boundary conditions

5. Enhancing SEMTEX by induction equations in order to simulate a dynamically consistent dynamo

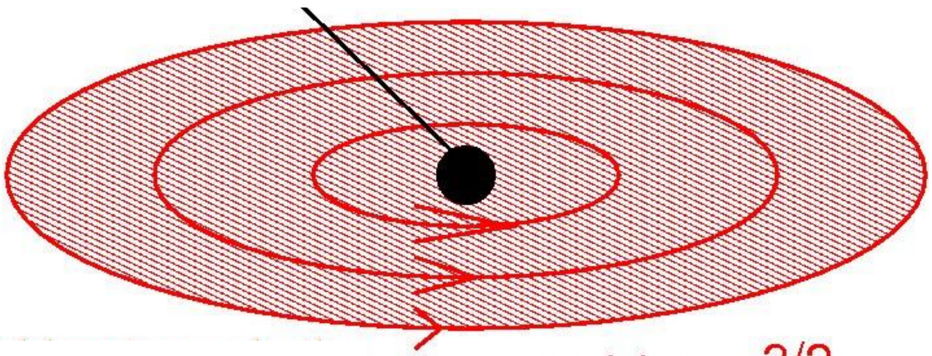
Magnetorotational and Tayler instability



Second part

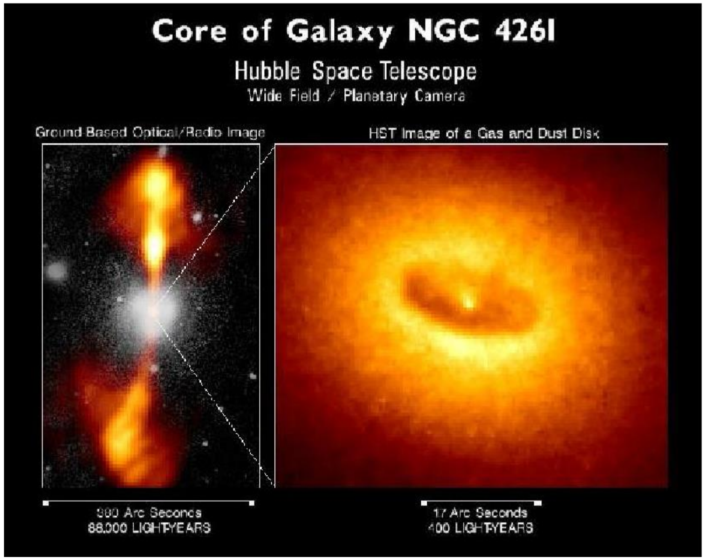
How do accretion discs work?

Central object (protostar, black hole)



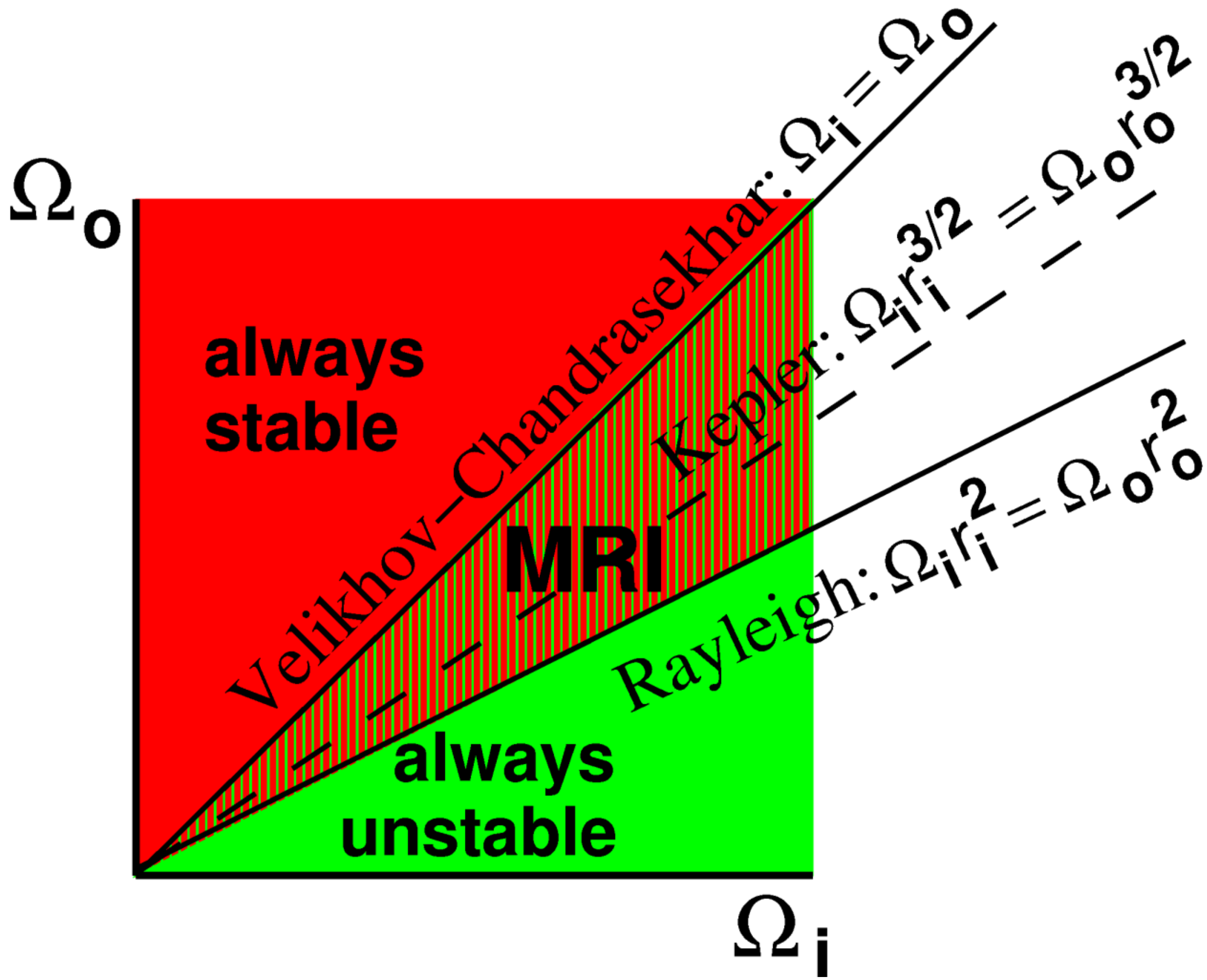
Accretion disk

$$\Omega(r) \sim r^{-3/2}$$
$$\Omega(r) r^2 \sim r^{1/2}$$



- 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?

History of MRI: Magnetized Tayler-Couette flow



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

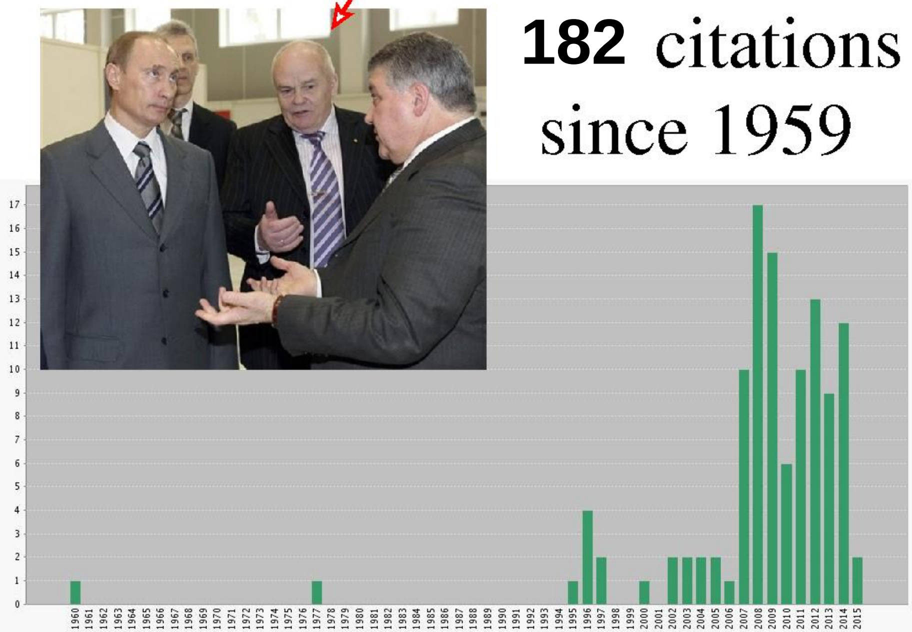
Rüdiger, Gellert, Hollerbach, Stefani, Phys. Rep. 741, 1 (2018)

DRESDEN concept HZDR

(Citation) history of MRI

E.P. Velikhov

182 citations since 1959



S.A. Balbus and J.F. Hawley

2689 citations since 1991

The discoverer (1959)

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

The adopters (1991)

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

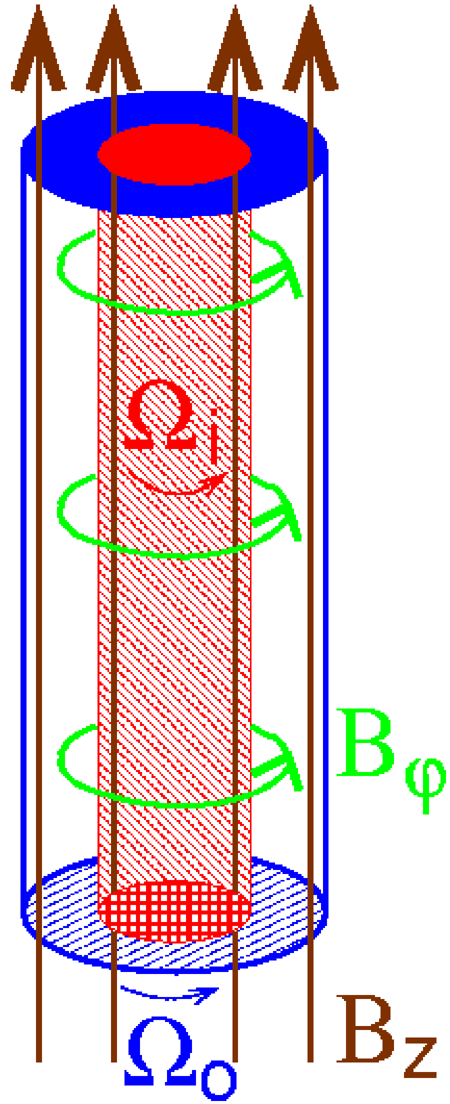
Standard MRI and helical MRI

- Standard MRI (with purely axial field) scales with Lundquist (S) und magnetic Reynolds (Rm)
- Experiments on SMRI with large Rm in Maryland and Princeton → DRESDYN
- Helical MRI: B_z replaced by B_z+B_φ: scales with Hartmann (Ha) and Reynolds (Re)

Hollerbach and Rüdiger: Phys. Rev. Lett. 95 (2005), 124501

- Re_{crit}: 10^3 instead of 10^6
- $Ha_{crit:}$ 30 instead of 1000

- → Potsdam ROssendorf Magnetic InStability Experiment (PROMISE)
- Drawback: does not work for Kepler (yet)!



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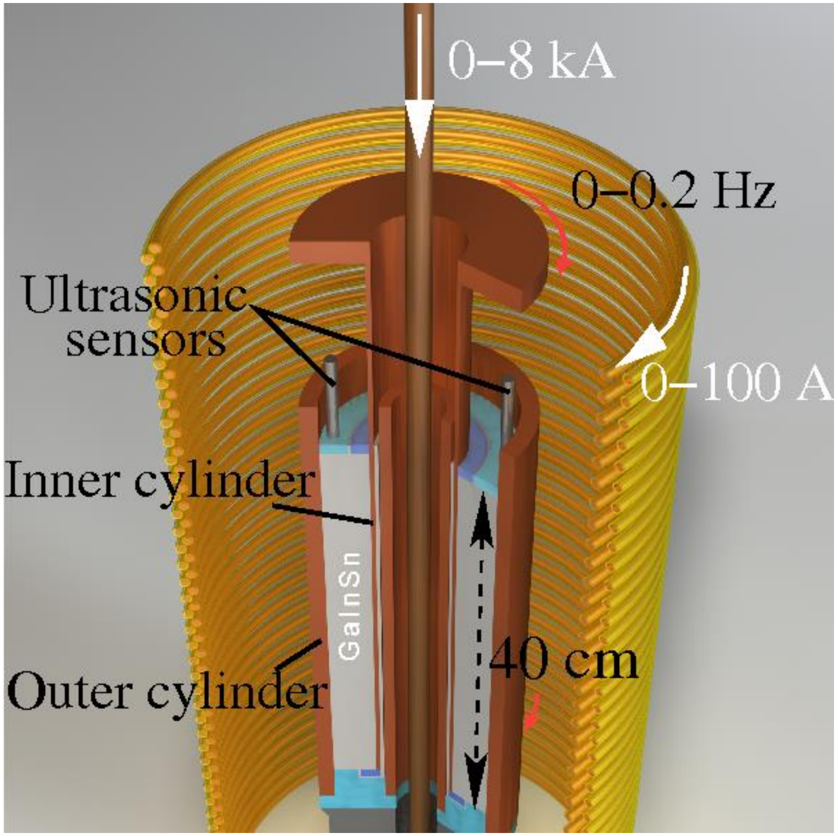
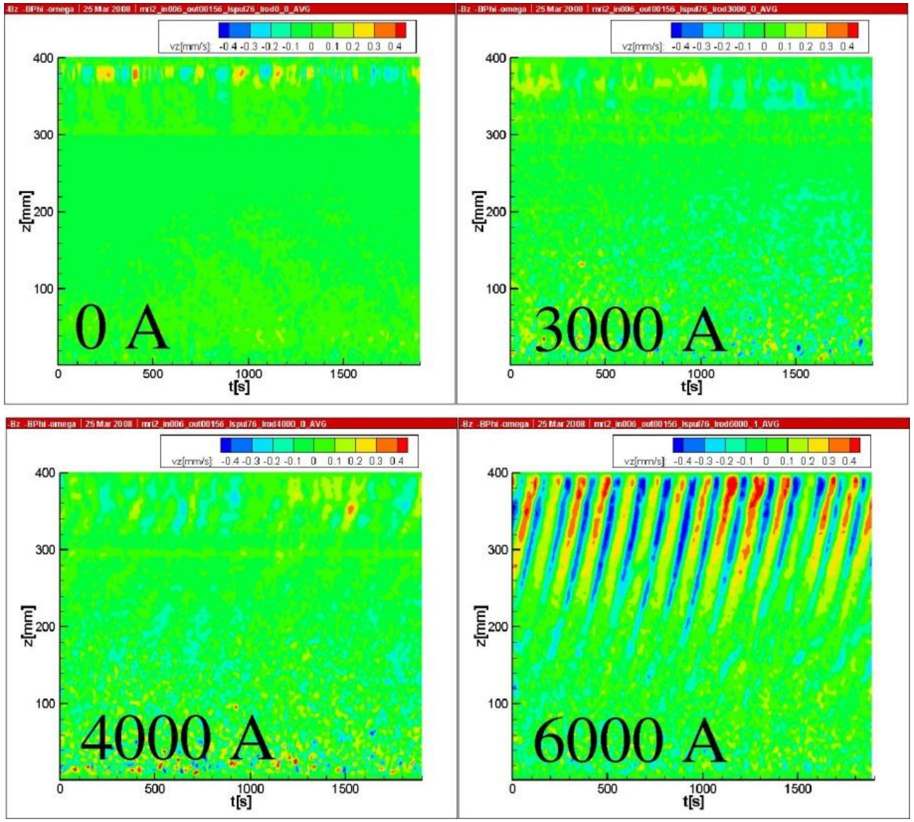
Helical magnetorotational instability (HMRI)

2006: First experimental evidence of HMRI

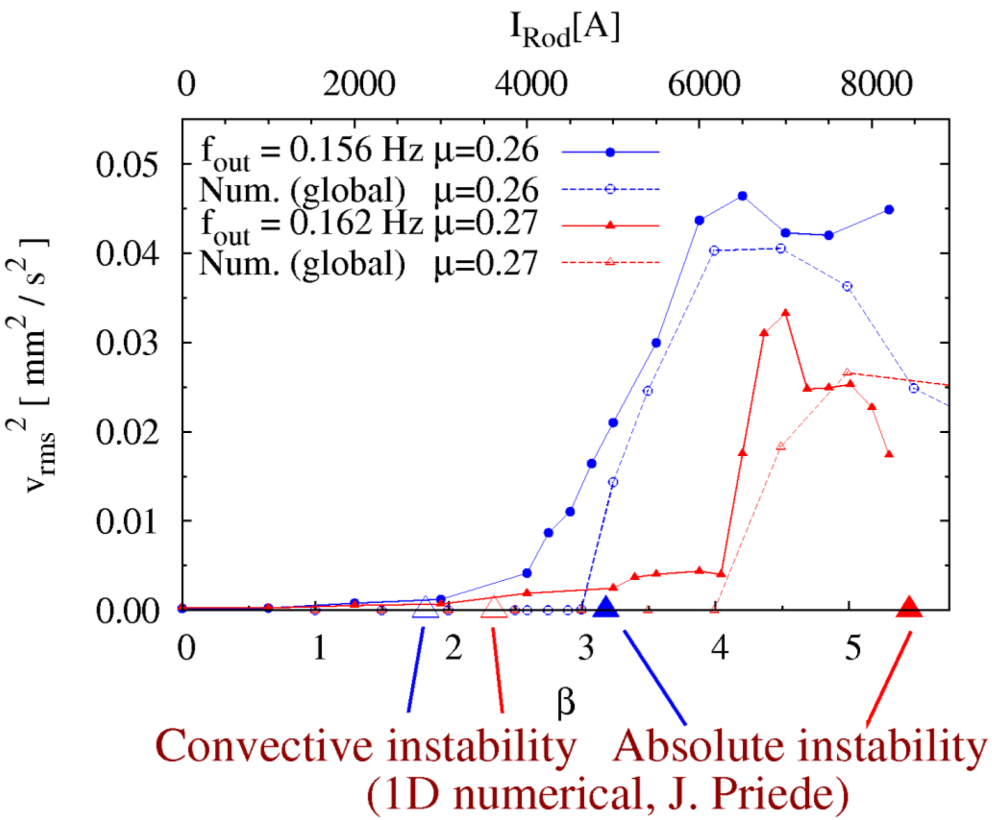


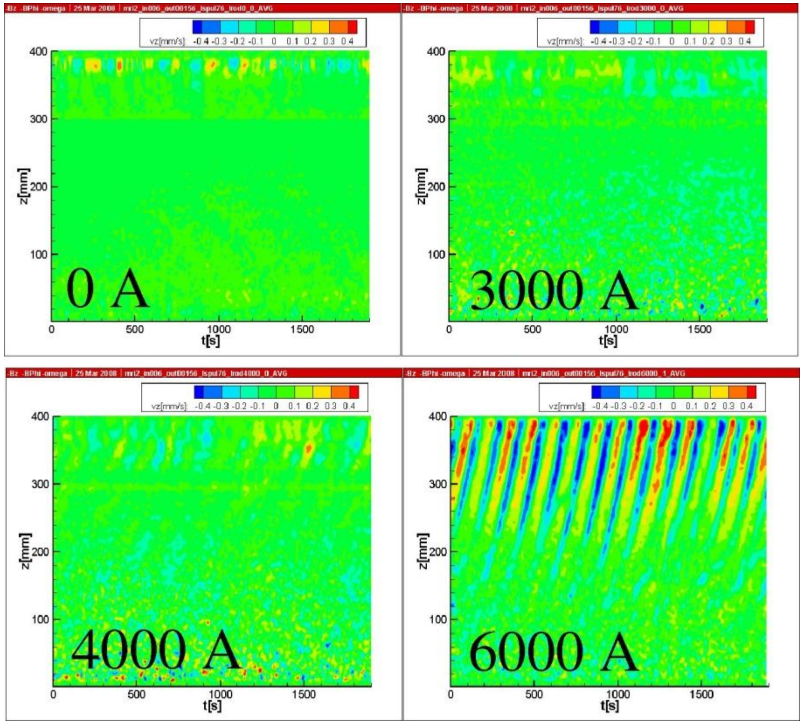


Stefani et al., Phys. Rev. Lett. 97 (2006), 184502; New J. Phys. 9 (2007), 295; Phys. Rev. E 80 (2009), 066303

HMRI: Experimental evidence, and good agreement with theory

Example: Increase of central current (i.e, of B_φ, and β)



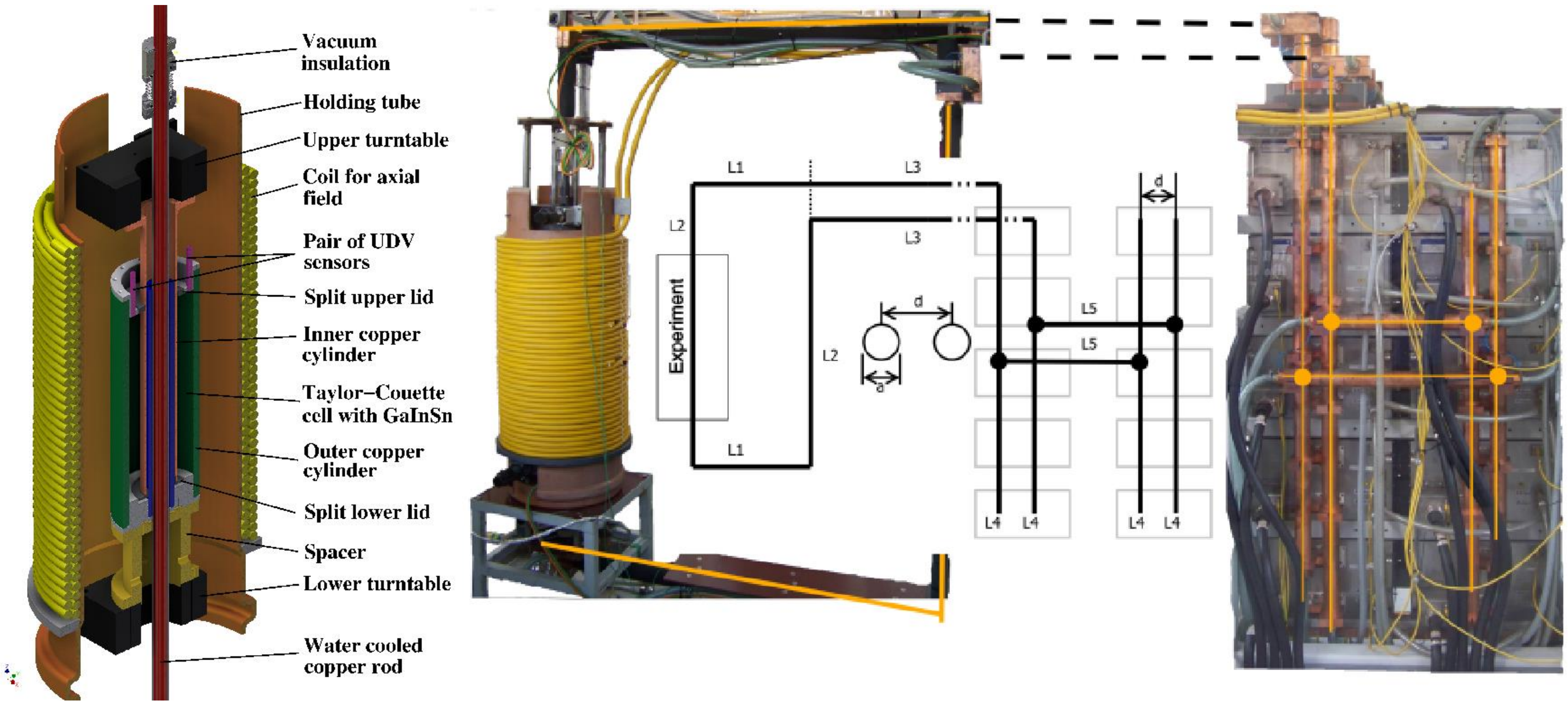


Stefani et al., Phys. Rev. E 80 (2009), 066303

Azimuthal MRI (AMRI): m=1 mode under influence of dominant B_φ

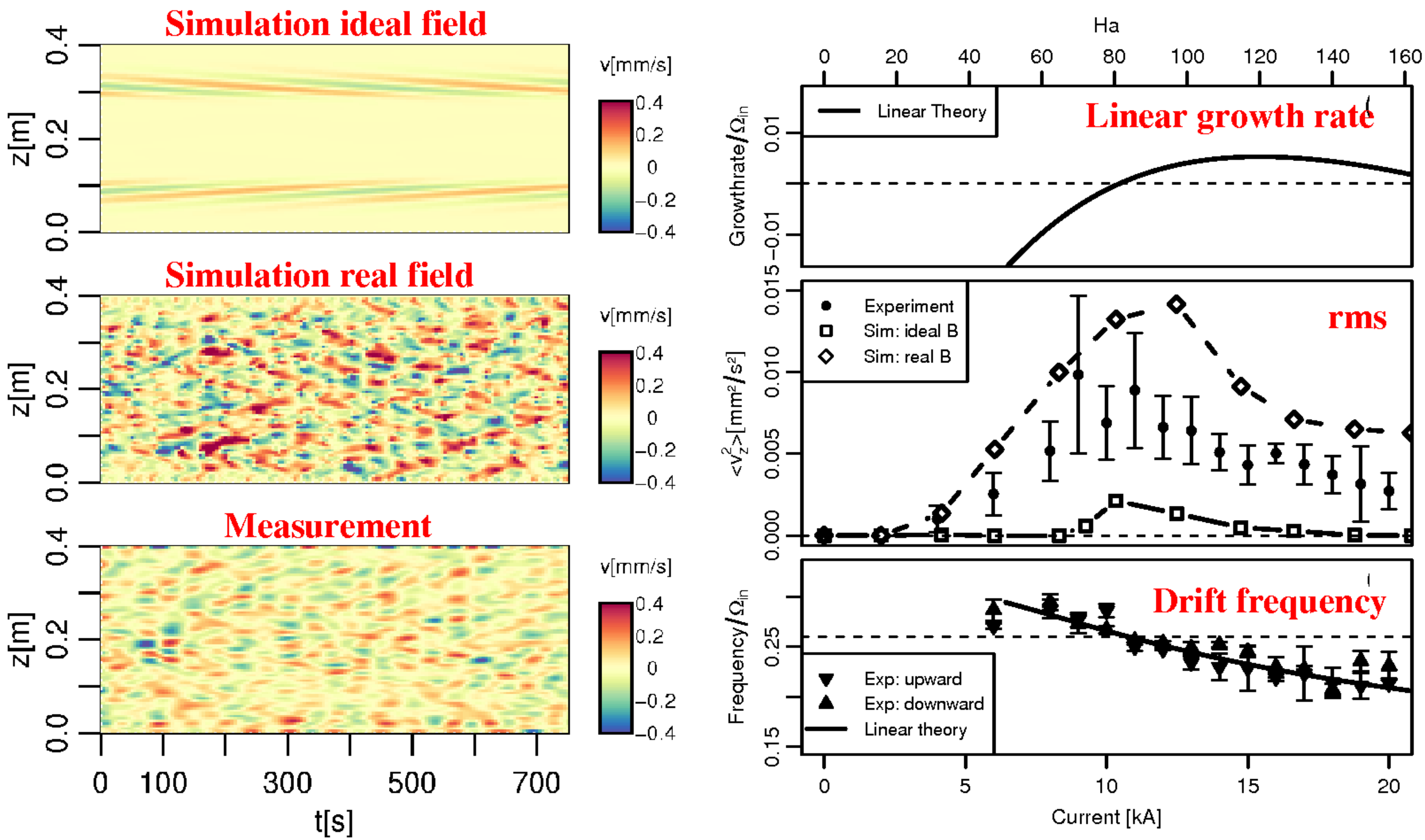
Hollerbach, Teeluck, Rüdiger:
Phys. Rev. Lett. 104 (2010), 044502

Power supply for 20 kA



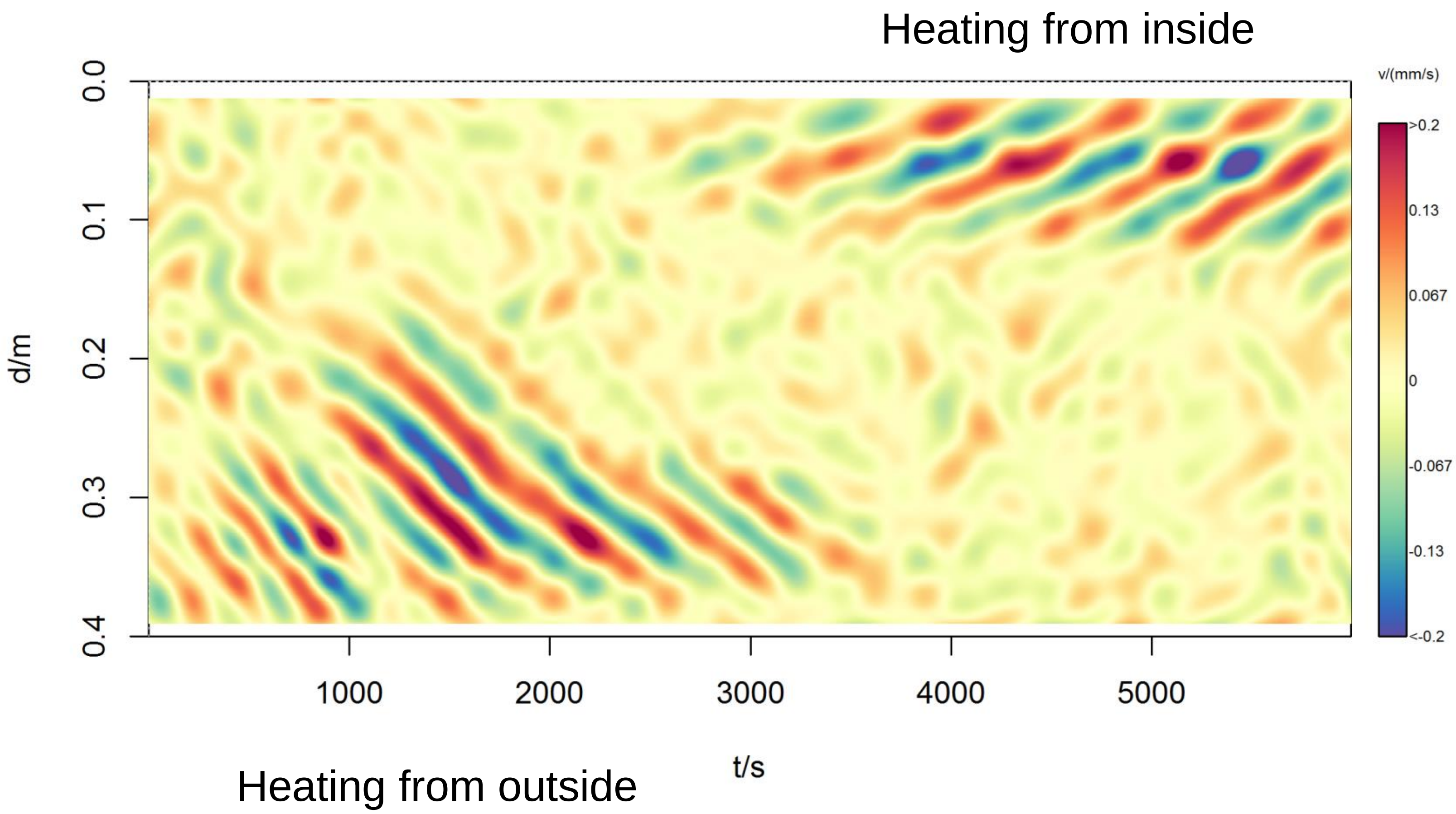
Very important: Numerical simulation of the real geometry, including the slight symmetry breaking of the applied magnetic field

Evidence for AMRI: m=1 mode under influence of (nearly) pure B_φ



Seilmayer et al., Phys. Rev. Lett. 113 (2014), 024505

New results show effect of convection on mode selection of AMRI



Seilmayer et al., PAMIR conference proceedings

Instabilities in spherical Couette experiment (HEDGEHOG)

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Research

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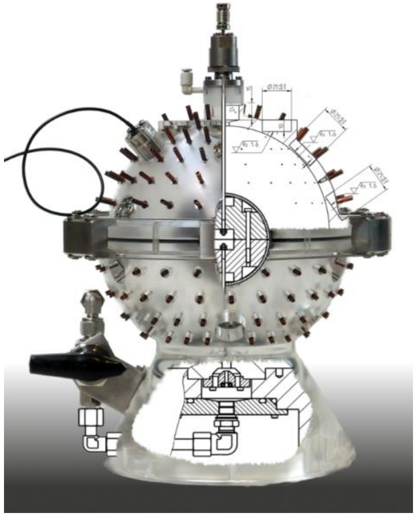
Article submitted to journal

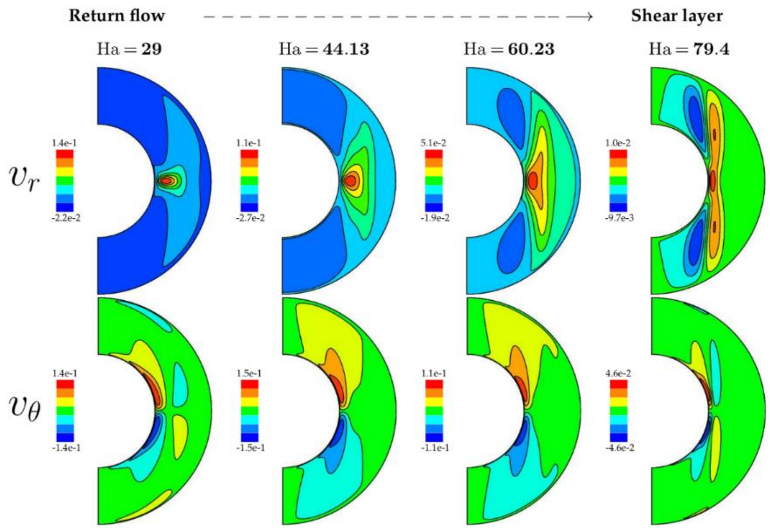
Subject Areas:
applied mathematics, fluid mechanics, astrophysics

Continuation and stability of rotating waves in the magnetized spherical Couette system: Secondary transitions and multistability

Ferran Garcia[1,2] and Frank Stefani[1]

[1]Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstraße 400, D-01328 Dresden, Germany
[2]Anton Pannekoek Institute for Astronomy, University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, The Netherlands





New results on modulated waves in HEDGEHOG

→ 2 April, Talk by Ferran

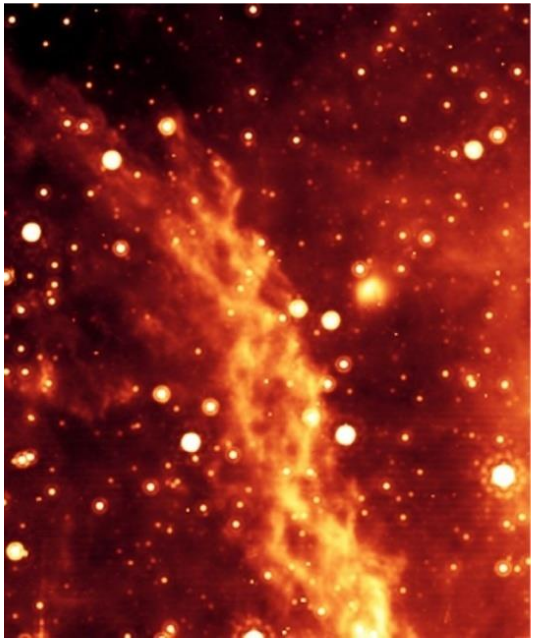
DRESDEN concept

HZDR

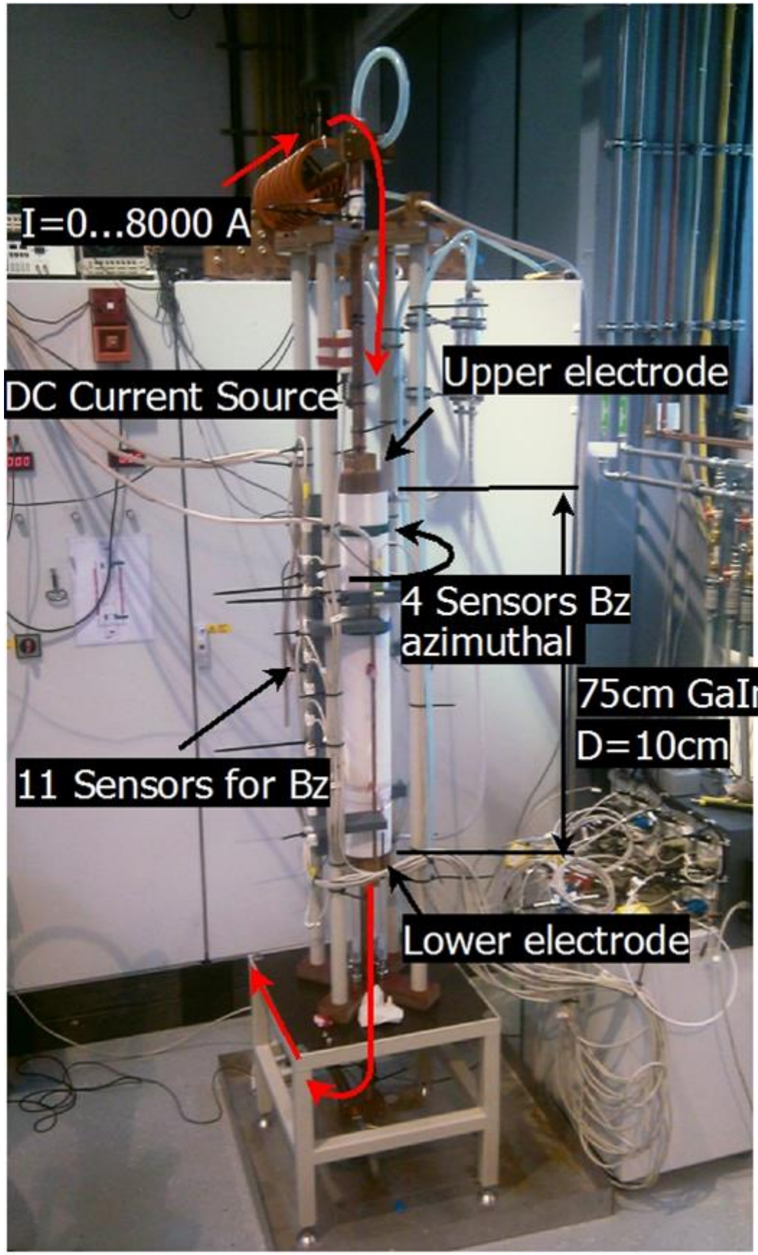
Kink-type Tayler instability (TI)

Astrophysical motivation:

- Alternative mechanism of solar dynamo (Tayler-Spruit dynamo)
- Braking of neutron stars
- Structure formation in cosmic jets

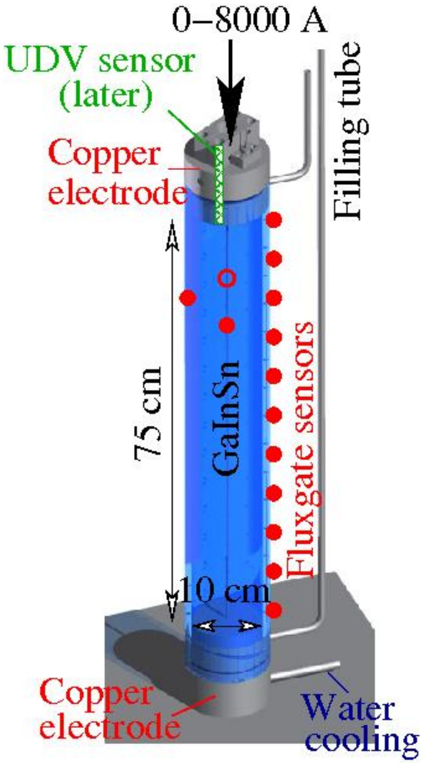


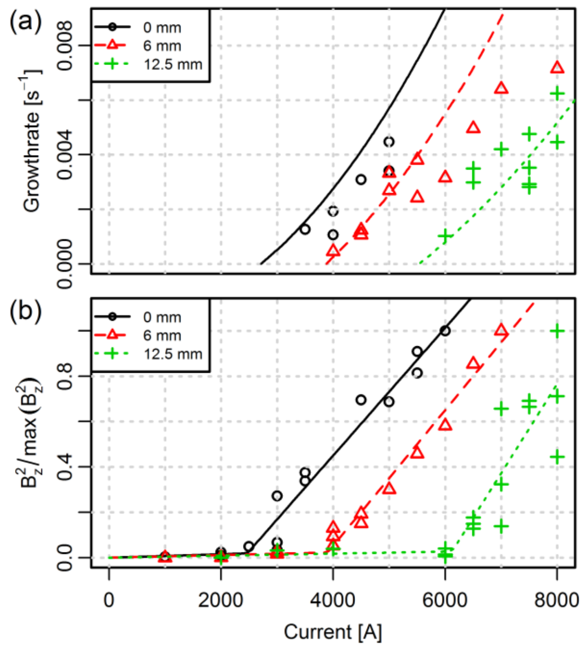
Seilmayer et al., Phys. Rev. Lett. 108 (2012), 244501



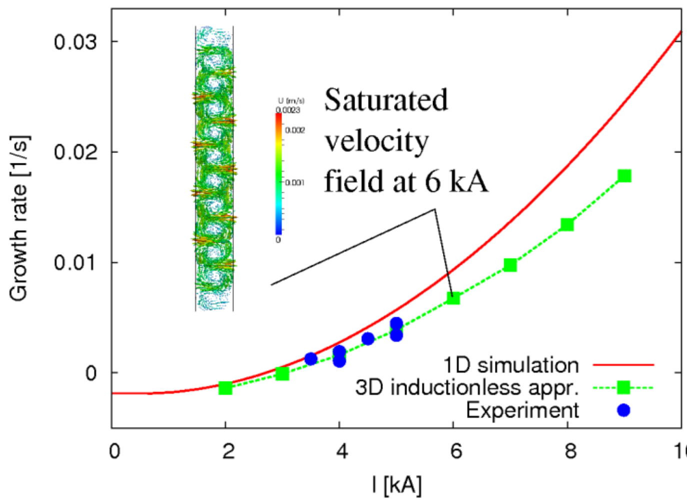
Tayler-Spruit dynamo: Experimental and numerical results for TI

Experiment





Numerics



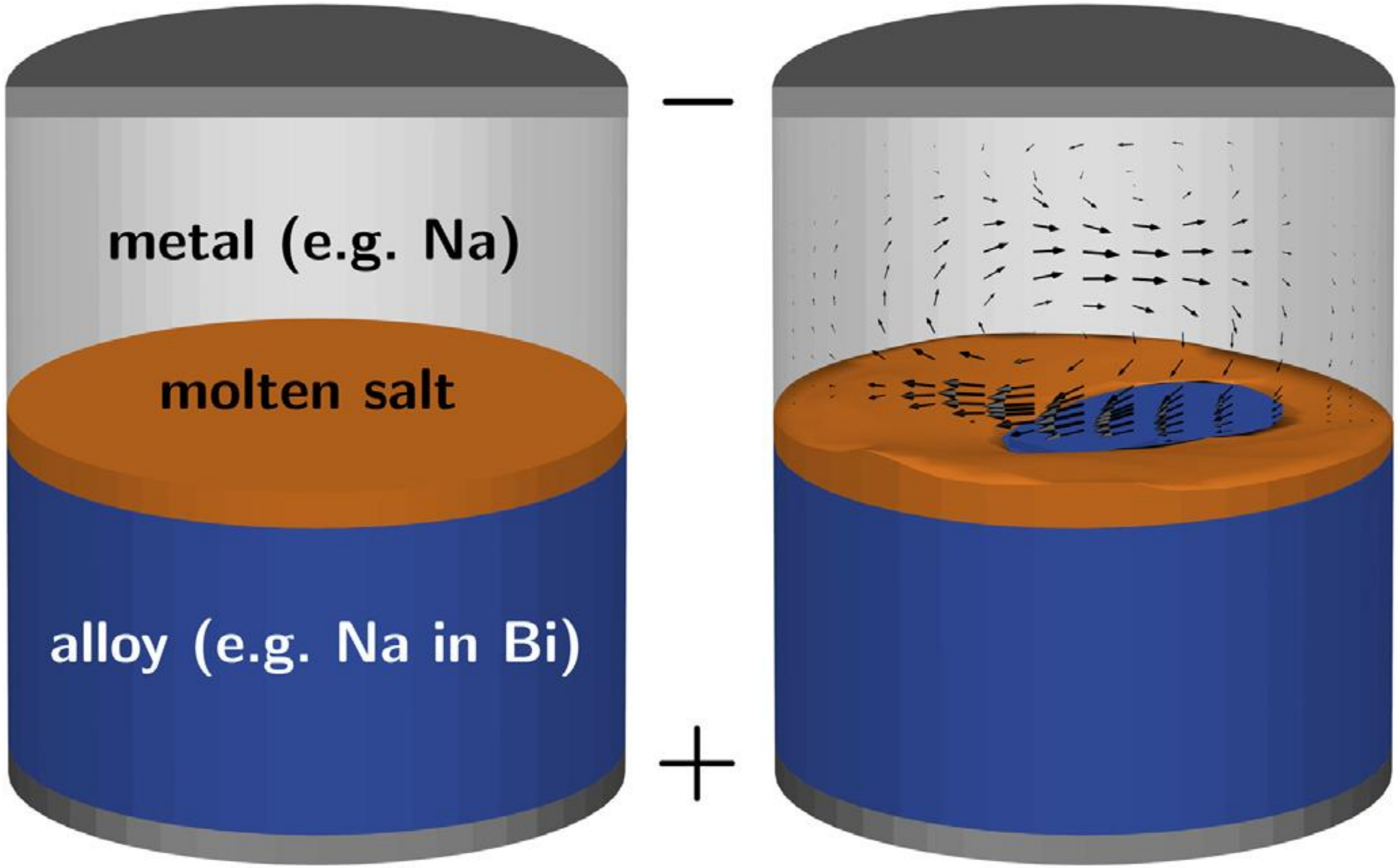
Weber et al., New J. Phys. 15 (2013), 043034

Seilmayer et al., Phys. Rev. Lett. 108 (2012), 244501

DRESDEN concept

HZDR

Relevance of TI (and other instabilities) for liquid metal batteries?



Stefani et al., Energy Conv. Managem. 52 (2011), 2982; Weber et al., J. Power Sources 265 (2014), 166; Stefani et al. IOP Conf. Ser.: Mater. Sci. Eng. 143 (2016), 012024

Combined MRI/TI experiment planned in the framework of DRESDYN

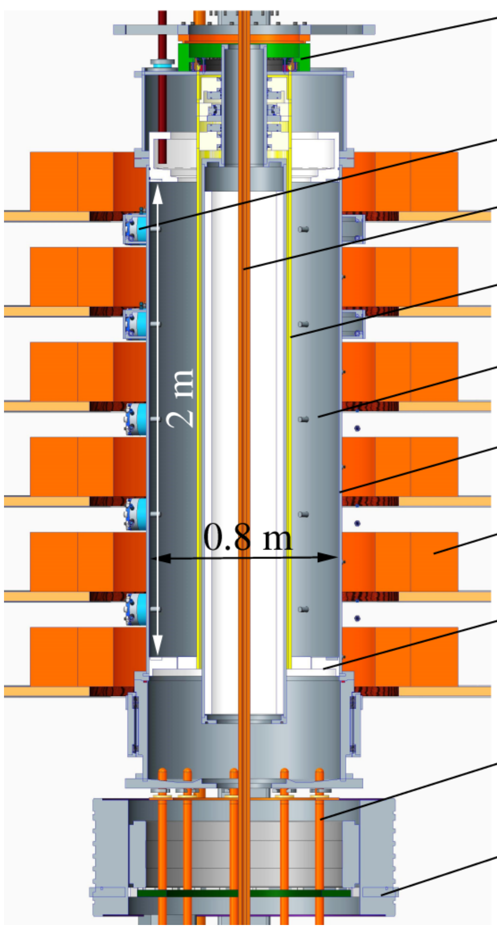
...will (hopefully) allow us to study helical MRI, azimuthal MRI, standard MRI, and their combinations with Tayler instability

- R_{in}=0.2 m
- R_{out}=0.4 m
- H=2 m

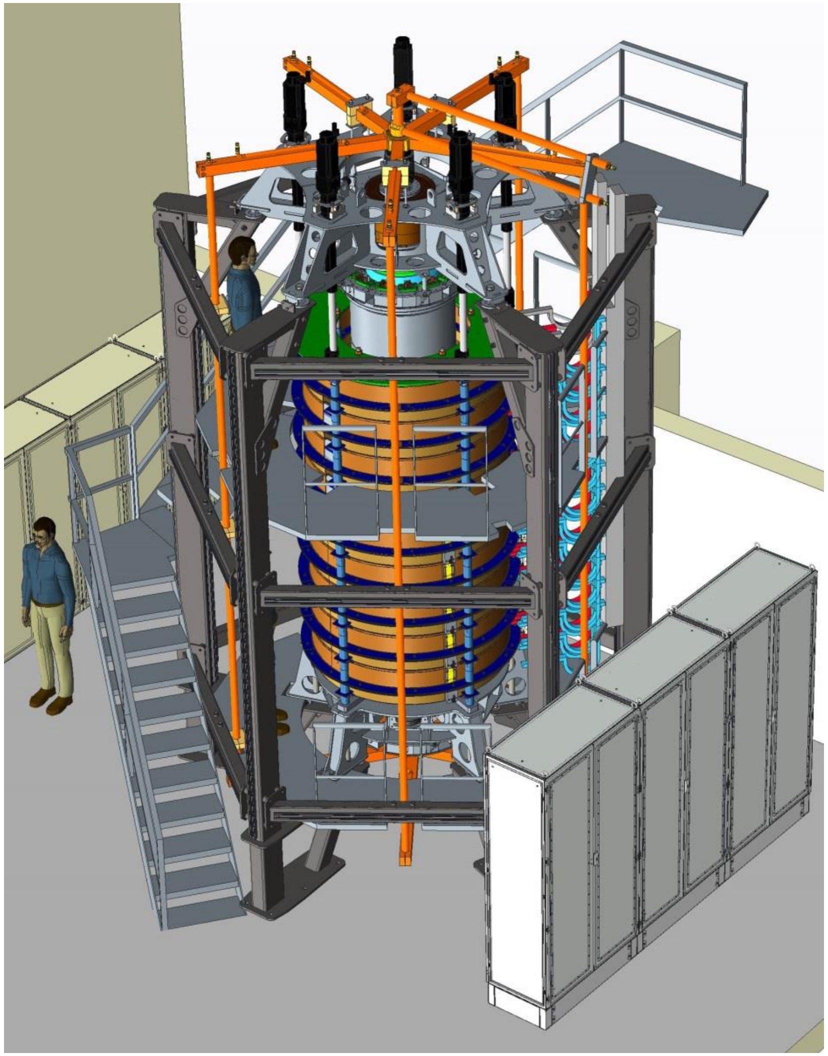
- f_{in}=20 Hz
- f_{out}=6 Hz

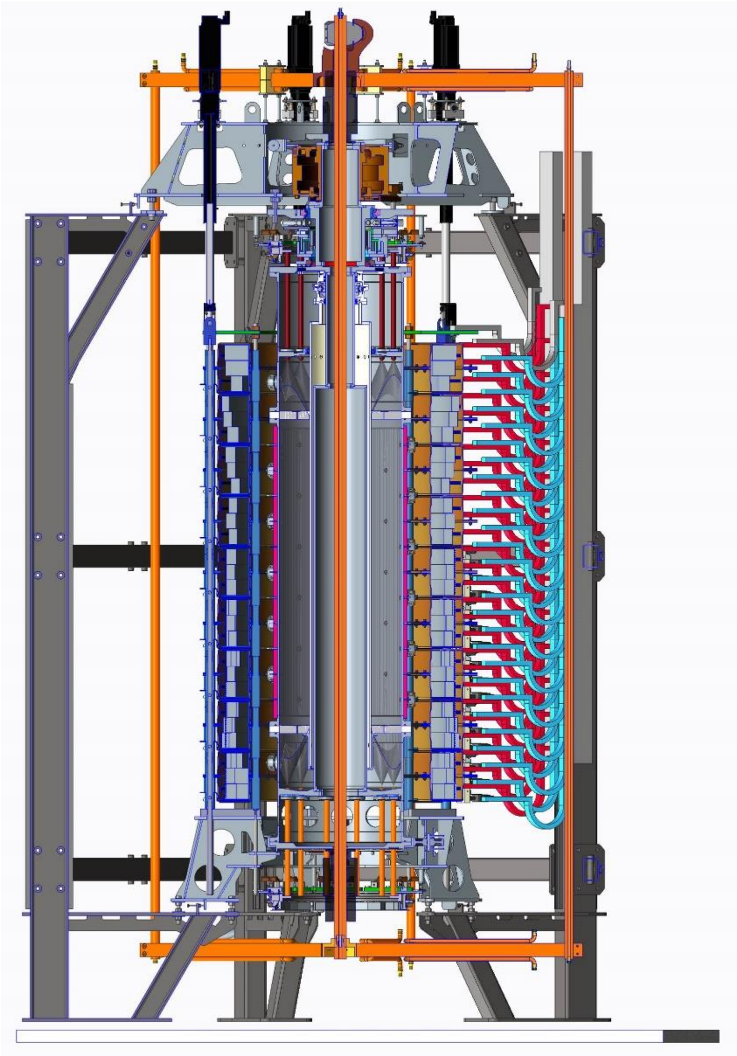
- B_z=120 mT
- (will need some 110 kW)

- Rm=40
- Lundquist=8

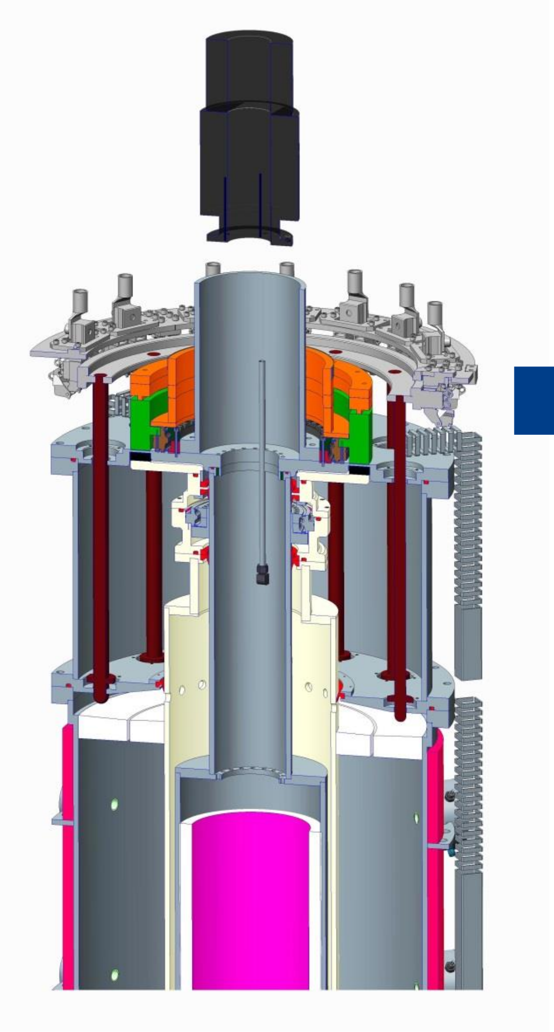


Combined MRI/TI experiment: (nearly) final design

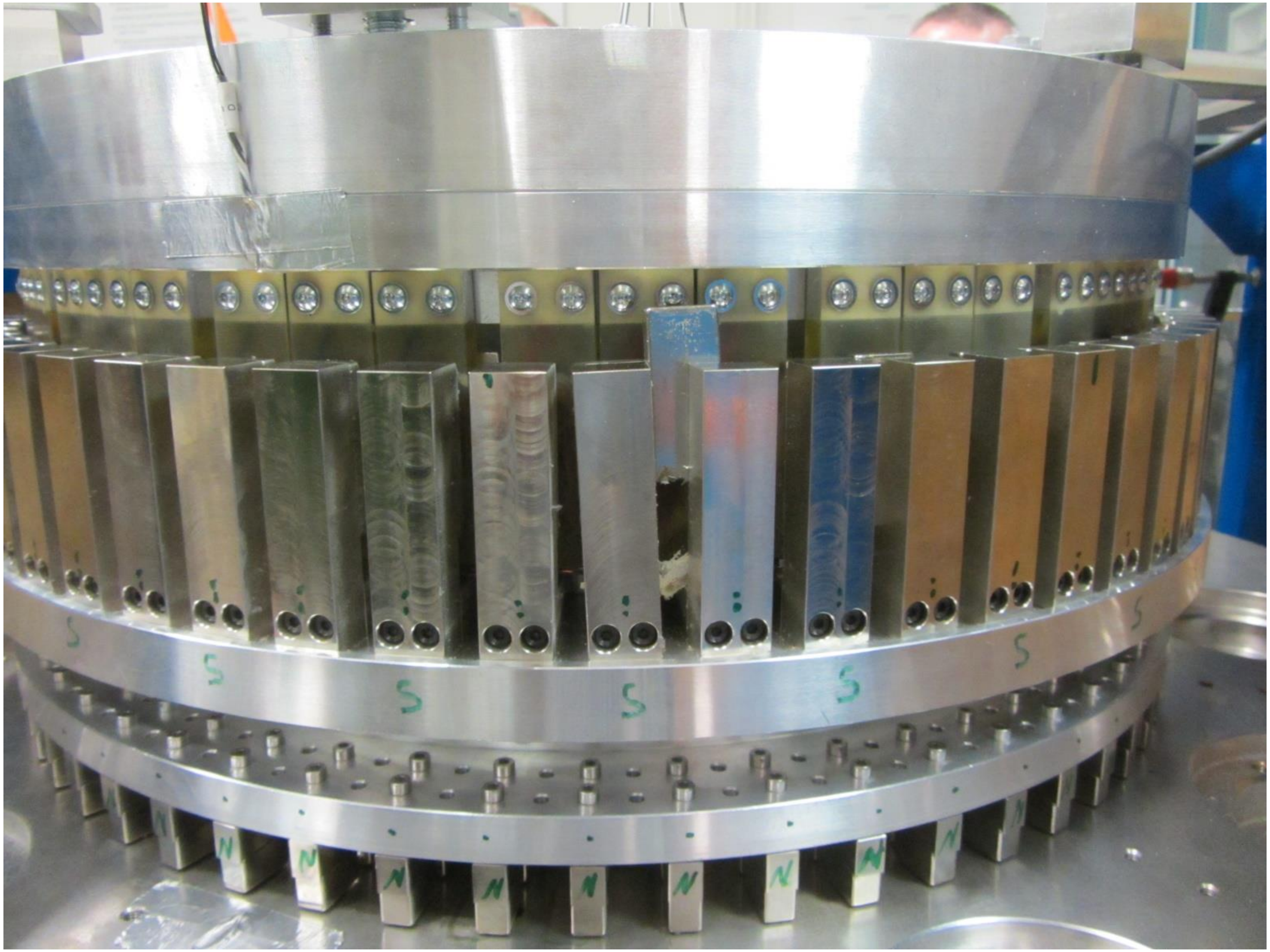




Combined MRI/TI experiment: test of magnetic coupler



First test failed with a crash at 1000 rpm! Repair is finished...

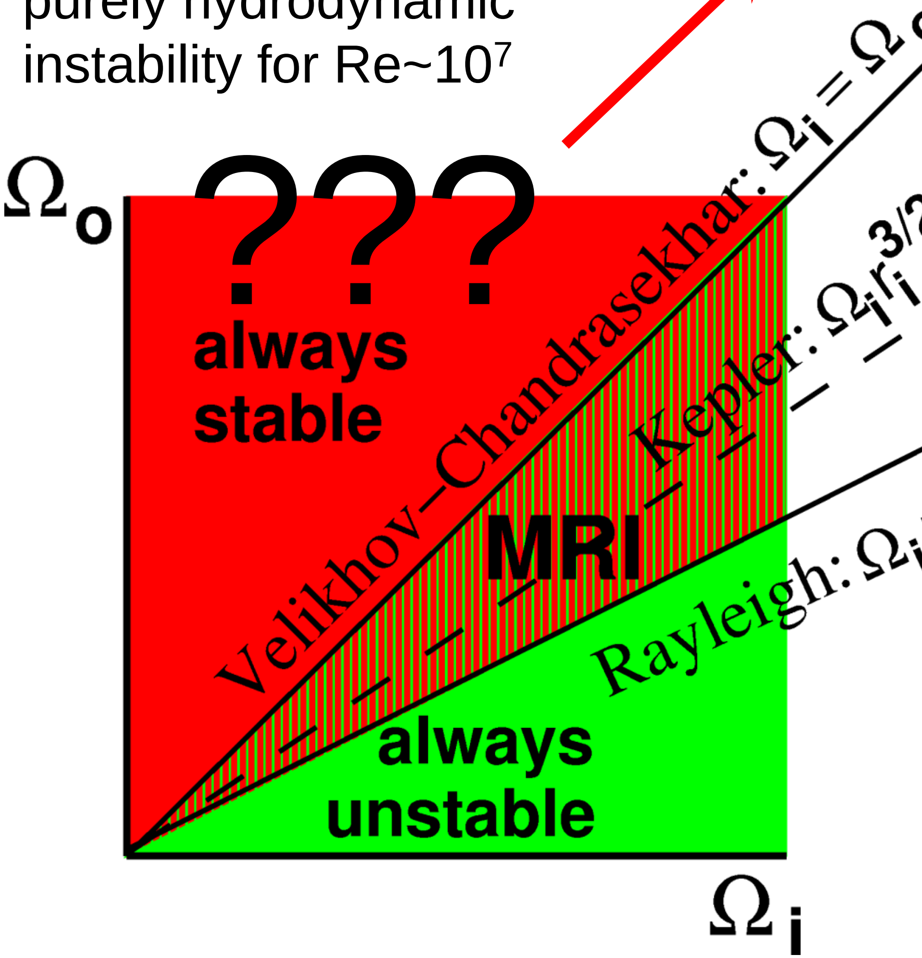


Basic problem: Are rotational flows with positive shear always stable?

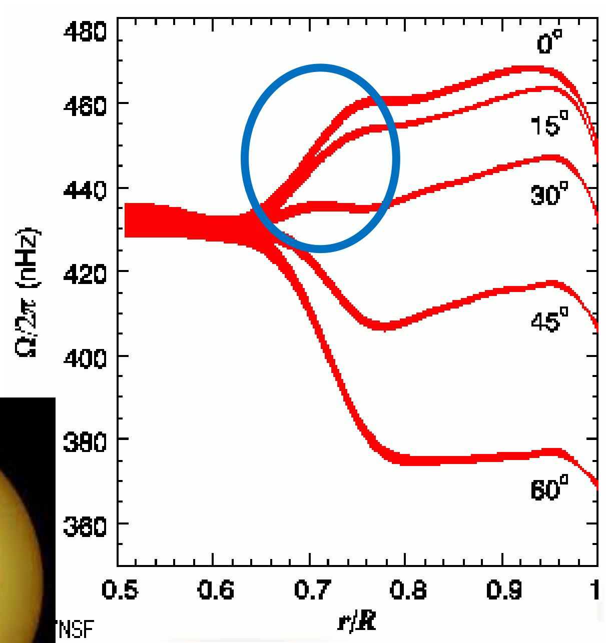
Deguchi, Phys. Rev. E 95 (2017), 021102

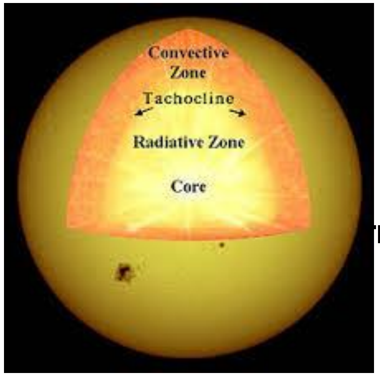
Non-axisymmetric purely hydrodynamic instability for Re~10^7

HERE: Prospects for **magnetic** destabilization

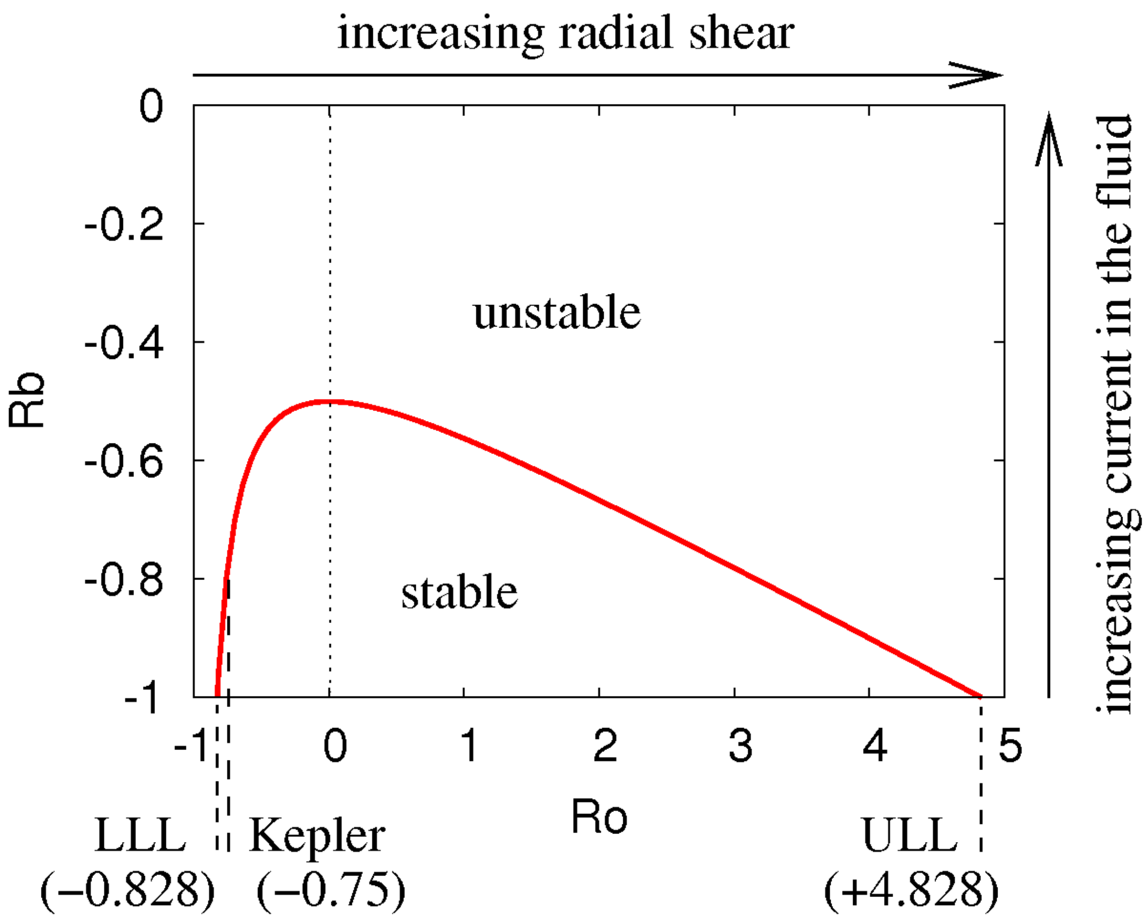


Possible relevance for the equator-near parts of the solar tachocline





Can magnetic fields destabilize rotational flows with positive shear?



Lower Liu Limit ⬆ **Upper Liu Limit** ⬆

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

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

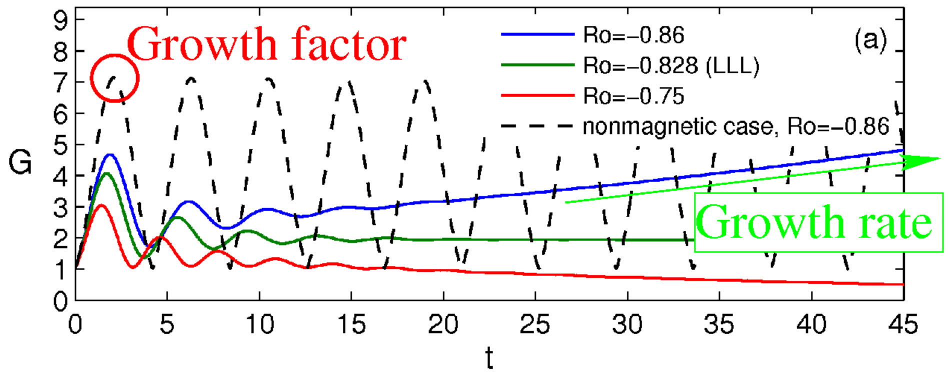
$$\boldsymbol{Rb = -\frac{1}{8}\frac{(Ro+2)^2}{Ro+1}}$$

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

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

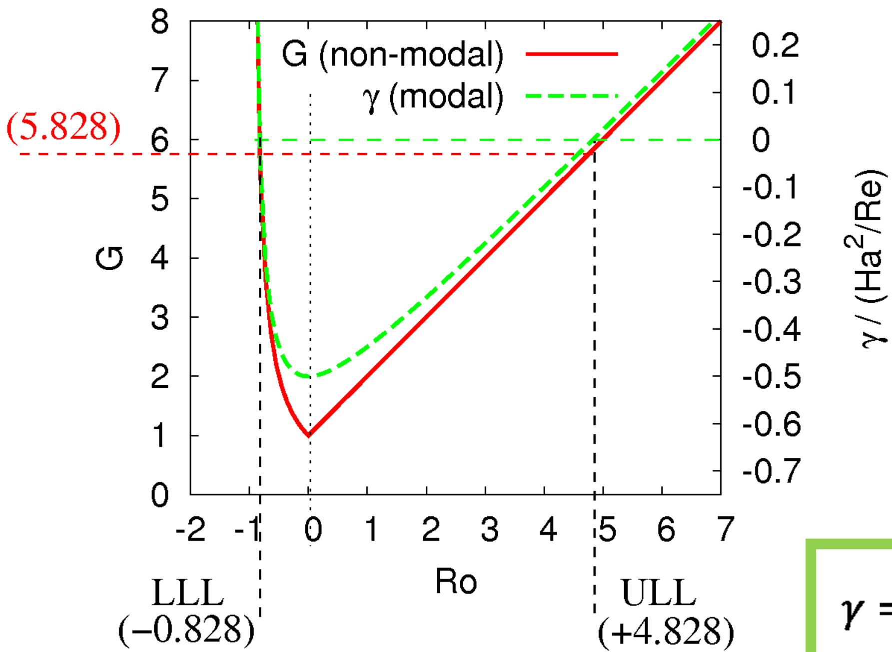
DRESDEN concept HZDR

Link between non-modal growth and dissipation-induced instabilities



Any physical reason for the lower and upper Liu limits (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

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

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

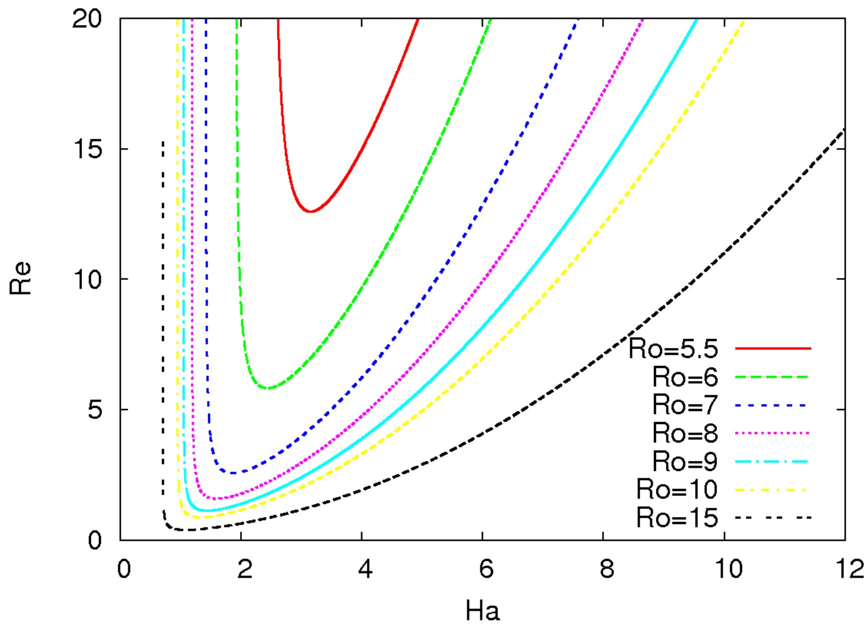
Mamatsashvili and Stefani, PRE 94, 051203 (R) (2016)

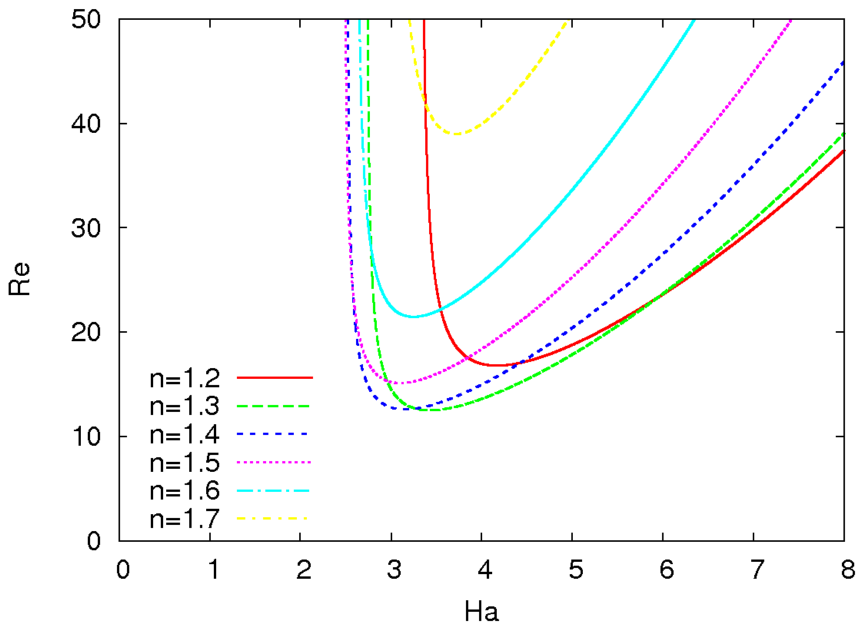
DRESDEN concept HZDR

AMRI at positive shear - „Super-AMRI" - operates at $Ro > Ro_{OLL} = 4.828$

Stability curve as a solution of :

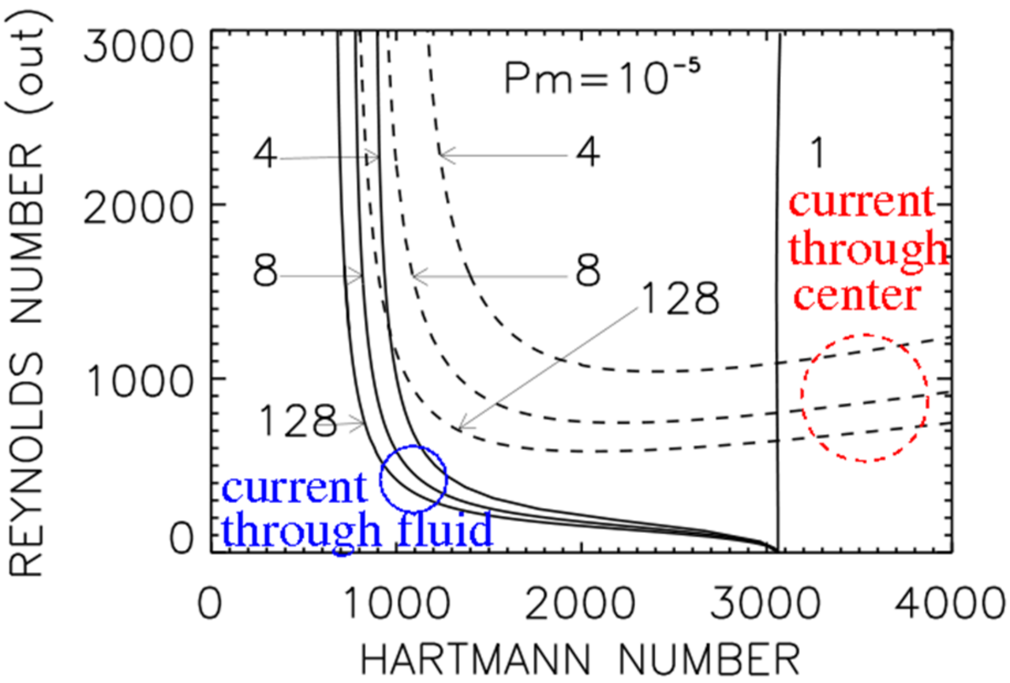
$$Re^2 = \frac{1}{4}\frac{[(1+Ha^2n^2)^2 - 4\,Ha^2Rb(1+Ha^2n^2) - 4Ha^4n^2][1+Ha^2(n^2-2Rb)]^2}{Ha^4Ro^2n^2 - \left[\left(1+Ha^2(n^2-2Rb)\right)^2 - 4Ha^4\,n^2\right][Ro+1]}$$





Stefani and Kirillov and Stefani, Phys. Rev. E 92 (2015), 051001

Super-AMRI also found in 1D-stability analysis



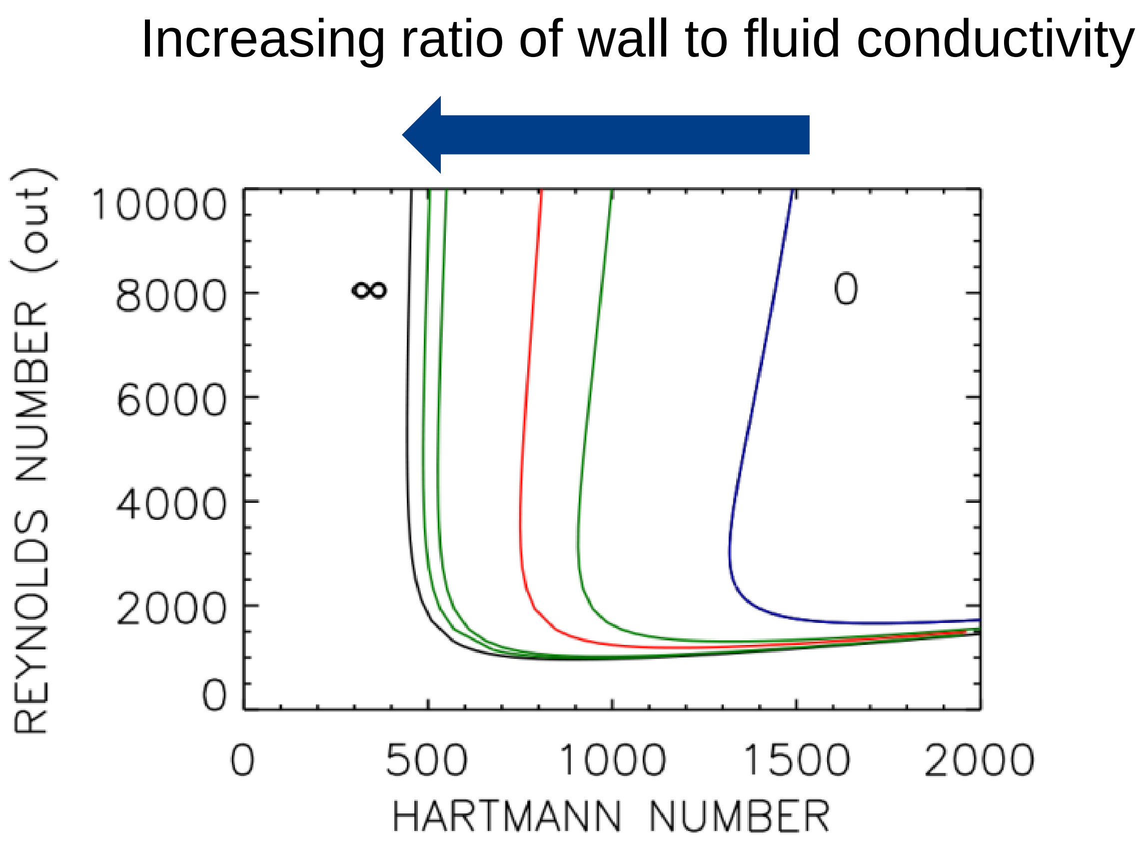
(dashed lines are the stability boundaries of Super-AMRI at different $\mu=\Omega_{out}/\Omega_{in}$ =4,8,128> 1)

Rüdiger et al., Phys. Fluids 28 (2016), 014105

Translation of the unstable range $Ro>Ro_{ULL}$ in the local analysis into the ratio of outer and inner cylinders' angular frequencies for super rotation $\mu=\Omega_{out}/\Omega_{in} > 1$ in the global case is crucial!

Taylor-Couette-Experiment with small gap is needed (at least r_{in}/r_{out}~0.8), Minimum central current ~ 30 kA

„Super-AMRI“ experiment with sodium seems feasible



R_i/R_o=0.9

- Using copper walls, best value for R_i/R_o=0.78: I=33 kA
- This should be doable in a dedicated sodium experiment

Rüdiger et al., Geophys. Astrophys. Fluid Dyn. 112, 301 (2018)

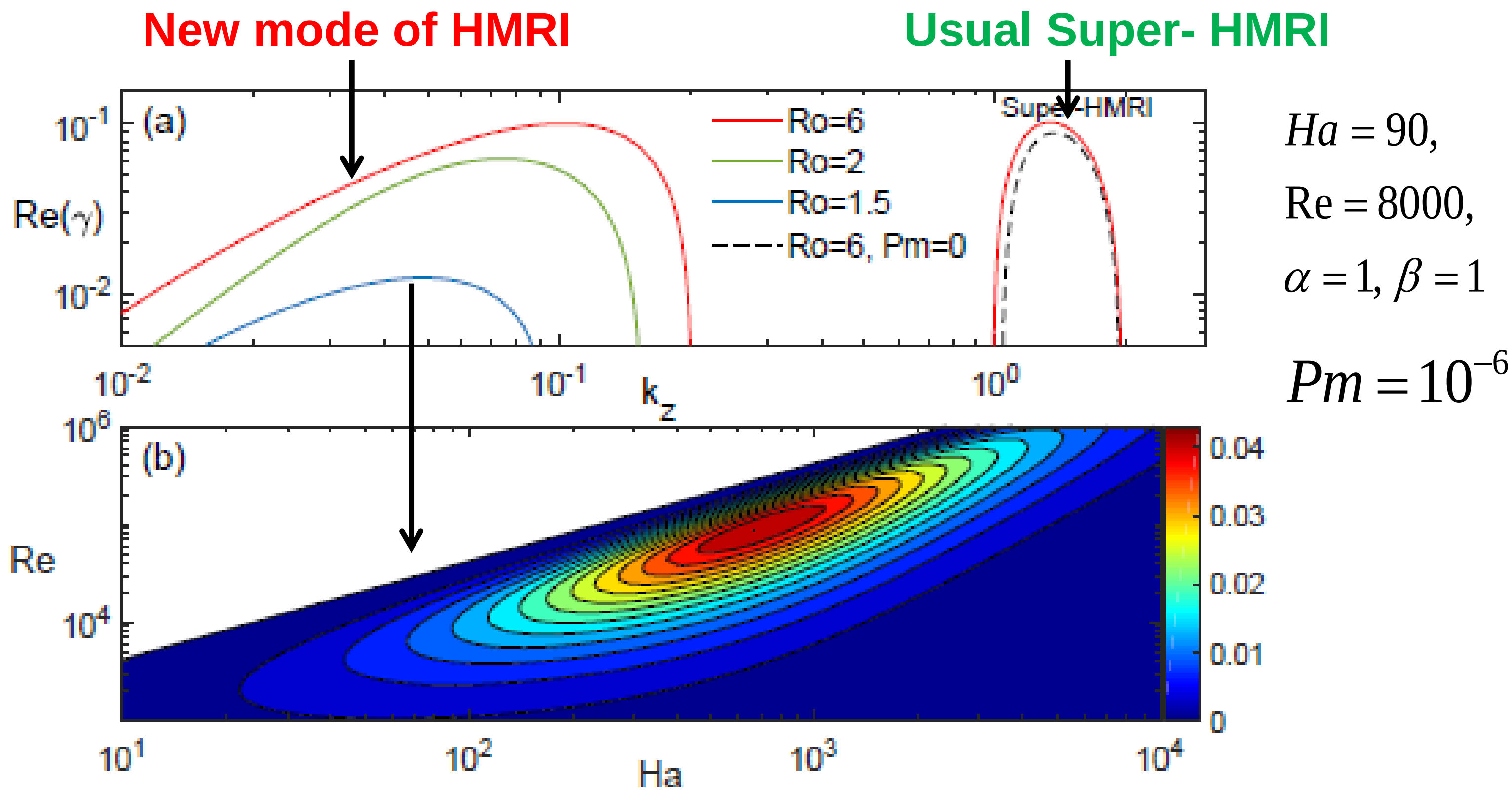
Yet, this type of Super-AMRI is a bit frustrating since...

...the upper Liu limit value $Ro>Ro_{OLL}$ =4.828 is quite a large positive shear compared to those found in astrophysical objects or in usual lab experiments. (for example, the positive shear in the equatorial parts of the solar tachocline is only Ro~0.5)

→ Open questions:

- Can any sort of HMRI and/or AMRI still survive at astrophysically relevant, smaller positive shear?
- Can such an instability still operate at wider gap width in TC flows (e.g., for $\boldsymbol{r_{in}/r_{out}}$**~0.5**) corresponding to **PROMISE** and the **DRESDYN** MRI/TI experiment

What about Super-HMRI? A big suprise…



$Ha = 90,$
$\mathrm{Re} = 8000,$
$\alpha = 1, \beta = 1$
$Pm = 10^{-6}$

1. A new mode of HMRI: at small k_z , all Ro and non-zero (finite) $Pm \neq 0$

2. Usual Super-HMRI: at larger k_z, high shear $Ro > Ro_{ULL}$, down to the inductionless limit $Pm = 0$ (dashed black line)

Mamatsashvili et al., arXiv:1810.13433

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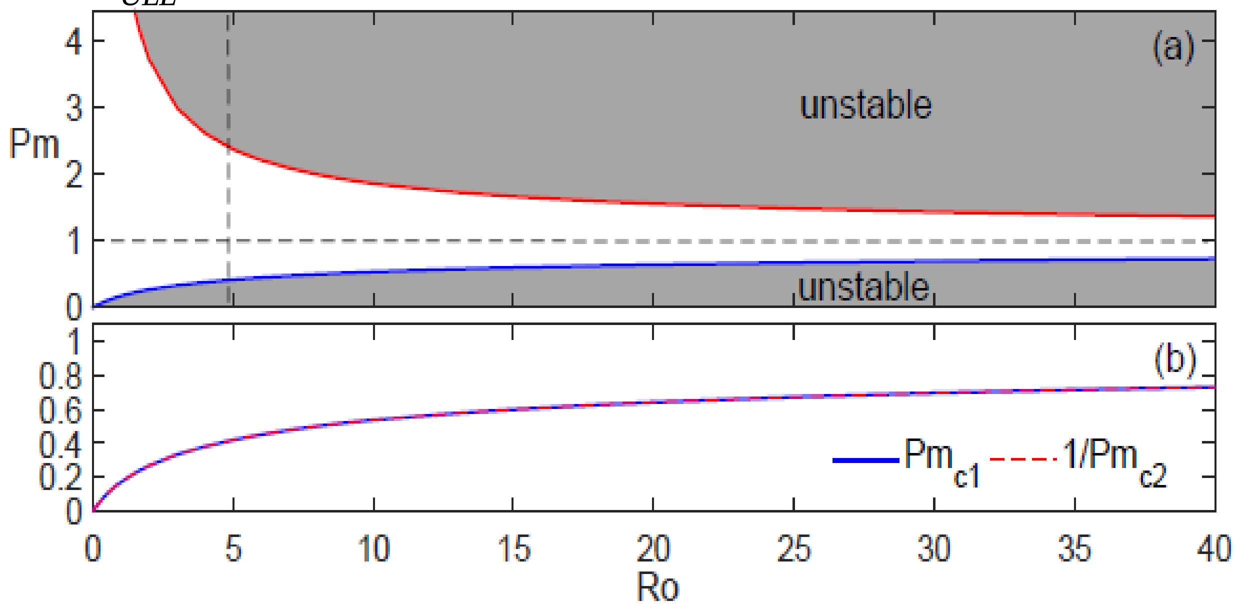
The instability domain in the Ro-Pm plane

$Ro_{ULL} = 4.828$



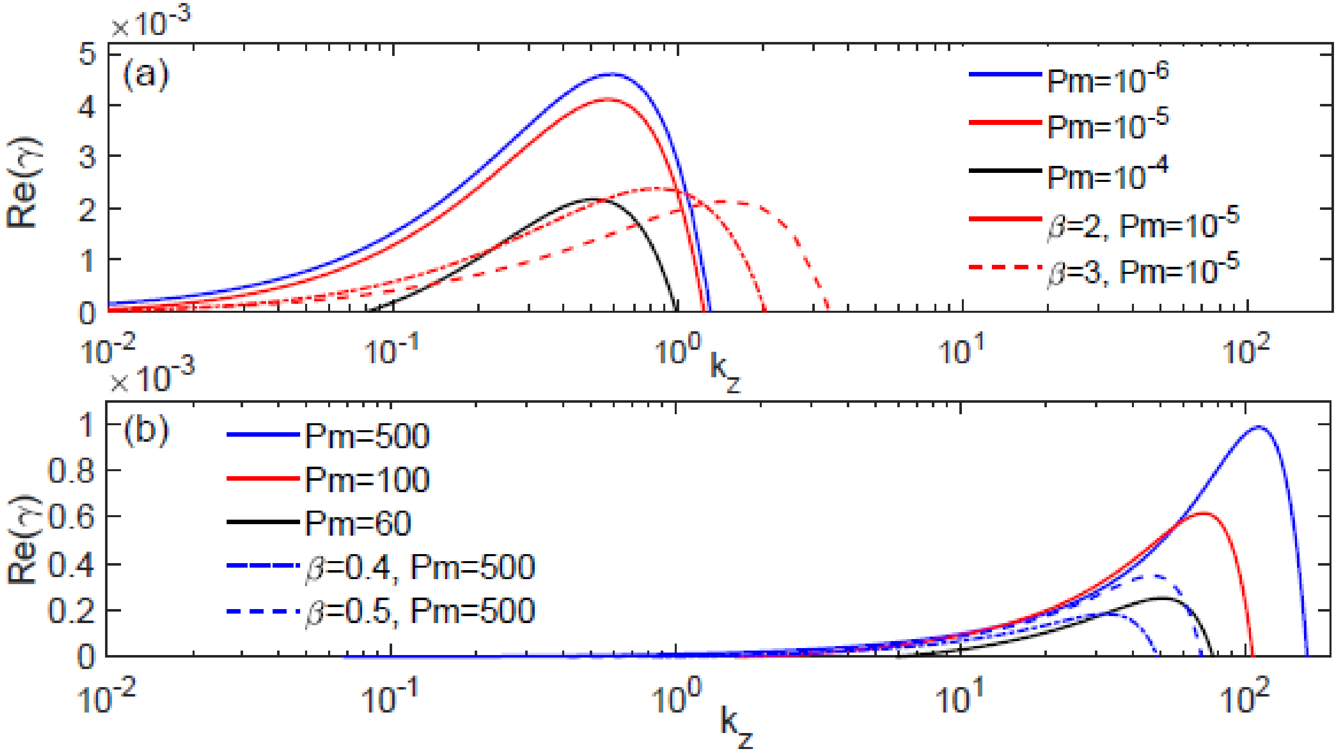
The stability boundaries at $Pm_{c2}(Ro) > 1$ (red) and $Pm_{c1}(Ro) < 1$ (blue) are related by

$$Pm_{c1} = \frac{1}{Pm_{c2}}$$

The new double-diffusive HMRI is not constrained by the upper Liu limit.

There is no instability at Pm=1 .

Results: 1D Confirmation of WKB result for Pm<<1 and Pm>>1



1. Ha and Re (or S and Rm), as well as k_z, increase with β in qualitative agreement with the scalings in the WKB analysis

2. At small $Pm << 1$, relevant parameters are again the Lundquist, S, and magnetic Reynolds Rm numbers, as in the WKB case

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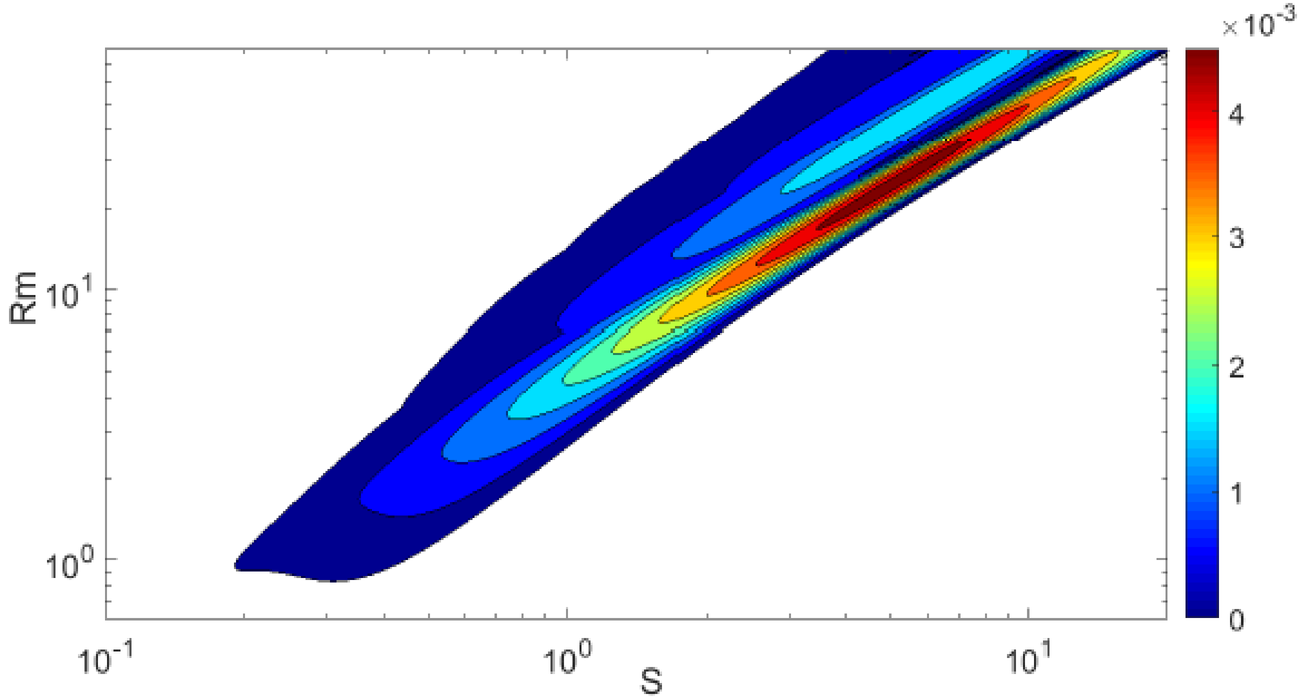
Results: Growth rate (optimized over k_z) in the (S-Rm) plane



$Pm = 10^{-6}$

$\beta = 1$

The unstable region is localized, as in the local analysis, reaching a maximum value $\gamma_m = 4.8 \cdot 10^{-3}$ at $S_m = 5.2,\ Rm_m = 25$

The instability emerges at the minimum $Rm_c = 0.9$ and $S_c = 0.3$

Prospects for an experiment

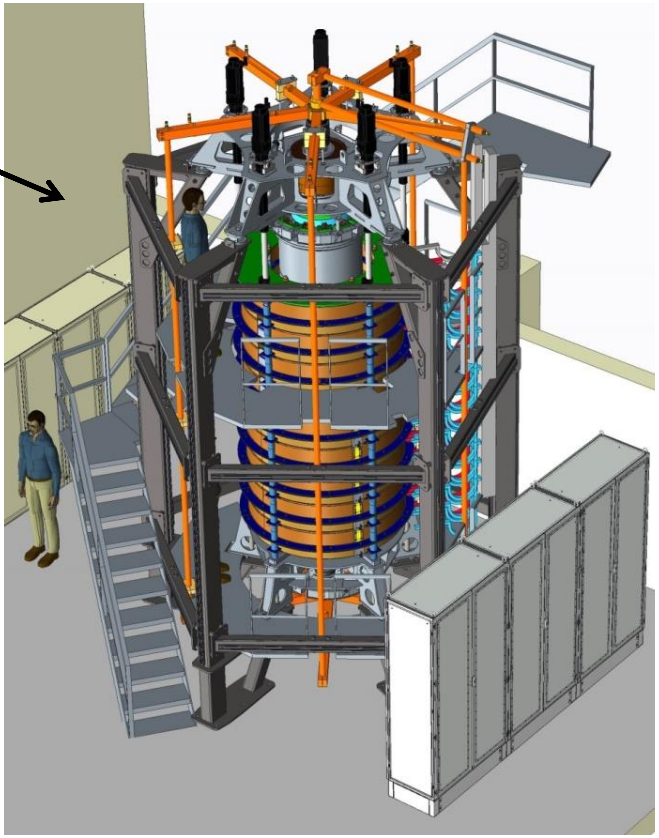
Those values *S~5* and *Rm~25* are well within the capabilities of the new Taylor-Couette device being currently built within DRESDYN…

- r_{in}=0.2 m
- r_{out}=0.4 m
- h=2 m

- f_{in}=20 Hz
- f_{out}=6 Hz

- B_z=120 mT

- Rm = 40
- S = 8



...offering a realistic prospect for experimental realization of this new double-diffusive, positive shear HMRI

Next steps for us…

1. Finalizing the experiments on transition between AMRI and HMRI at PROMISE (with effect of convection): Martin, Jude…→ meeting on 26 March

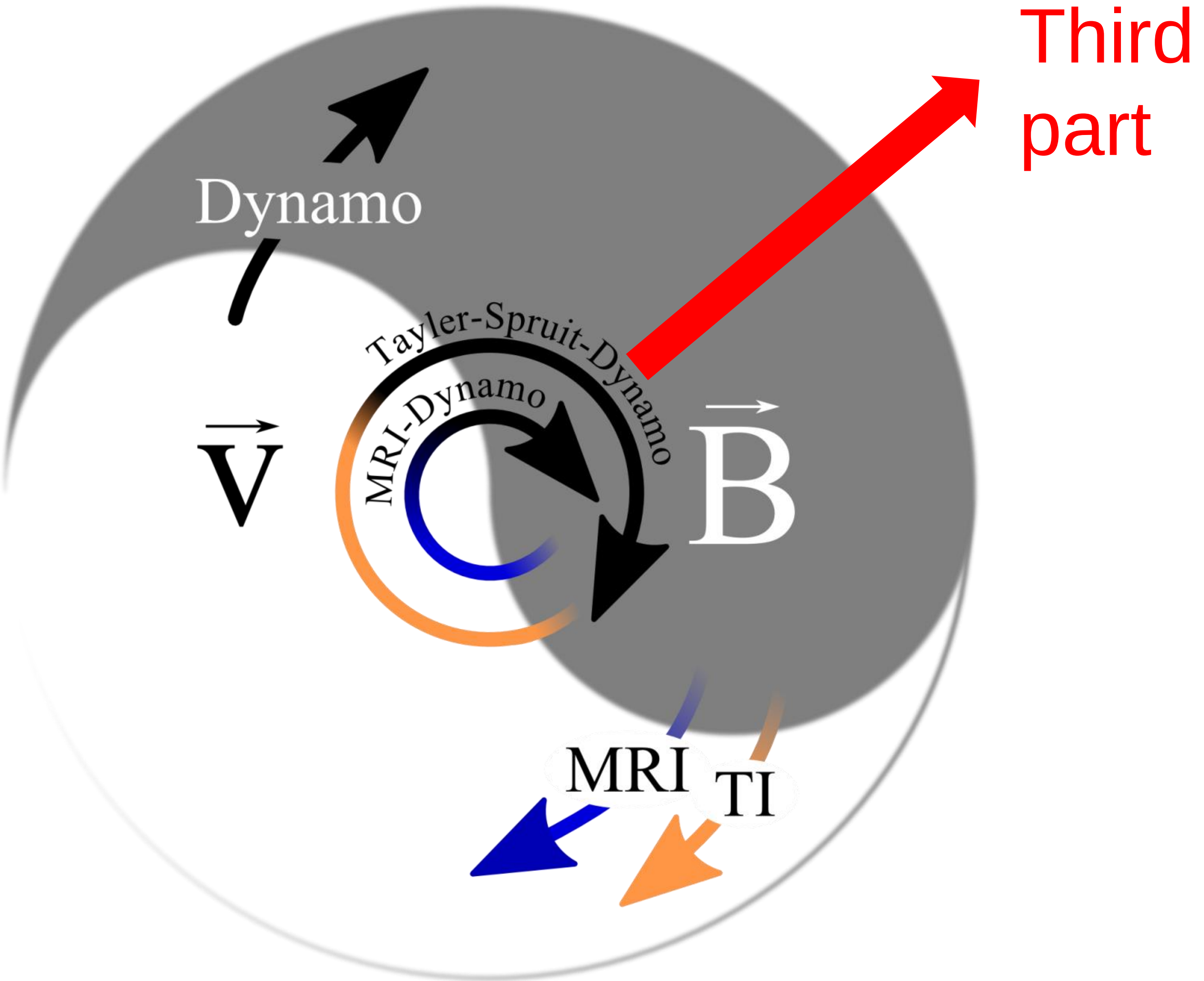
2. Finalizing the design of the large MRI/TI experiment: Martin with Sebastian Köppen (FWF)

3. Validating the feasibility of Super-HMRI in the MRI/TI set-up: George+N.N.

4. Optimizing the design of a dedicated Super-AMRI experiment (33 kA minimum!!!)

5. Evaluating the consequences of Super-HMRI for a nonlinear dynamo in the solar tachocline…

Nonlinear Tayler-Spruit dynamos (and their tidal synchronization???)



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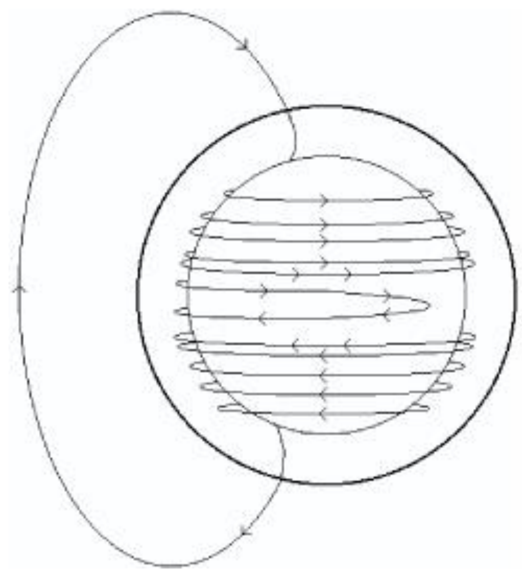
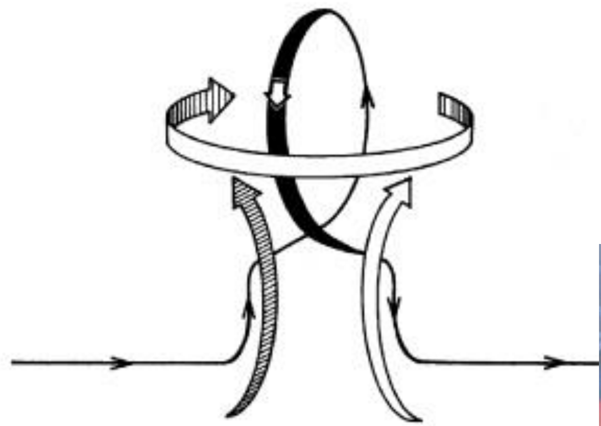
Solar dynamo models: Basics

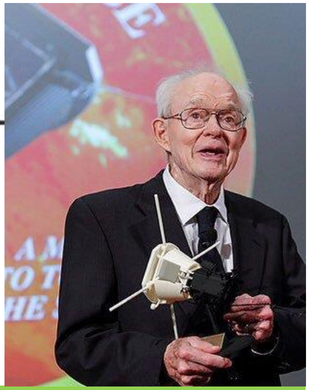
Any solar dynamo needs:
- some Ω effect to regenerate toroidal field from poloidal field
- some α effect to regenerate poloidal field from toroidal field



Ω effect



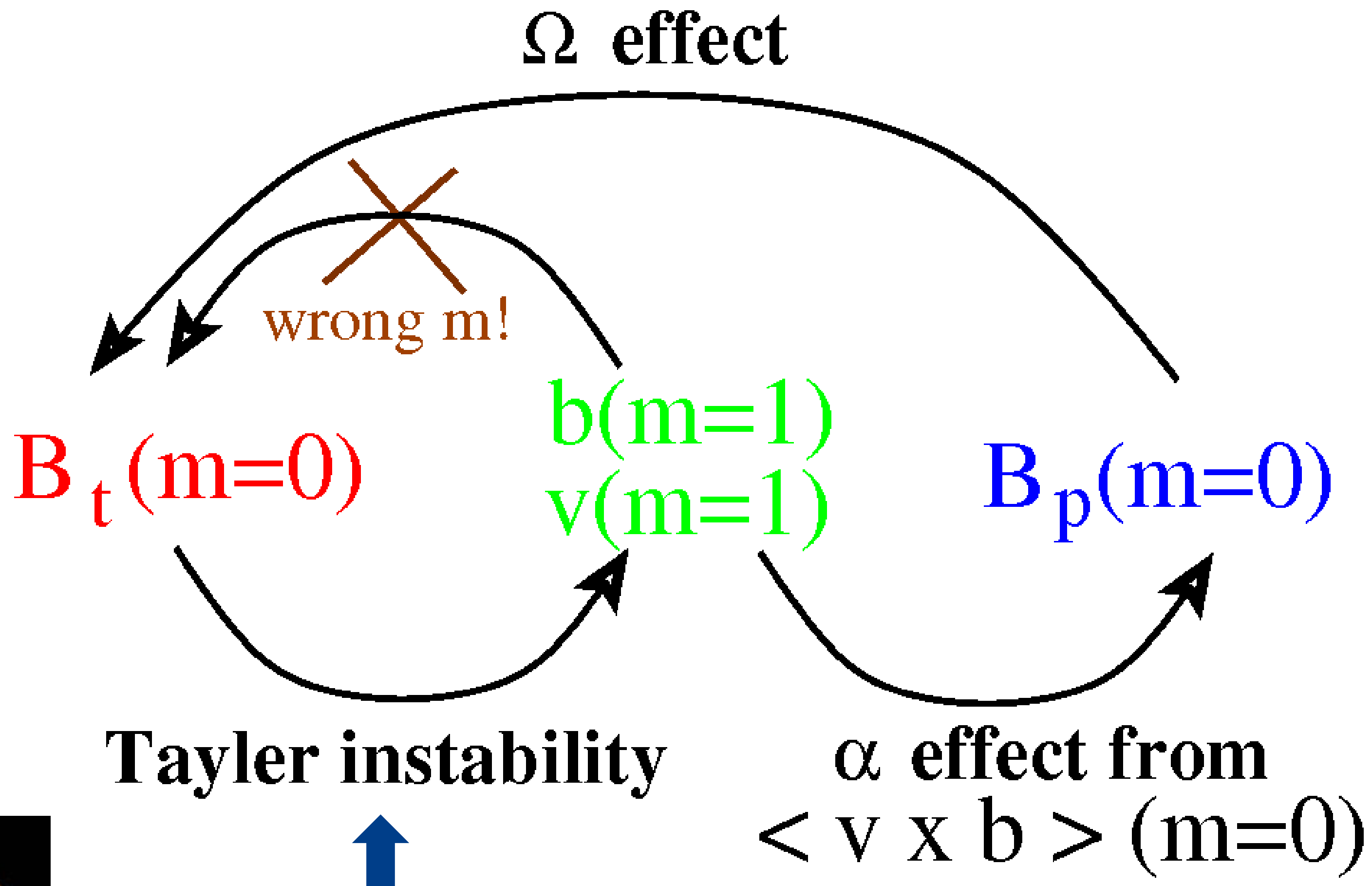
α effect

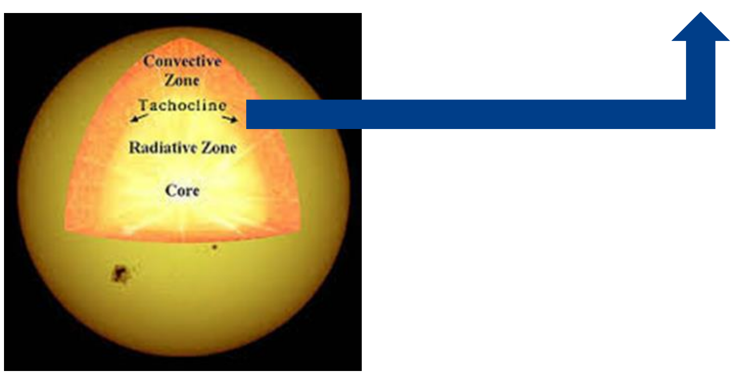


Parker, Astrophys J. 122, 293 (1955)

DRESDEN concept HZDR

Tayler-Spruit dynamo in the solar tachocline: The main problem



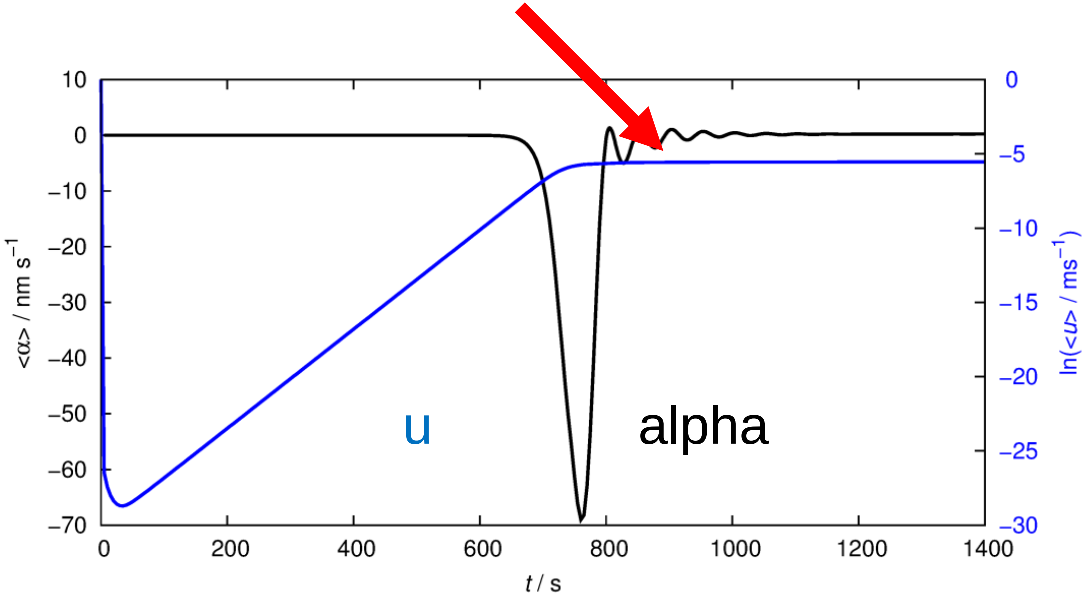


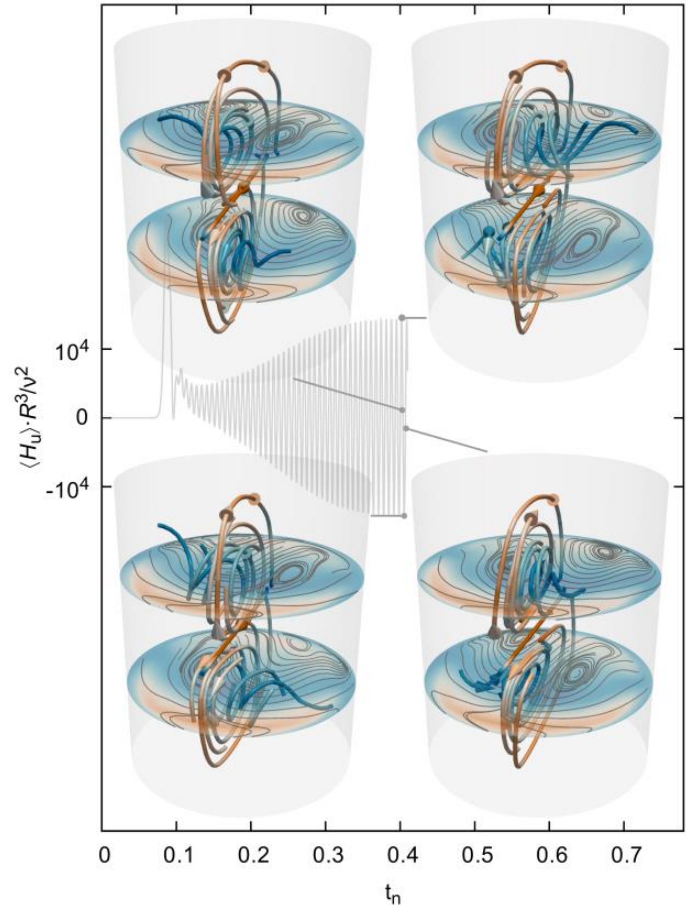
Spruit, Astron. Astrophys. 381 (2002) 923;

Zahn et al., Astron. Astrophys. 474 (2007) 147

Tayler instability: Saturation and helicity oscillations at Pm=10^{-6}

(Damped) helicity oscillations Ha =70

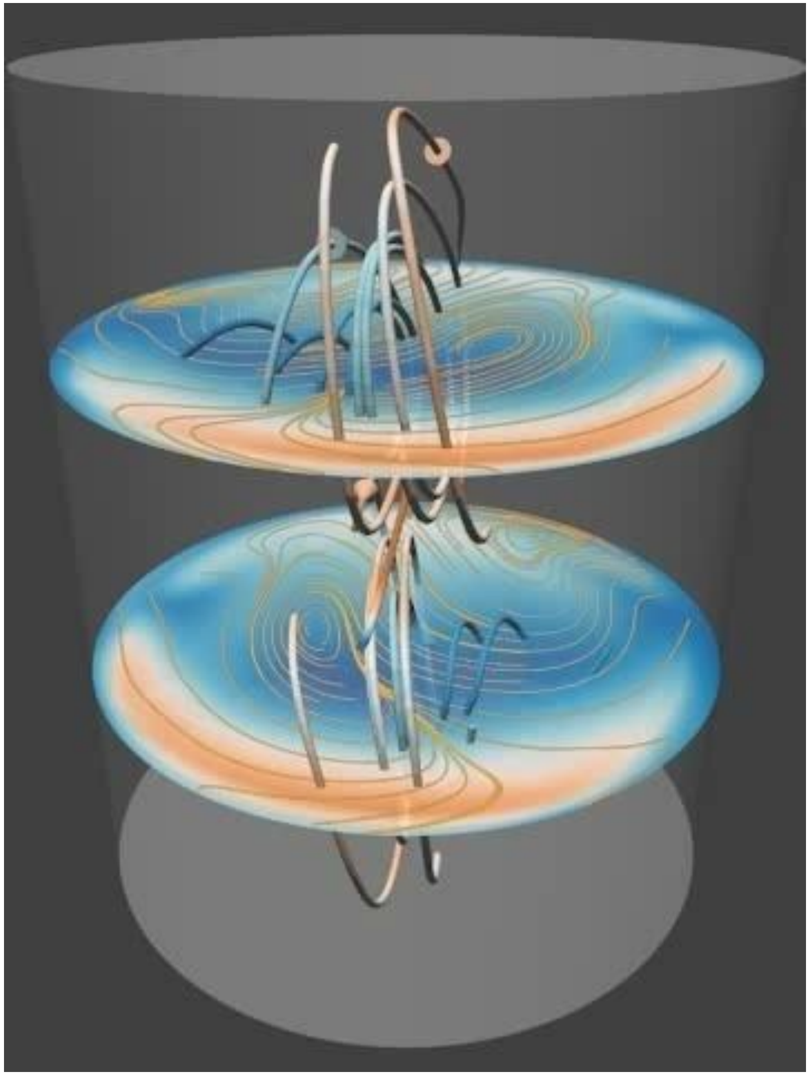




Ha =100

Weber et al., New J. Phys. 17 (2015), 113013

Character of the helicity oscillations

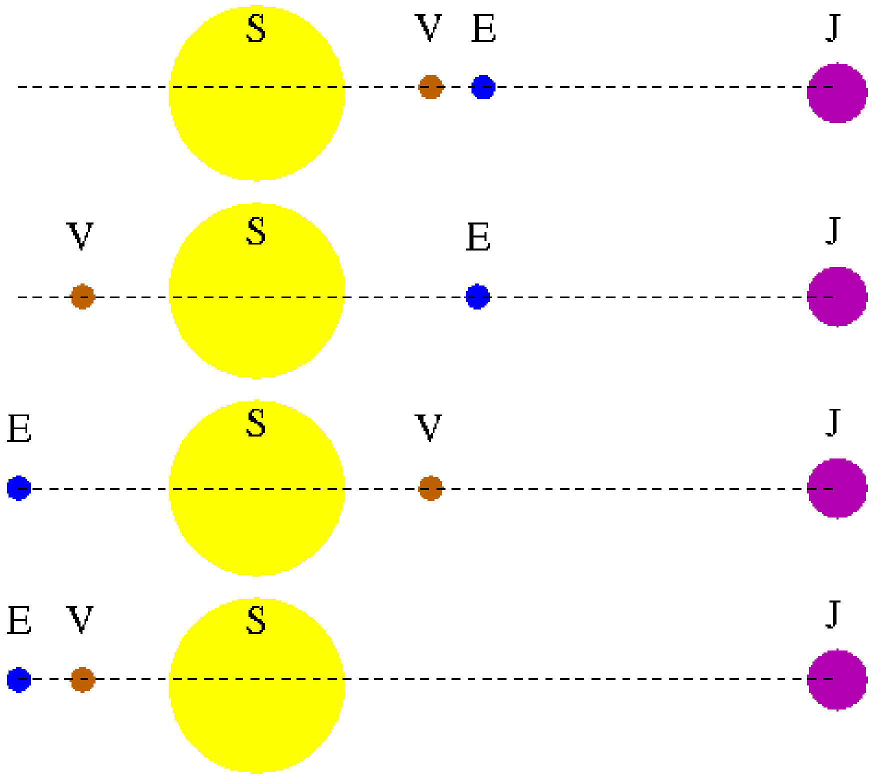


Ha =100
Pm=10^{-6}

Weber et al., New J. Phys. 17 (2015), 113013

Planetary tides and the solar cycle: Venus-Earth-Jupiter alignments

Amazing synchronization of solar cycle with the 11.07 years alignment cycle of the Venus-Earth-Jupiter system (despite tiny tidal forces!)



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

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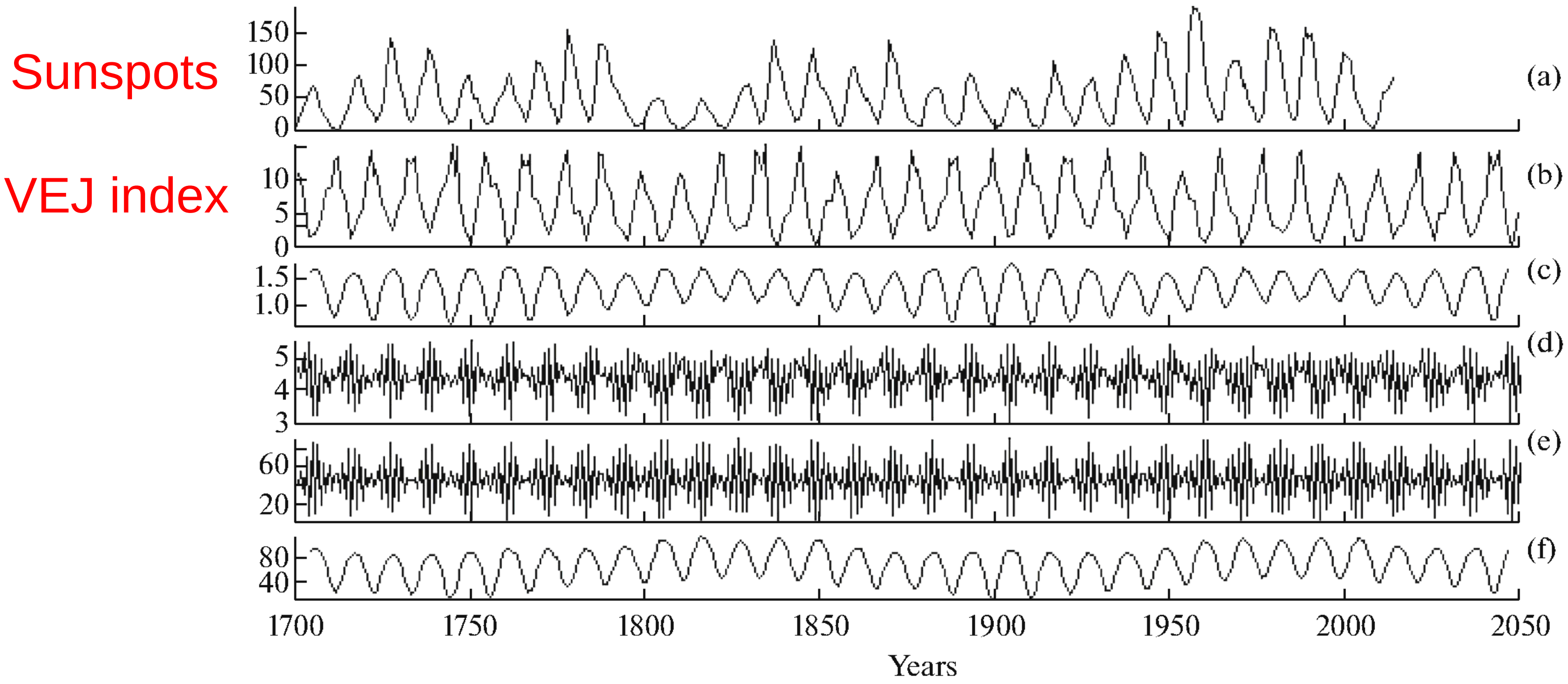

Bollinger, Proc. Okla. Acad. Sci. 33 (1952), 307; Takahashi, Solar. Phys. 3 (1968), 598; Wood, Nature 240 (1972), 91; Wilson, Pattern Recogn. Phys. 1 (2013), 147; Okhlopkov, Mosc. U. Bull. Phys. B. 69 (2014), 257; **Okhlopkov, Mosc. U. Bull. Phys. B. 71 (2016), 444**; Scafetta, Pattern Recogn. Phys.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

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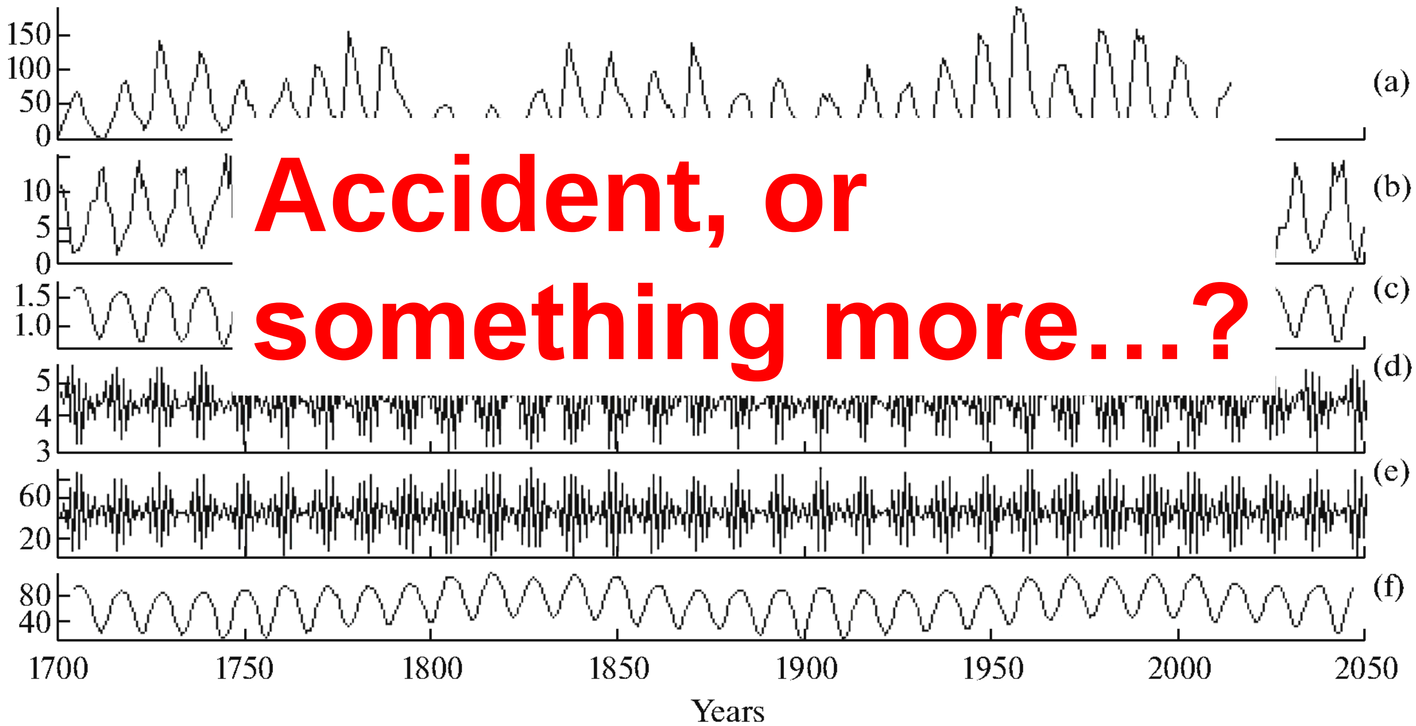
Sunspots

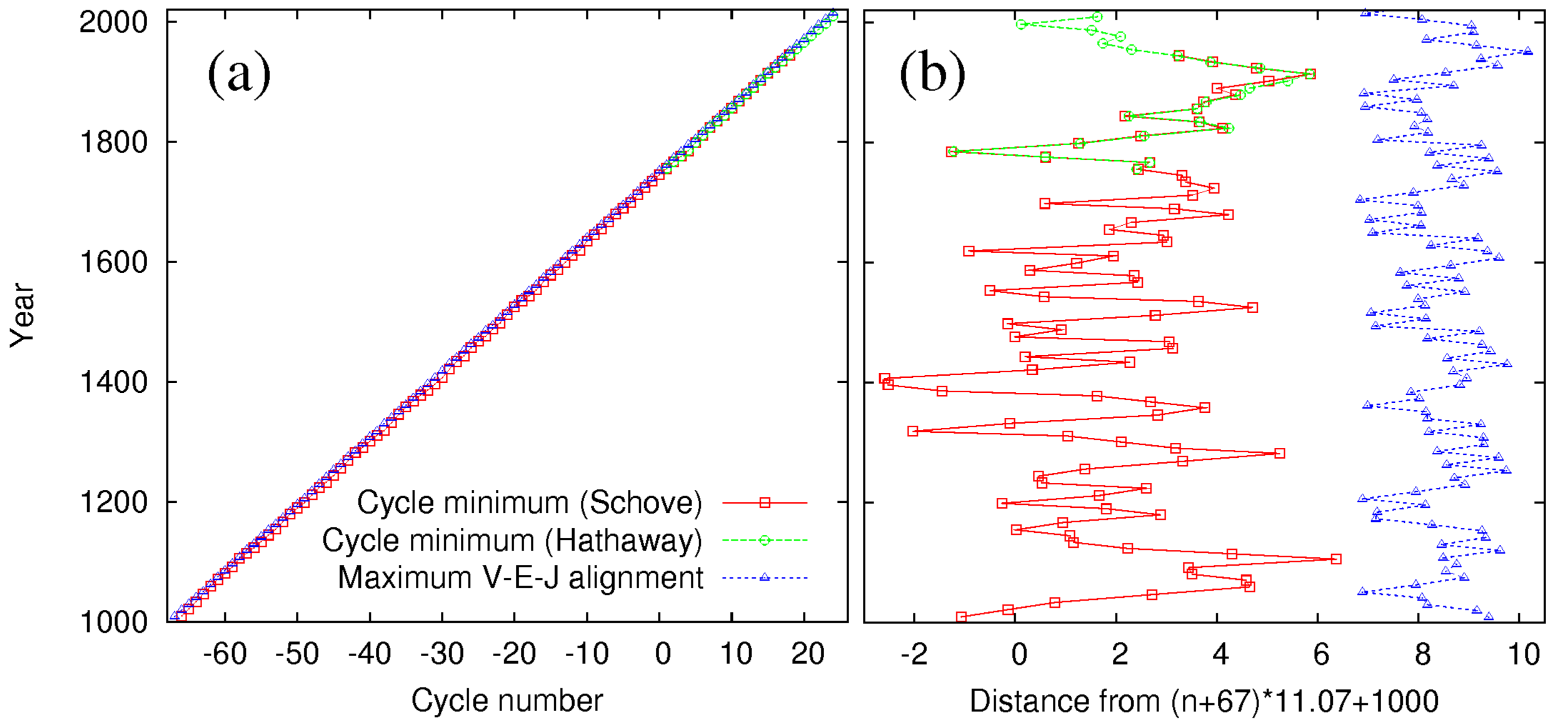
VEJ index



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

Planetary tides and the solar dynamo: The basic 22 years cycle

Amazing synchronization of solar cycle with the 11.07 years conjunction cycle of the Venus-Earth-Jupiter system (despite tiny tidal forces!)



Schove, D.J.: J. Geophys. Res. 60 (1955), 127; Hathaway, D.H., Liv. Rev. Sol. Phys. 7 (2010), 1; Okhlopkov, Mosc. U. Bull. Phys. B. 71 (2016), 444

Stefani et al., arXiv:1803.08692

DRESDEN concept

HZDR

Dicke´s argument

Is there a chronometer hidden deep in the Sun?

R. H. Dicke
Joseph Henry Laboratories, Physics Department, Princeton University, Princeton, New Jersey 08540

No support is found for the conventional view of the sunspot cycle, that there exists a large random walk in the phase of the cycle. Instead, both sunspots and the [D/H] solar/terrestrial weather indicator seem to be paced by an accurate clock inside the Sun.

It has long been believed that "the sunspot disturbances, like the eruptions of a geyser, are inherently only roughly periodic"[1]. Observations show a large variation in the ~11 yr

cycle as follows: "It was previously believed that the sunspot cycle resulted from the superposition of different periodic cycles. . . . Since then it has become clear that the rise and fall in the number of spots is due to a number of practically independent individual processes. Thus the idea of a true periodic phenomenon was dropped in favour of the so-called 'eruption hypothesis'. On this hypothesis, each cycle represents an independent eruption of the Sun which takes about 11 yr to die down". This conception of an irregular sunspot cycle, implying a random walk in the phase of the cycle, seems to agree with the Babcock theory and with subsequent modifications of the

Dicke, R.H., Nature 276 (1978), 676

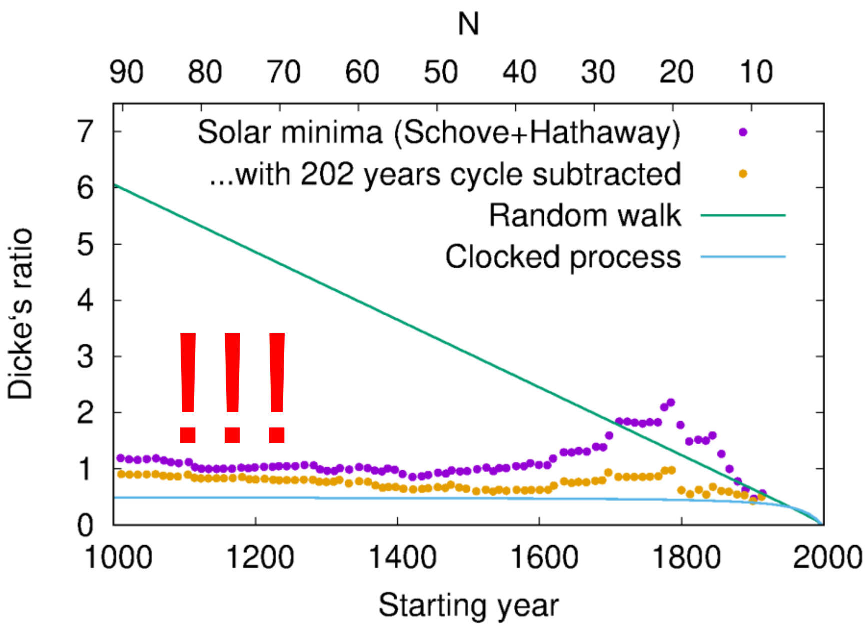
Distinction between random walk (RW) and clocked process (CP) for the instants y_n of sunspot maxima (Dicke) or minima (here):

Residuals: $\delta y_n = y_n - y_0 - p(n-1)$,
with p being the mean cycle period

A telling measure for discriminating between RW und CP is the RATIO between the mean square of δy_n and the mean square of $(\delta y_n - \delta y_{n-1})$

	RATIO	Dicke (N=25)	Here (N=90)
Random walk	$(N+1)(N^2-1)/3(5N^2+6N-3)$	1.72	6.12
Clocked process	$(N^2-1)/2(N^2+2N+3)$	0.46	0.49
Observation		**0.87**	**1.19**

Dicke´s argument



- After subtraction of Suess/de Vries cycle, Dicke's ratio fits nearly perfectly to a clocked process (CP)

Distinction between random walk (RW) and clocked process (CP) for the instants y_n of sunspot maxima (Dicke) or minima (here):

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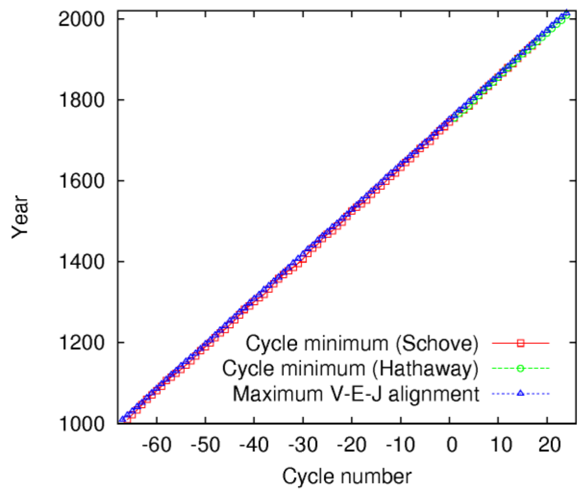
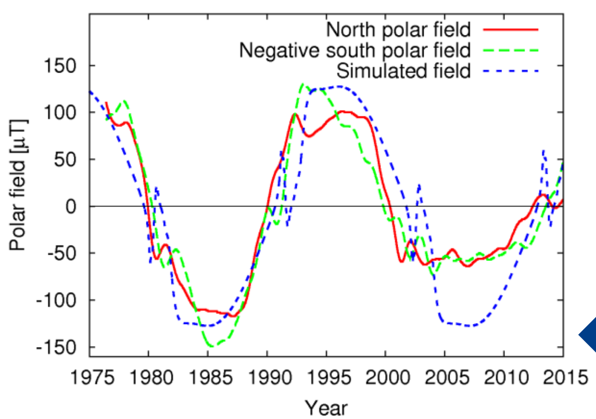
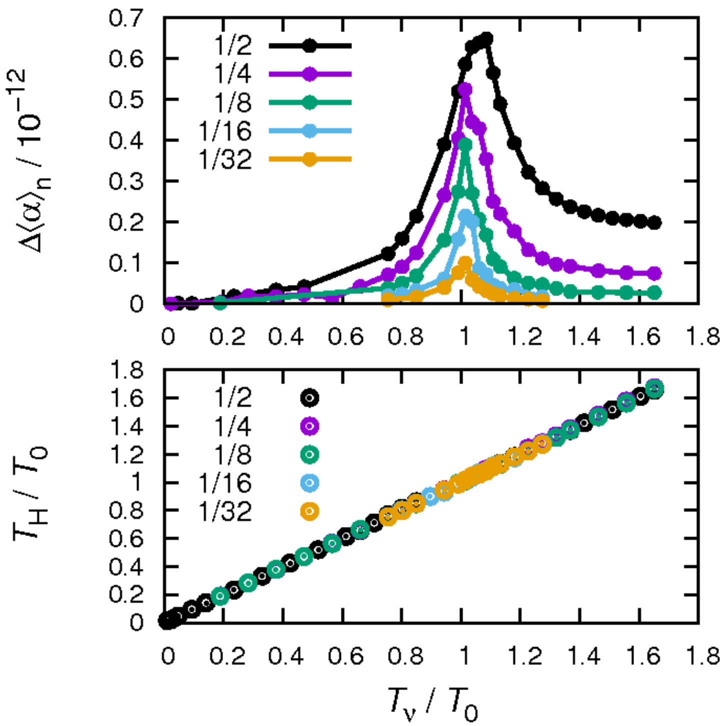
Modelling the planetary synchronization of the solar dynamo

Clear observational evidence for synchronization of solar cycle with Venus-Earth-Jupiter alignments







1:1 synchronization of the helicity of the Tayler instability with tidal (m=2) perturbations of the VEJ-system: This yields a 22.14 years solar cycle.

Stefani et al, Solar Phys. 291 (2016), 2197

1D-Model (after Parker, but with periodic, synchronized α term):

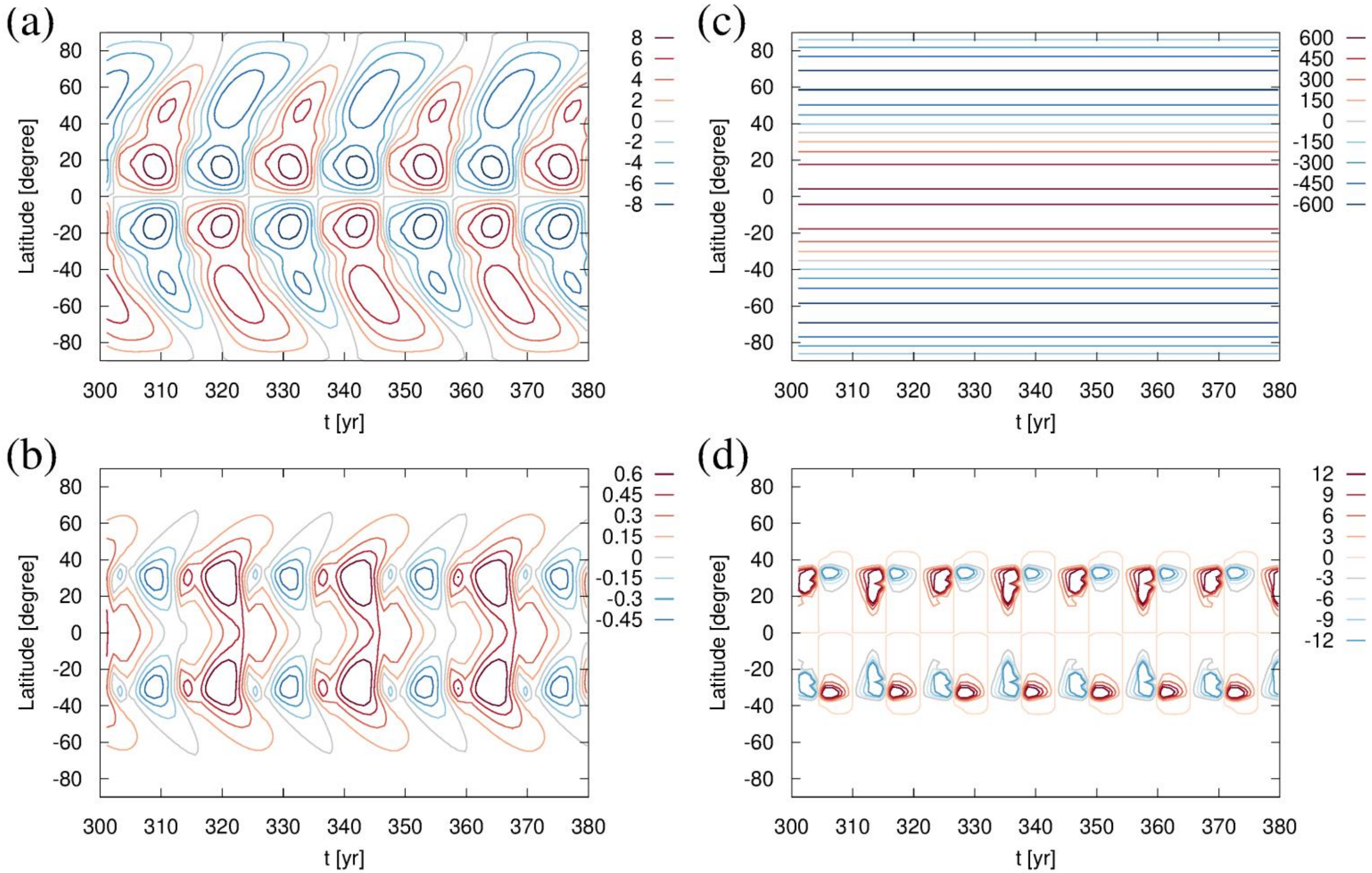
$$\frac{\partial B(\theta,t)}{\partial t} = \omega(\theta,t)\frac{\partial A(\theta,t)}{\partial \theta} - \frac{\partial^2 B(\theta,t)}{\partial \theta^2} - \kappa B^3(\theta,t)$$

$$\frac{\partial A(\theta,t)}{\partial t} = \alpha(\theta,t)B(\theta,t) - \frac{\partial^2 A(\theta,t)}{\partial \theta^2},$$

$$\omega(\theta,t) = \omega_0(1 - 0.939 - 0.136\cos^2(\theta) - 0.1457\cos^4(\theta))\sin(\theta),$$

$$\alpha^p(\theta,t) = \alpha_0^p \sin(2\pi t/11.07)\mathrm{sgn}(90^\circ - \theta)\frac{B^2(\theta,t)}{(1 + q_\alpha^p B^4(\theta,t))} \text{ for } 55^\circ < \theta < 125^\circ$$

B(θ,t)



ω(θ,t)

A(θ,t)

α(θ,t)

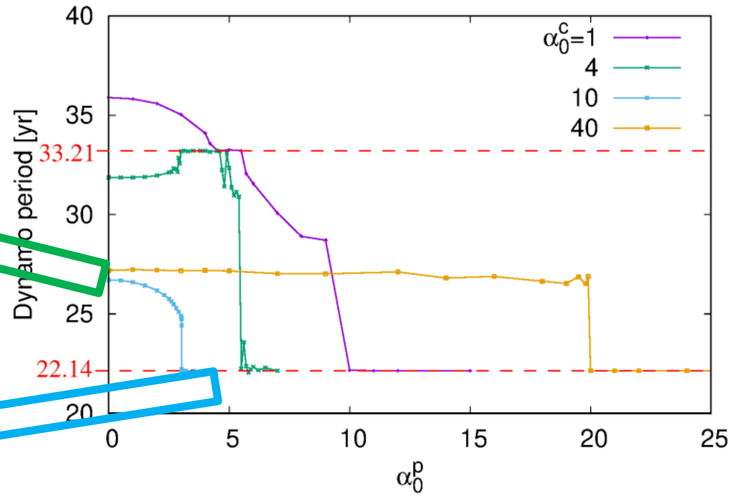
$\omega_0=10000$, $\kappa=0.2$, $q_\alpha^p=0.2$, $\alpha_0^p=100$

DRESDEN concept HZDR

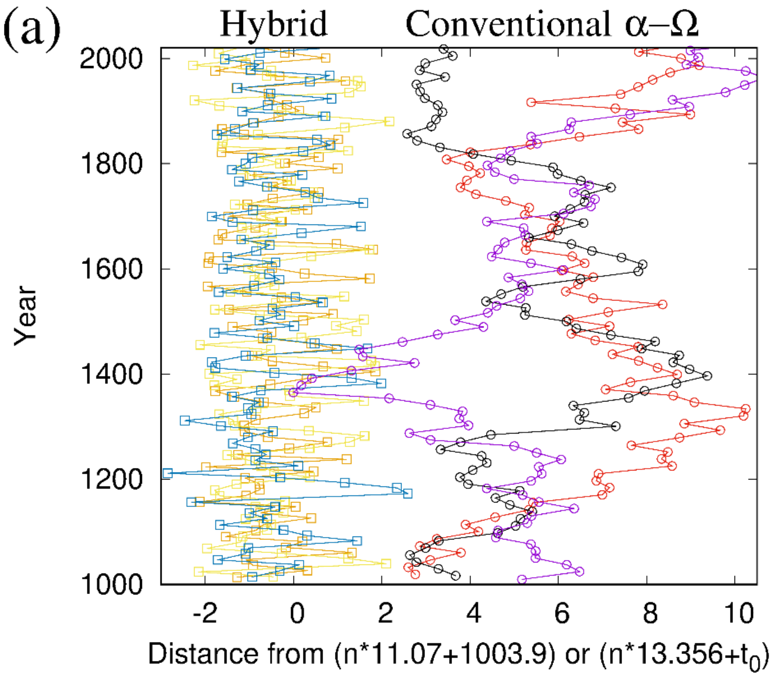
1D-Model with Noise

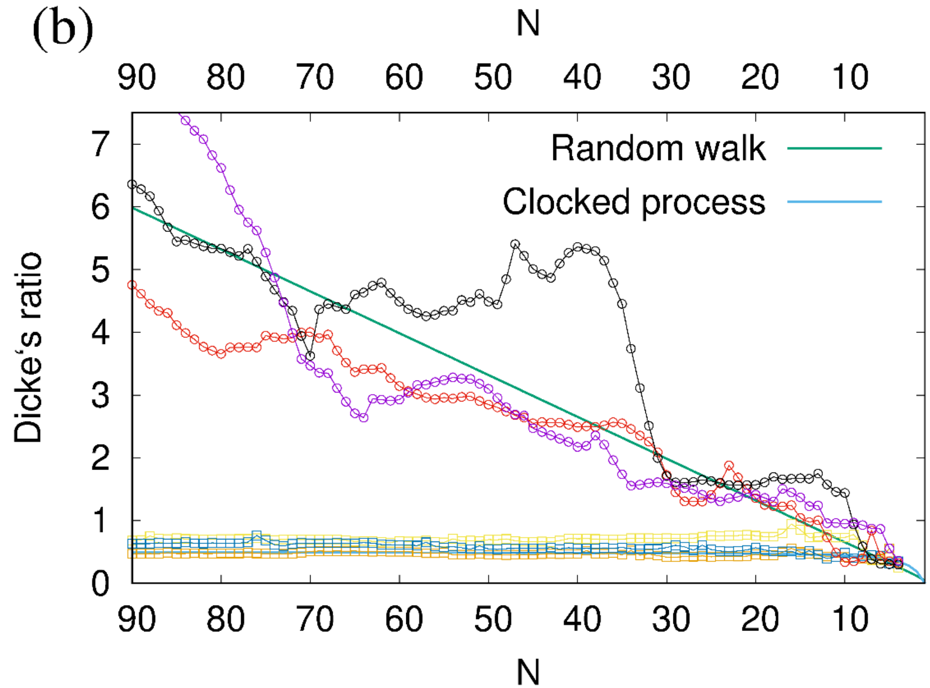
Conventional alpha-Omega dynamo yields random walk (RW)

Synchronized (hybrid) modell yields clocked process (CP)



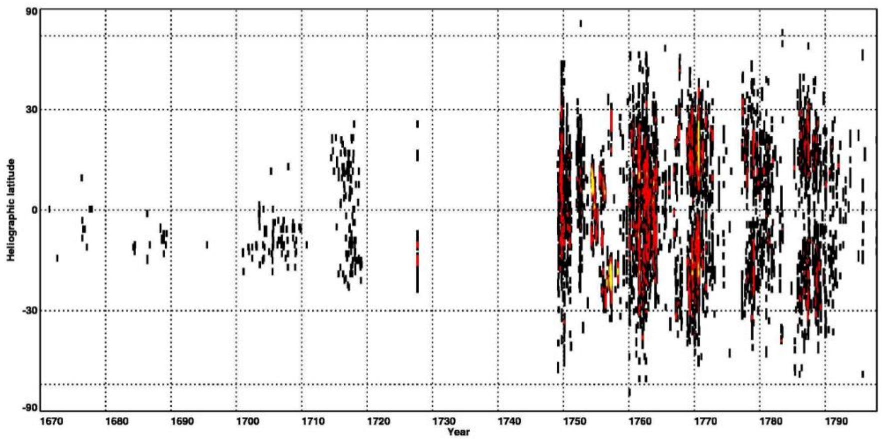
(CP) (RW)

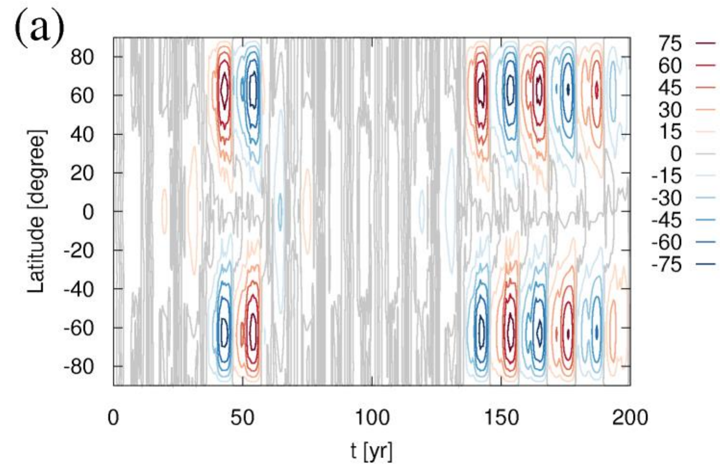




Some interesting features: Quadrupole fields around grand minima

During, or shortly after grand minima, dipole fields are replaced by quadrupole fields. They also appear in our model, with maintained phase coherence…

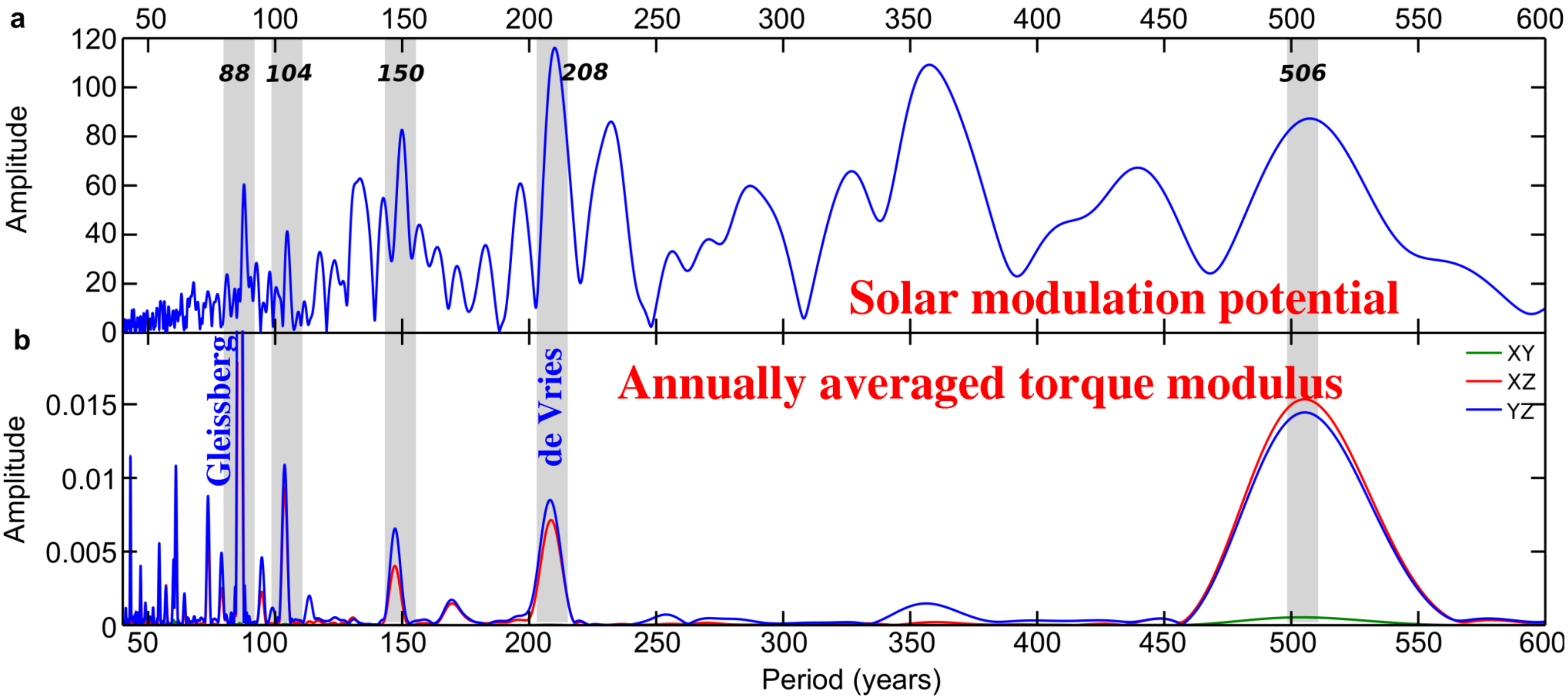




Arlt and Weiss, Space Sci. Rev. 186 (2014), 525

Stefani et al, arXiv:0803.08692

Planetary motion and long periods → Relevance for climate



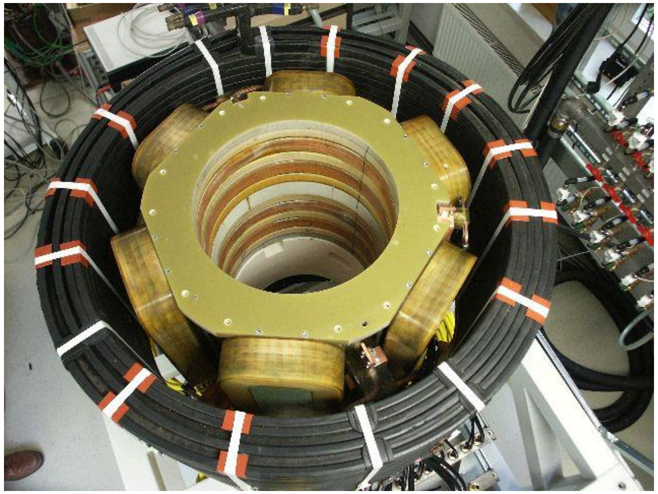
Abreu et al., Astron. & Astrophys. 548 (2012), A88

Experiment on synchronization of helicity with m=2 forcing

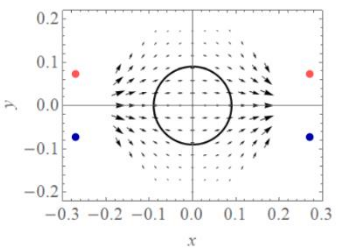
- Generic experiment to show resonant excitation of helicity (connected with the sloshing of an m=1 mode) by an m=2 perturbation

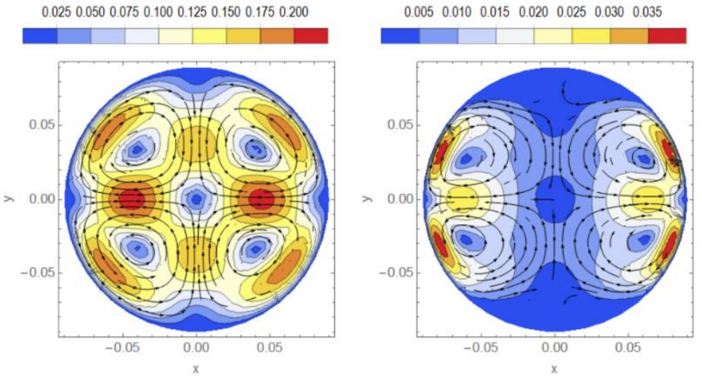
- Tayler instability (TI) experiment is difficult. However: m=1 Large Scale Circulation (LSC) of Rayleigh-Benard is similar to m=1 mode of TI, we expect similar resonance of sloshing/torsional mode mit m=2 perturbation

- How to realize m=2 perturbation?
  - Magnetic pressure by coils in MULTIMAG system (in Helmholtz-RSF Projekt)



Magnetic field



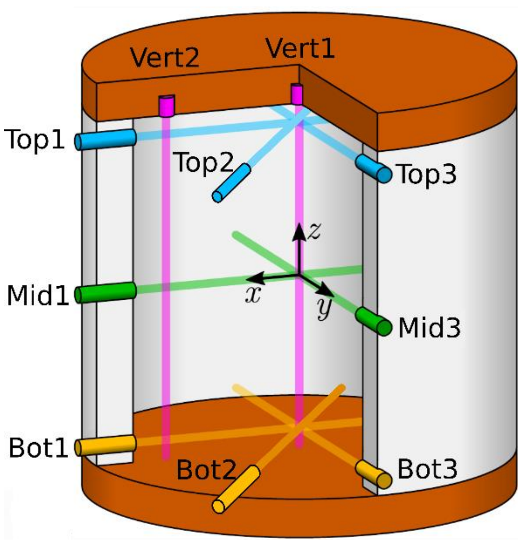


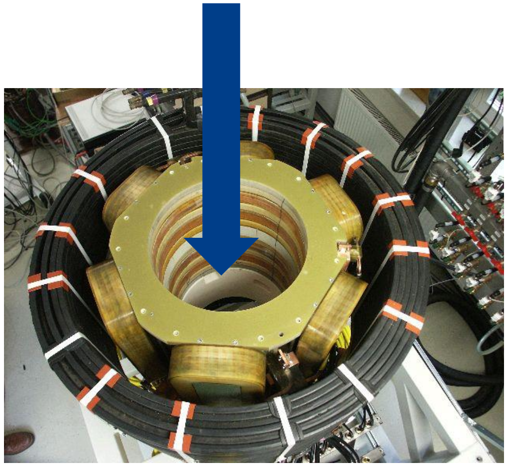
m=2 Velocity at
100 Hz 1600 Hz

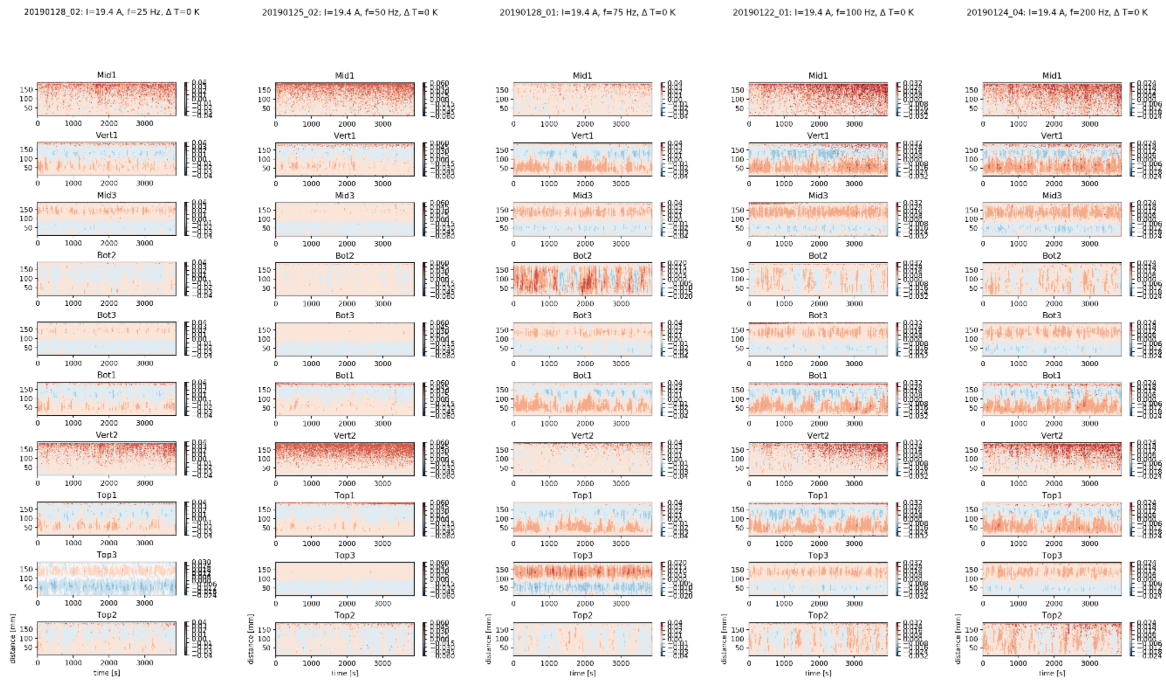
Stepanov, Stefani: Magnetohydrodynamics, in press

Experiment on synchronization of helicity with m=2 forcing

- First results in RB experiment with m=2 forcing without heating (Felix)







25 Hz 50 Hz 75 Hz 100 Hz 200 Hz

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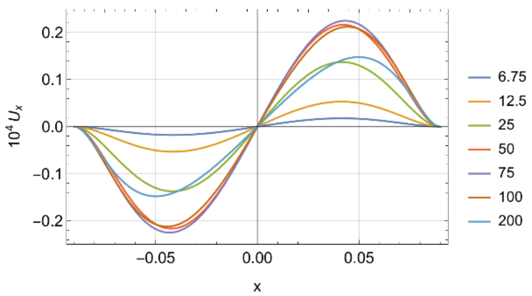
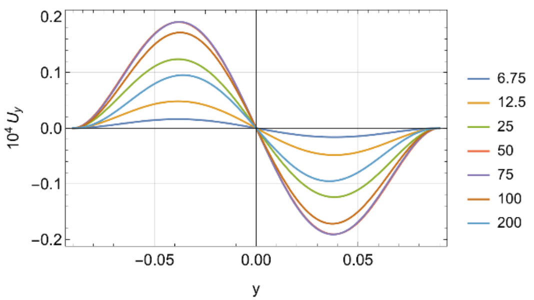
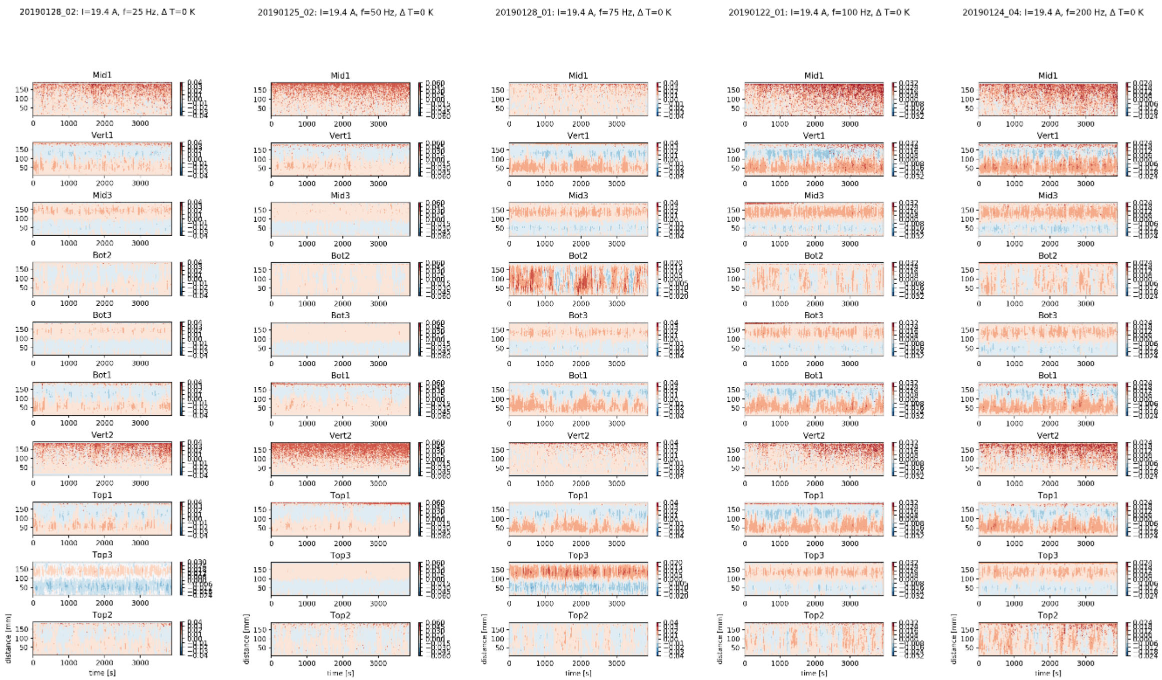






25 Hz 50 Hz 75 Hz 100 Hz 200 Hz

- Good agreement with Rodion Stepanov‘s numerics

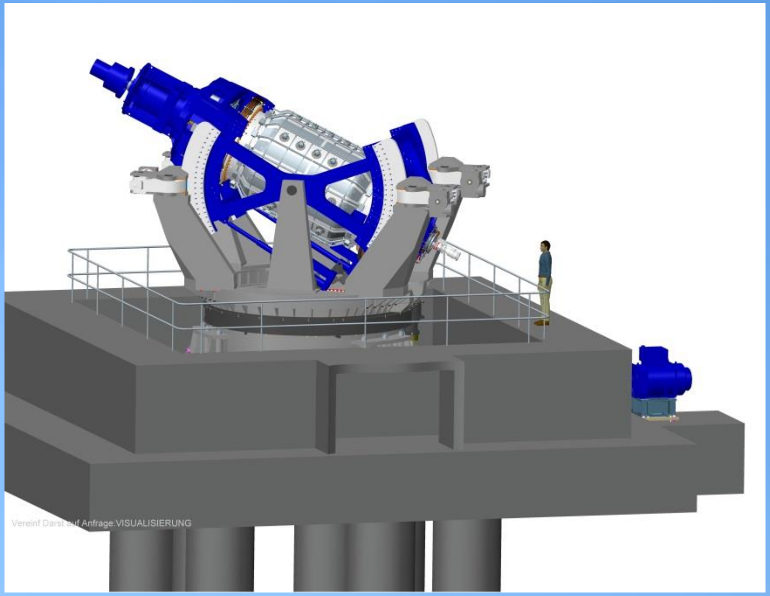
DRESDEN concept HZDR

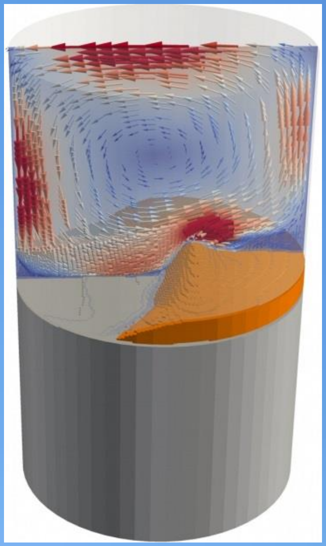
Next steps for us…

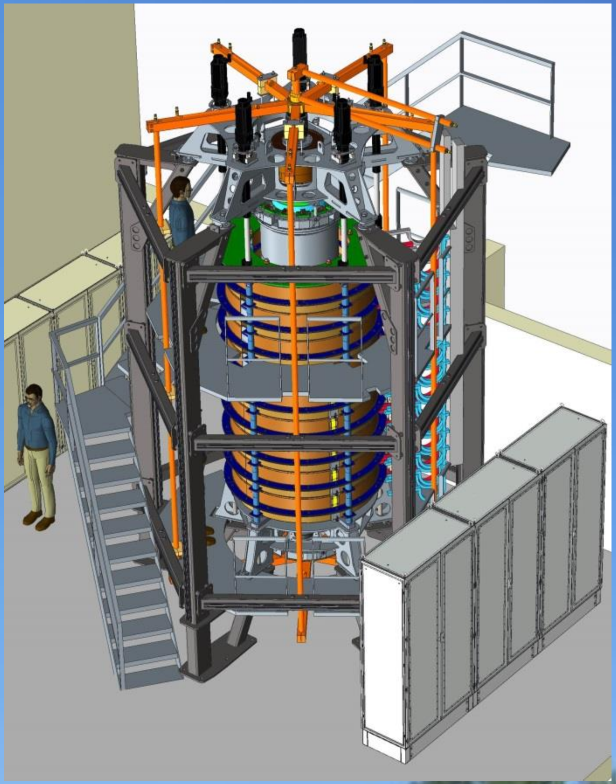
1. Preparing the first combined RB/m=2 forcing experiment at MULTIMAG: Felix, Tobias, Peter, Sebastian…

2. Simulations of RB/m=2 forcing experiment with OpenFoam: Sebastian, Vladimir

3. More aspects of solar dynamo:
   - stochastic resonance (might further reduce the oscillatory alpha term that is necessary for synchronization)
   - 2D/3D simulations (with Toulouse and/or Potsdam)
   - Extension of the synchronization idea to m=1 Rossby waves
   - New version of Tayler-Spruit dynamo based on Super-HMRI???







Thank you for your attention