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Magnetic Fields in Space: Phenomena and Related Lab Experiments

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with thanks to:

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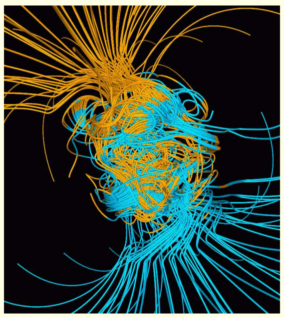
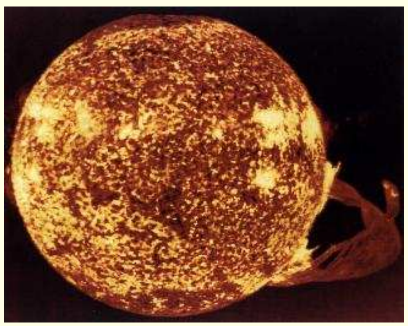
Outline of the talk

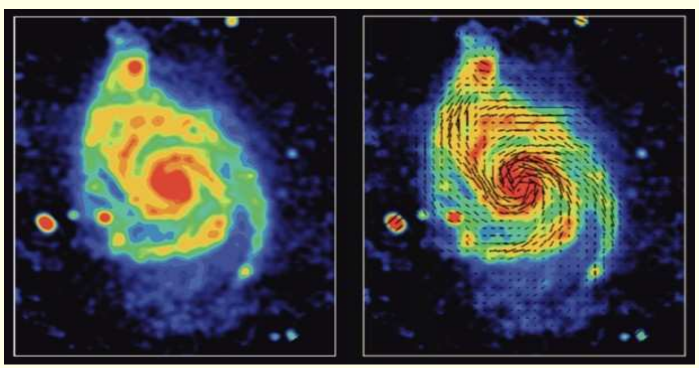
- Motivation
- How cosmic magnetic fields are produced:
  Dynamo effect
- How cosmic magnetic fields act:
  Magnetorotational instability and Tayler instability
- Prospects:
  DRESDYN

Motivation: Cosmic magnetic fields...

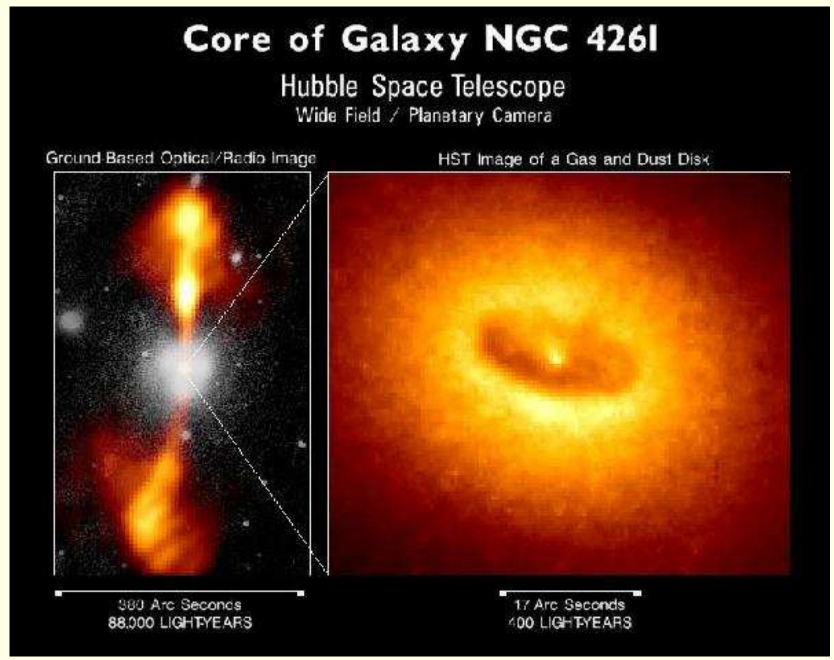
...are self-excited by the hydromagnetic dynamo effect





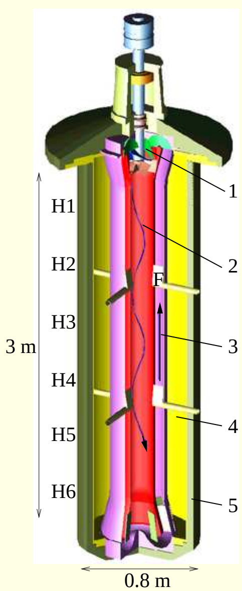


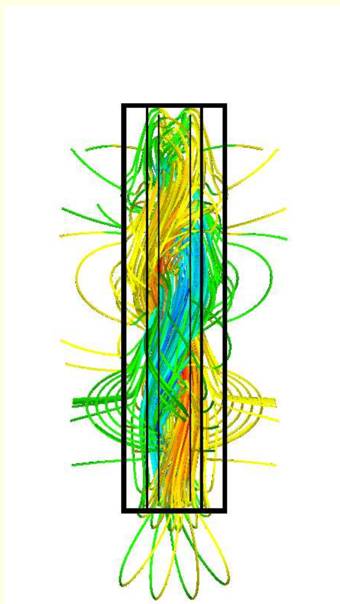
...help in cosmic structure formation by virtue of the magnetorotational instability (MRI) in accretion disks



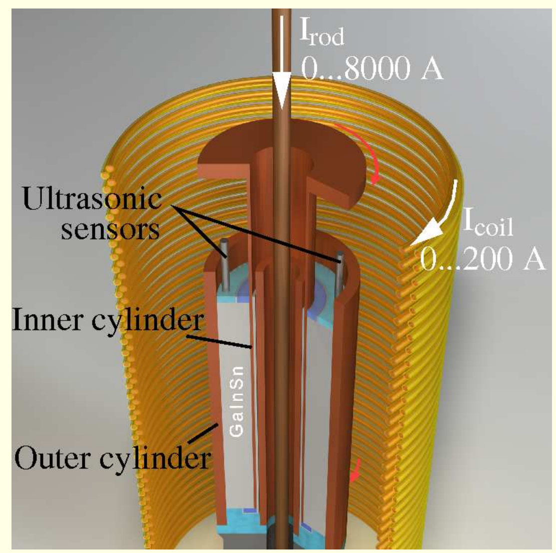
Cosmic magnetism in the liquid metal lab...

Dynamo experiments: **Riga, Karlsruhe, Cadarache**, Madison, Maryland, Perm...





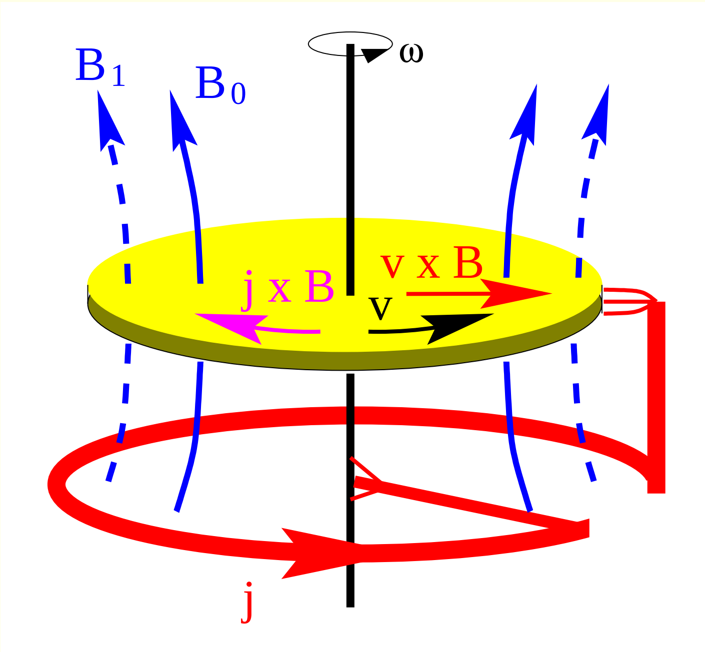
MRI related experiments: Maryland, Princeton, Socorro, Grenoble, **Rossendorf**

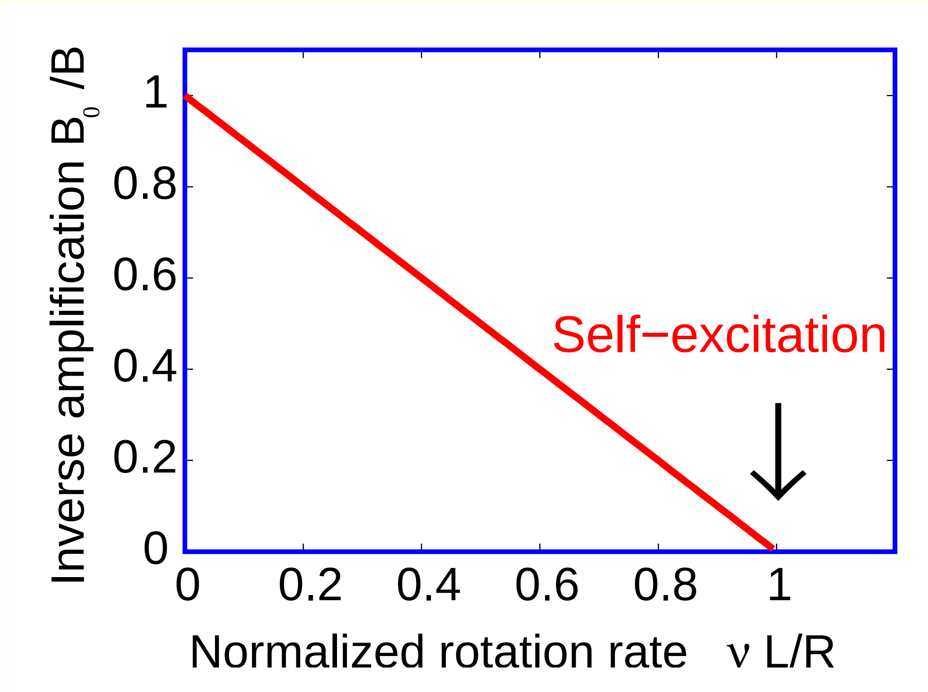


How cosmic magnetic fields are produced

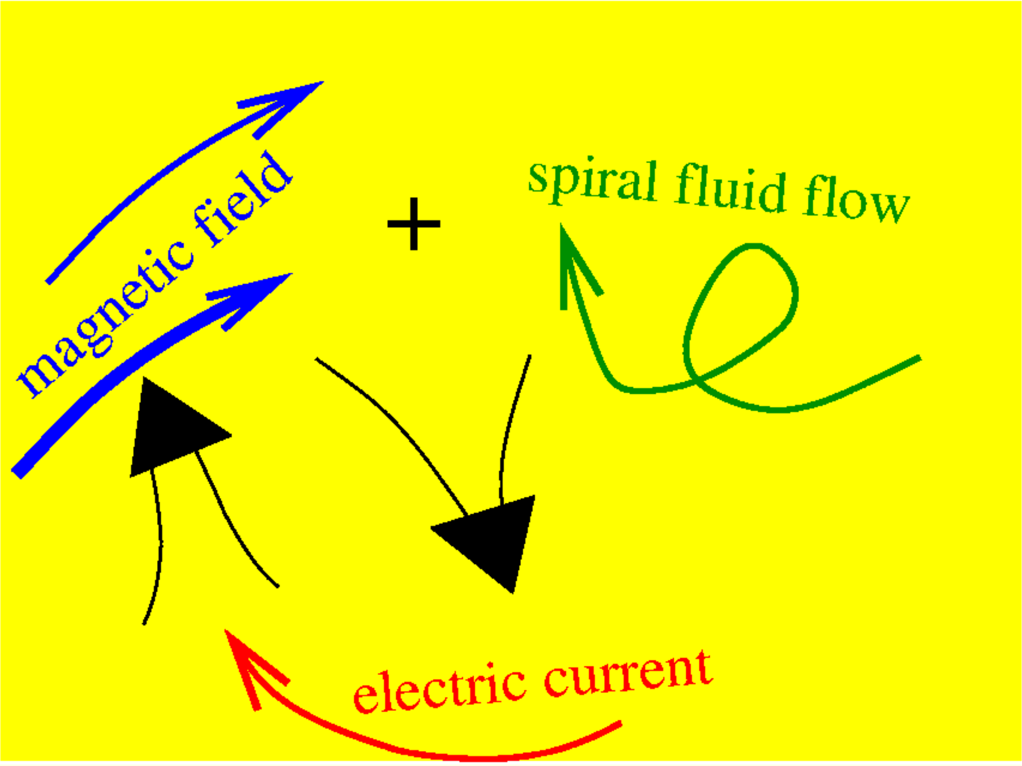
Dynamo effect

Dynamos: The disk dynamo as a simple model



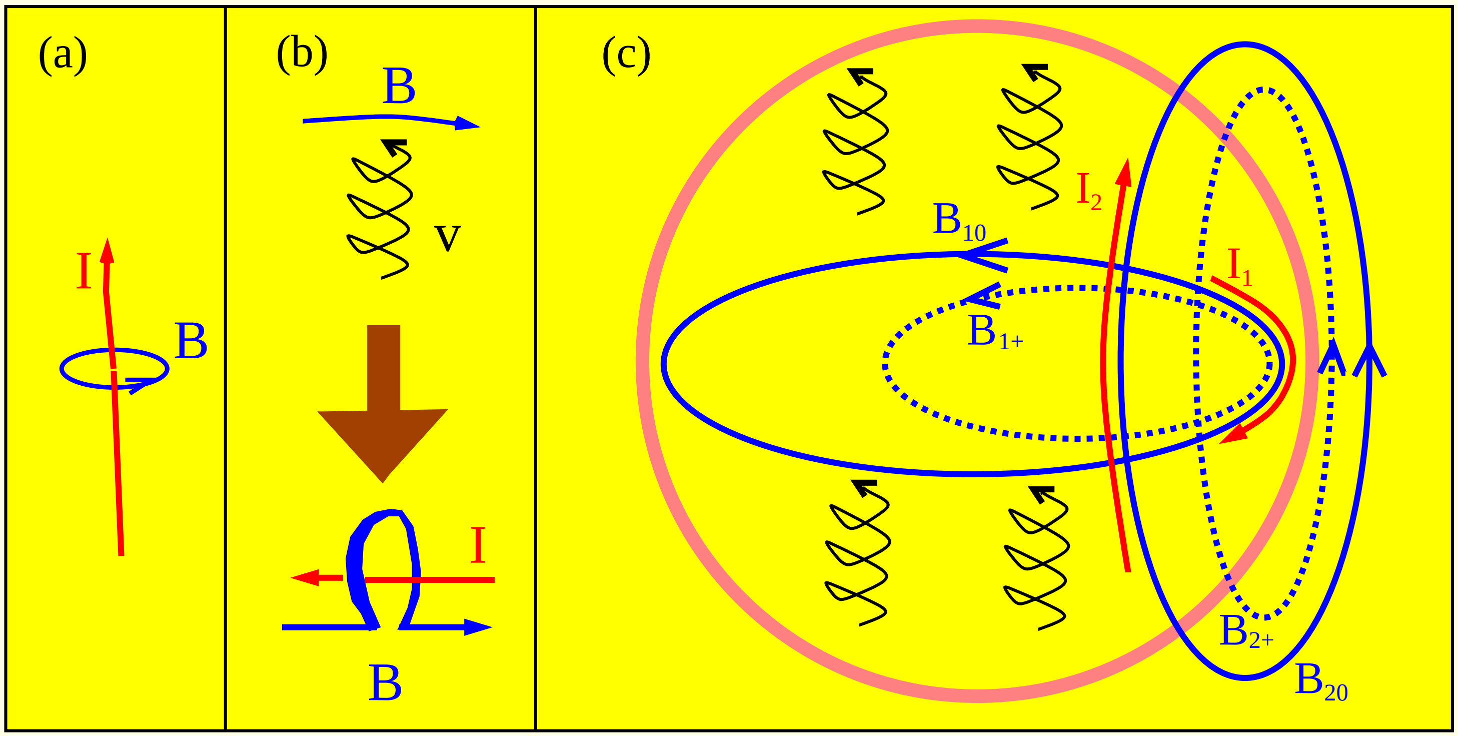


Dynamos: Self-excitation in homogeneous media



Dynamos: Self-excitation in homogeneous media

Right hand rule (a). α-effect (b). α^2-dynamo (c)



Dynamos: Theory

$\mathbf{j}$:	electric current density;	$\mathbf{B}$:	magnetic field
$\mathbf{E}$:	electric field;	$\mathbf{v}$:	fluid velocity
σ:	electrical conductivity;	μ_0:	magnetic permeability

Ampère's law	$\nabla \times \mathbf{B} = \mu_0(\mathbf{j} + \not{\dot{\mathbf{D}}})$
Faraday's law:	$\nabla \times \mathbf{E} = -\dot{\mathbf{B}}$
Magnetic field is source-free:	$\nabla \cdot \mathbf{B} = 0$
Ohm's law:	$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B})$

$\Longrightarrow$ Induction equation

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

Dynamos: Theory

Induction equation comprises two competing effects:

- Diffusion (decay) of the magnetic field:

$$\frac{\partial \mathbf{B}}{\partial t} \sim \Delta \mathbf{B}/(\mu_0 \sigma)$$

- "Stretch, twist, and fold" (produktion):

$$\frac{\partial \mathbf{B}}{\partial t} \sim \nabla \times (\mathbf{v} \times \mathbf{B})$$

Dynamos: Theory

- Ratio of production to decay $\sim$ magnetic Reynolds number

$$Rm := \mu\sigma v L$$

- Rm must be large enough ($Rm > 10$) for magnetic field production to win against decay

Dynamos: Theory

- Kinematic regime: Velocity $\mathbf{v}$ is supposed to be given. Exponential decay or growth of magnetic field is governed by induction equation:

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

- Saturated regime: Exponential growth is limited by back-reaction of self-excited magnetic field on the velocity (Lenz's rule). Simultaneous solution of Navier-Stokes-equation is needed for the description of dynamically consistent dynamos, and of magnetic instabilities.

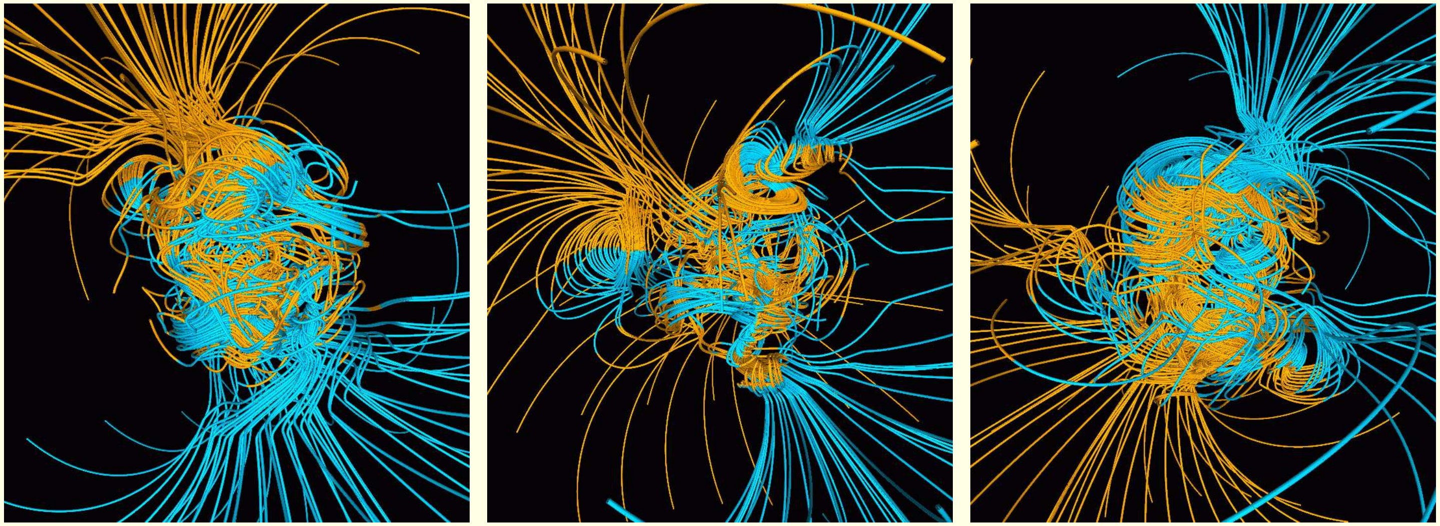
$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{\nabla p}{\rho} + \frac{1}{\mu_0 \rho}(\nabla \times \mathbf{B}) \times \mathbf{B} + \nu \Delta \mathbf{v} + \mathbf{f}_{extern}$$

Dynamos: Theory - Dimensionless parameters

Reynolds:	Re	$= RV/\nu$
Magnetic Reynolds:	Rm	$= RV\mu_0\sigma =$ Re Pm
Hartmann:	Ha	$= BR\sqrt{\frac{\sigma}{\rho\nu}}$
Magnetic Prandtl:	Pm	$= \nu\mu_0\sigma =: \nu/\lambda$
Rossby:	Ro	$= \frac{1}{2}\frac{r}{\Omega}\frac{d\Omega}{dr}$
Ekman:	Ek	$= \nu/(2\Omega R^2)$

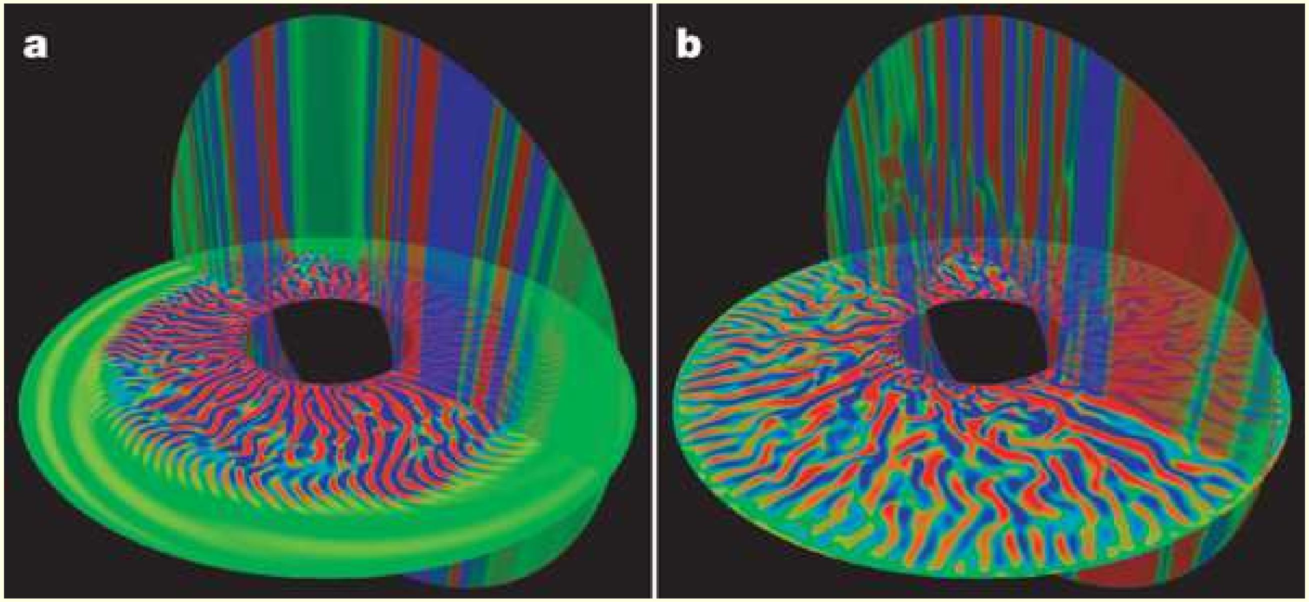
Dynamos: Simulations

Roberts and Glatzmaier (Nature 1995): First fully 3D simulation of an Earth's magnetic field reversals



Dynamos: Simulations

Kageyama et al. (Nature 2008): Simulation on a $2 \times 511 \times 514 \times 1538$ grid on 4096 processors (Earth Simulator): Vorticity ω_z for Ek=2.3 10^{-7} (left) and Ek=2.6 10^{-6} (right)



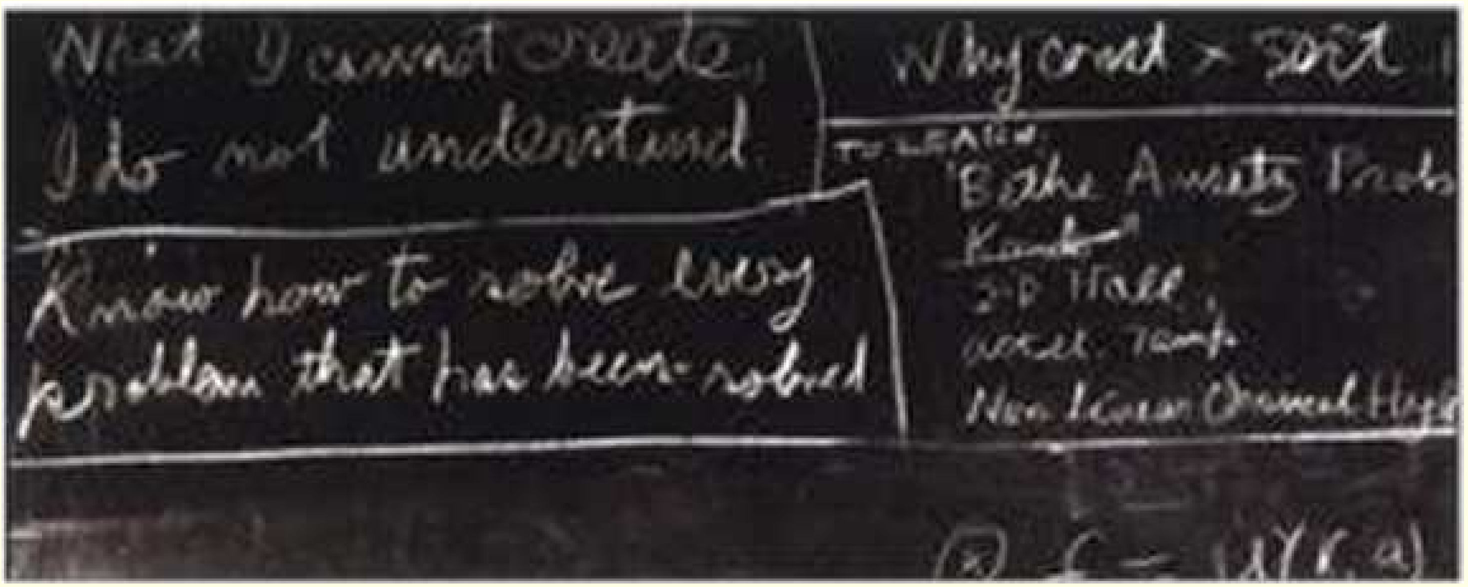
Dynamos

Simulations are impressive, but...

- ...various parameters of the Earth (Ekman number, magnetic Prandtl number) are practically inaccessible for simulations.
- Hence, turbulent structures are not completely resolved.
- We might miss essential features, e.g. anisotropic turbulent resistivity (β effect), which play a key role for the selection of magnetic eigenmodes.
- How to proceed: Faster computers? Test-field methods? ...**Experiments**

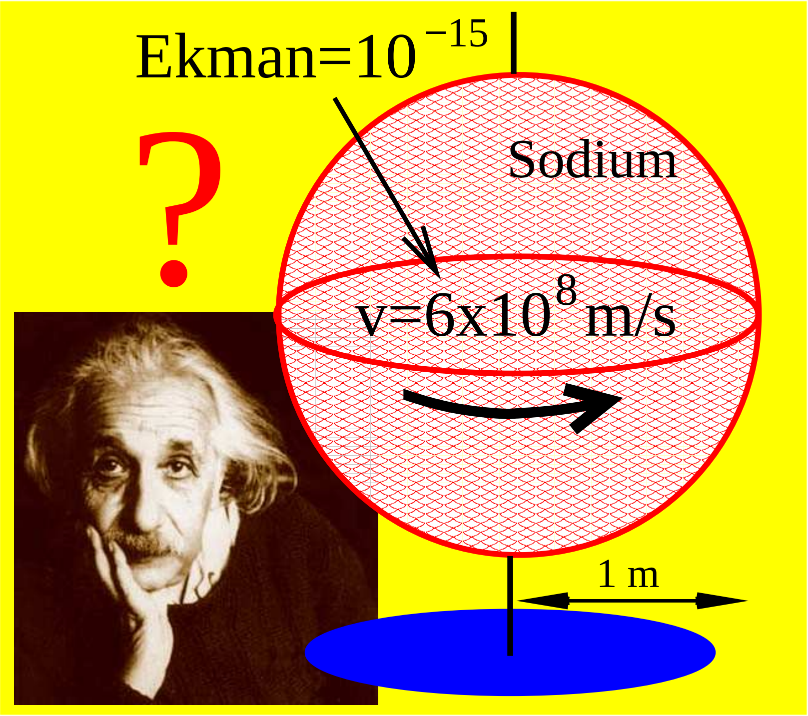
Dynamos: Experiments

Richard Feynman: What I cannot create I do not understand



Dynamos: Experiments - Don't expect too much!

- Not all dimensionless numbers of natural dynamos can be realized in experiment
- Striking Example: Geodynamo, Ekman number $E = \nu/\Omega r^2$
- There is no perfect BONSAI VERSION of the geodynamo



Dynamos: Experiments - Basic technical problem

- Necessary condition:
  $Rm := \mu\sigma LV \geq 10$
  μ...Permeability,
  σ...conductivity,
  L...Typical length,
  V...Typical velocity

- For sodium: $\mu\sigma = 10$ s/m^2

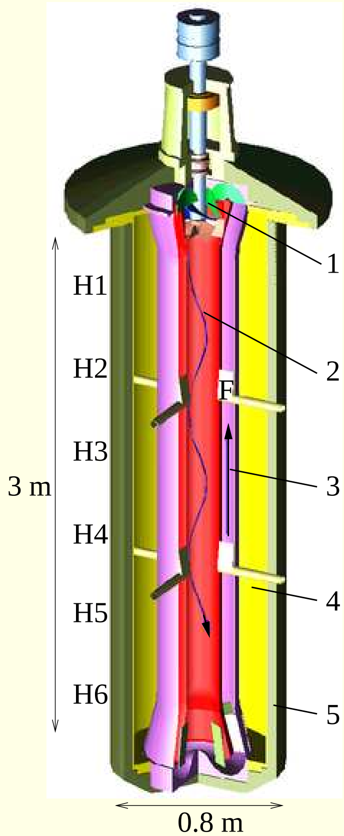
- Hence: $LV \geq 1$ m^2/s

An early pessimistic estimate (Max Steenbeck, 1975):

"...that remarkable effort would be necessary for such an experiment - **a vessel with approximately 10 m^3 of liquid sodium and with a pump rate of not less than 10 m^3/s**"

Dynamos: Riga

- 2 m^3 sodium
- Propeller (1). Helical flow (2). Back flow (3). Sodium at rest (4).
- Two motors (200 kW in total) produce flow speed up to 20 m/s.



Dynamos: Riga

Agris Gailitis, the "father" of the Riga dynamo

Dynamos: Riga

Thomas Gundrum, installing a "lance" of Hall sensors

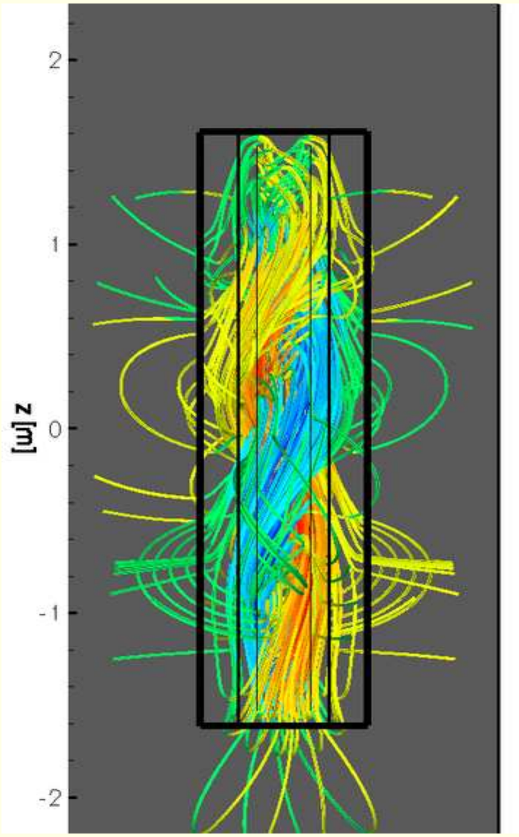
Dynamos: Riga

- Optimized flow (maximum helicity...nice duality with Taylor relaxation in plasma physics)

- Self-excitation at propeller rotation rate of $\sim$ 1900 rpm.

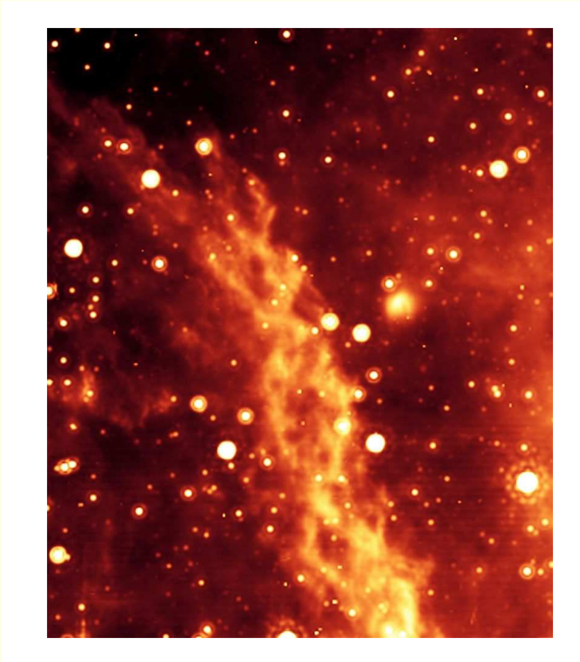
- Field structure rotates slowly (1-2 Hz) around vertical axis.

- Axial field component: up to 120 mT

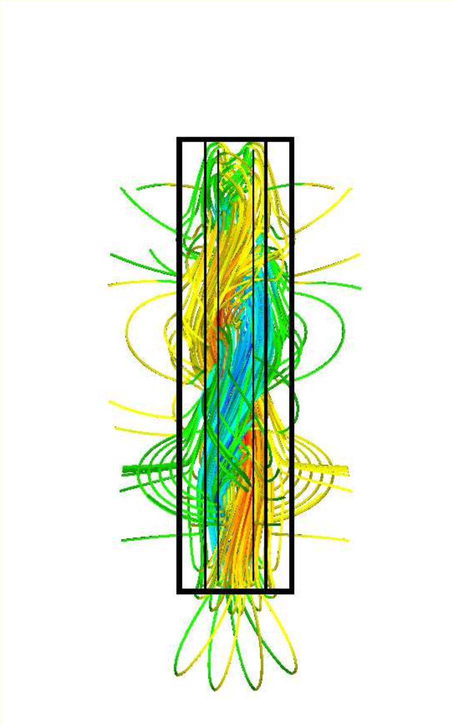


Dynamos: "Double helix nebula" and Riga dynamo

Similar dynamos in nature? Maybe...but the (kink-type) Tayler instability could also do the job...



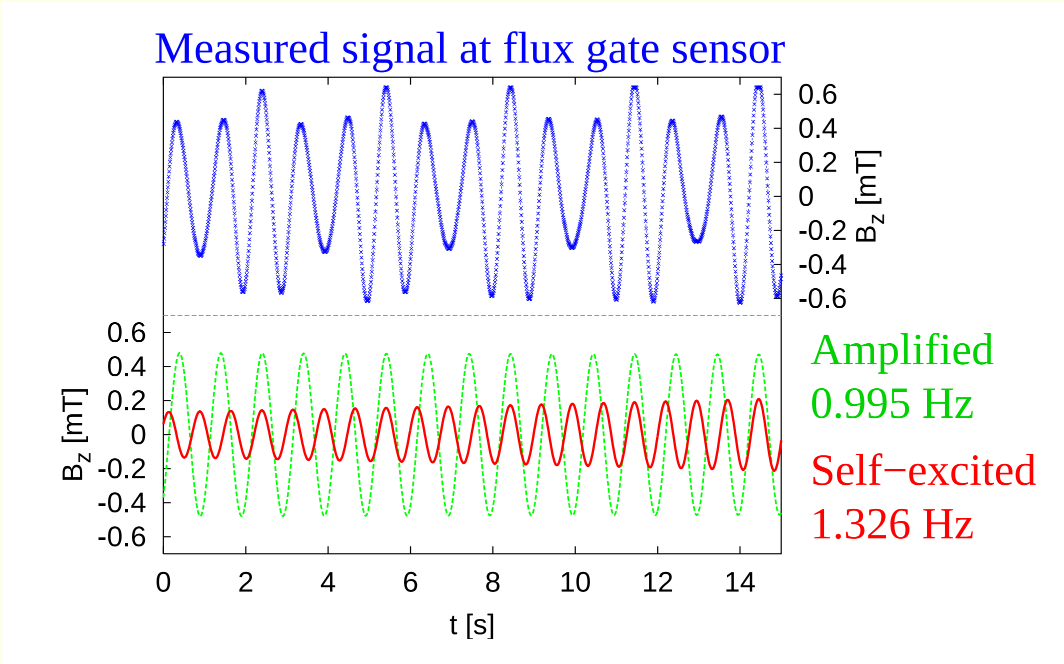
Morris, Nature 2006



Dynamos: Riga

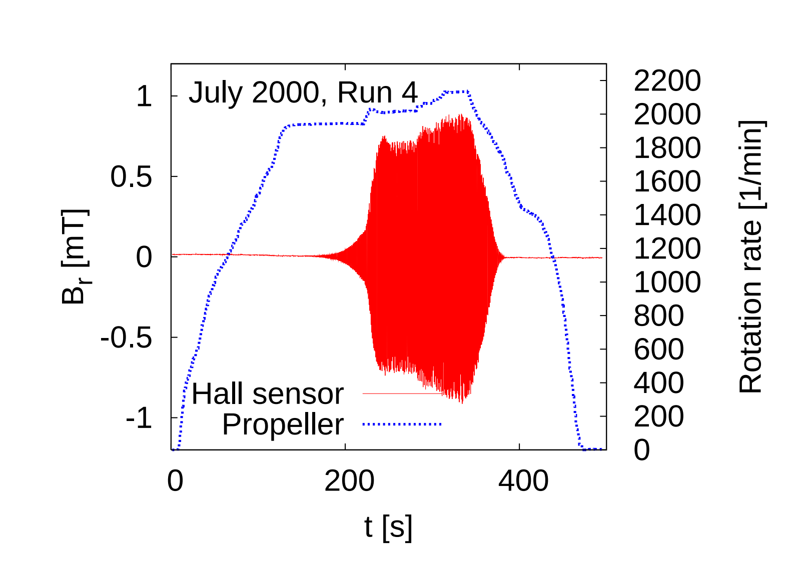
- 11 November 1999: First observation of a self-excited eigenfield of a hydromagnetic dynamo, on the background of an amplified externally applied signal

- Experiment had to be stopped before saturated regime was reached

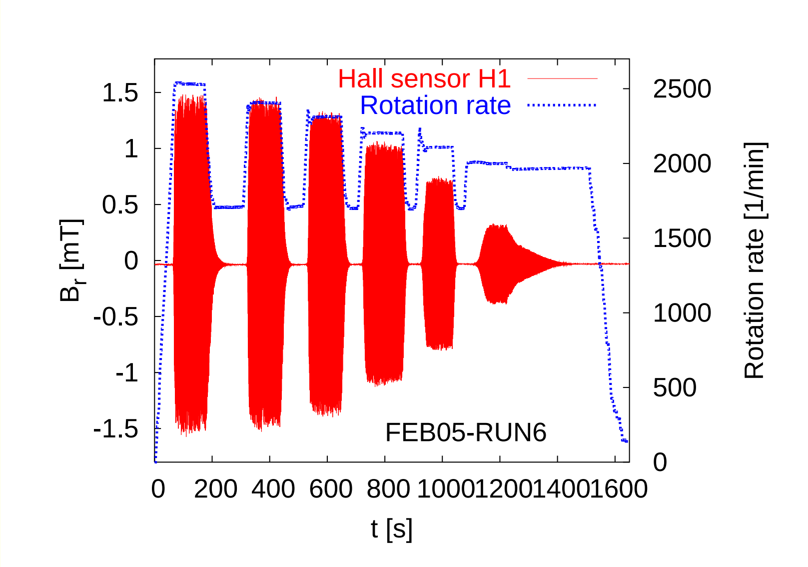


Dynamos: Riga

From 1999-2007: 8 experimental campaigns with reproducible results. Gailitis et al. Phys. Rev. Lett. 2000, 2001, Rev. Mod. Phys. 2002, Surv. Geophys. 2003, Phys. Plasmas 2004, 2006, Compt. Rend. Phys. 2008



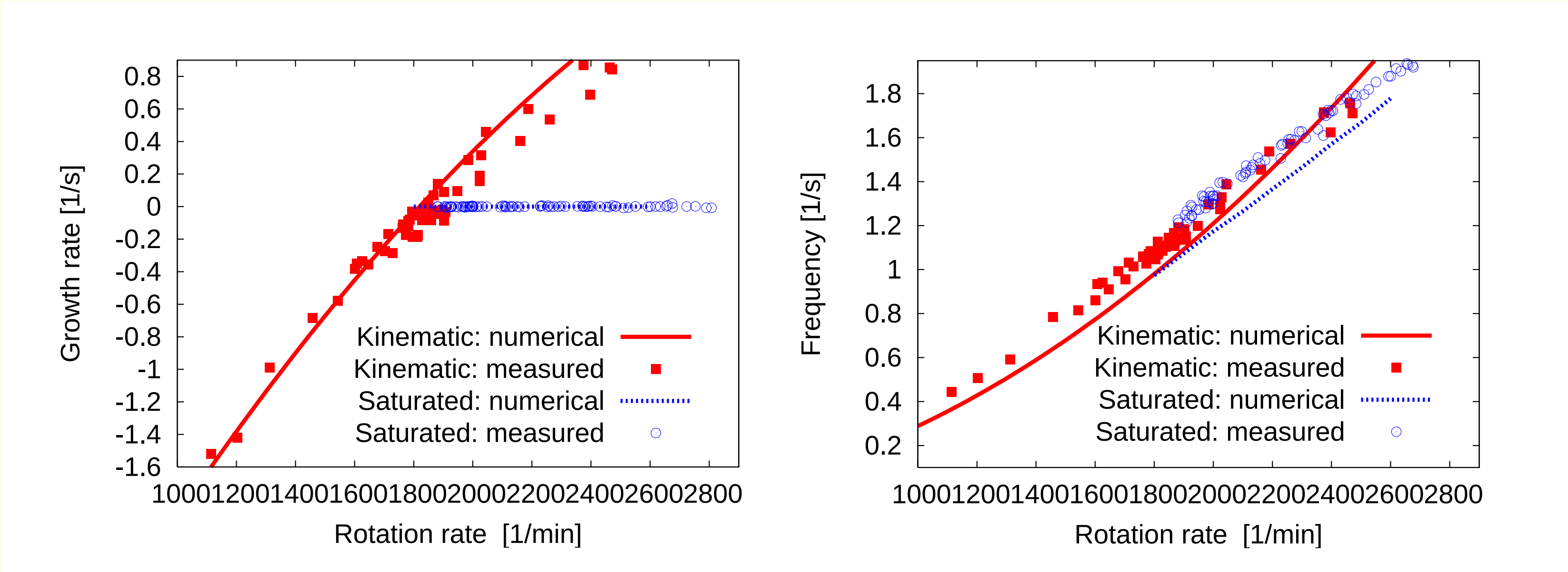
July 2000



February 2005

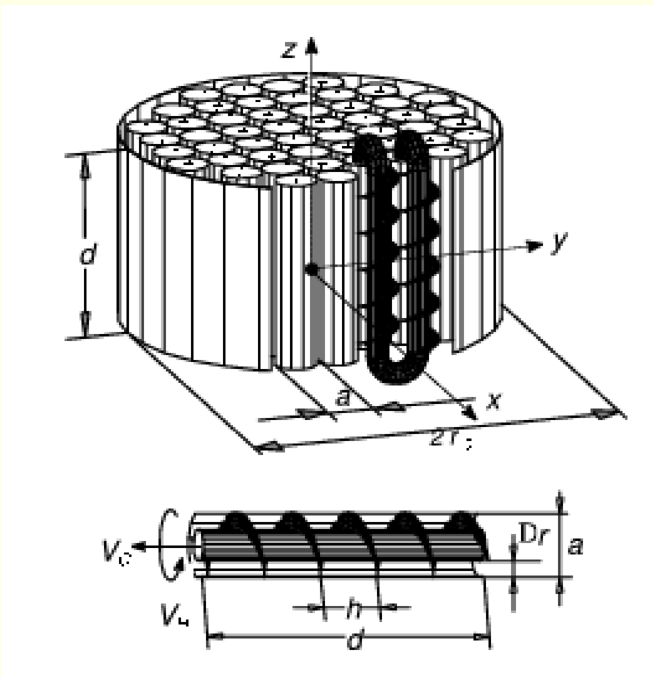
Dynamos: Riga

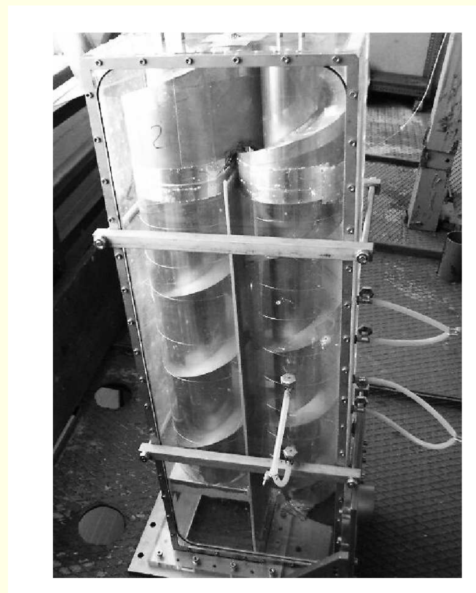
Comparison of measured and simulated growth rates and frequencies.



Dynamos: Karlsruhe

Anisotropic α^2 dynamo actualized by 52 "spin generators"

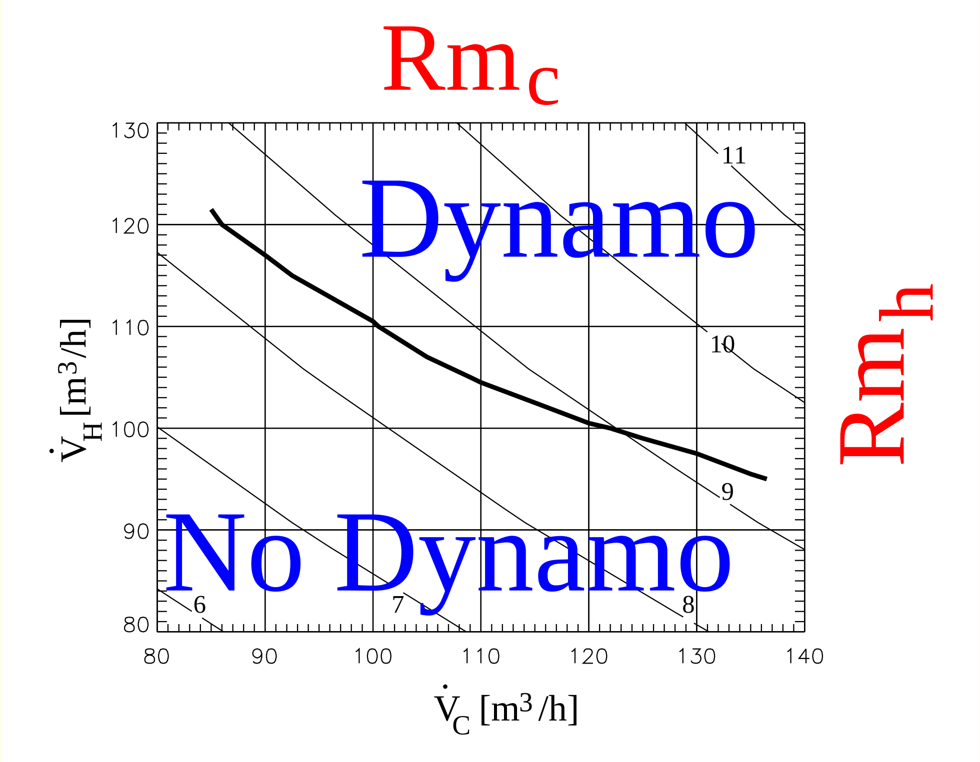




Dynamos: Karlsruhe

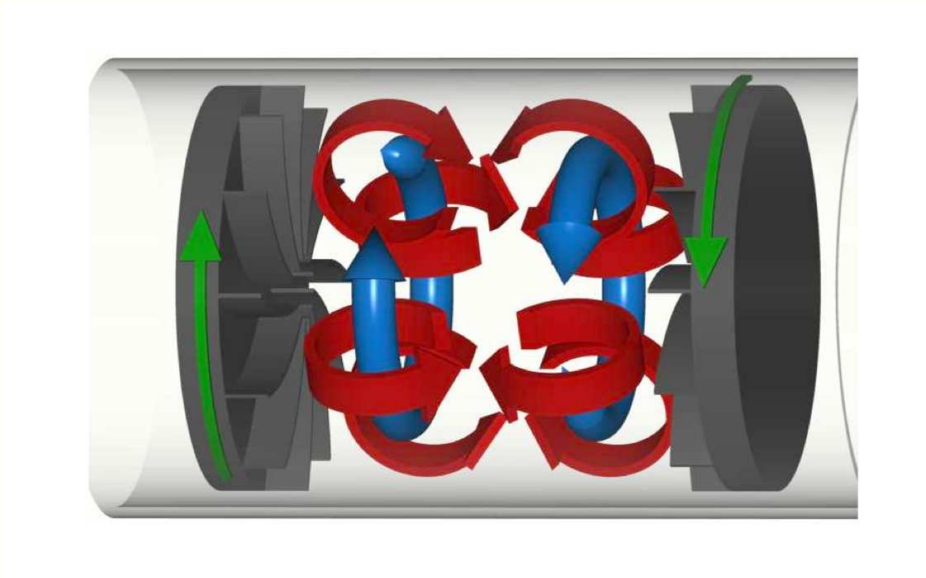
- Measuring campaigns between 1999 and 2003 provided stability diagram in dependence on the magnetic Reynolds numbers in the central and in the helical flow channel.

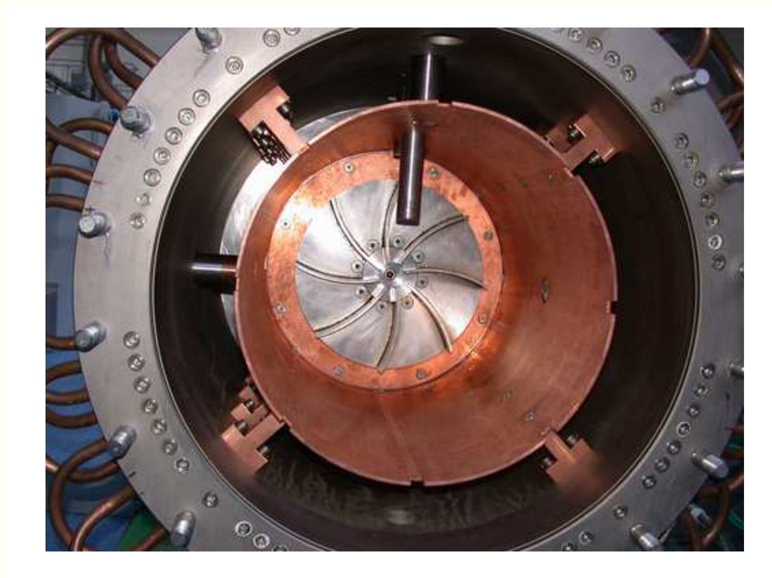
- Facility was disassembled in 2004



Dynamos: VKS (Cadarache)

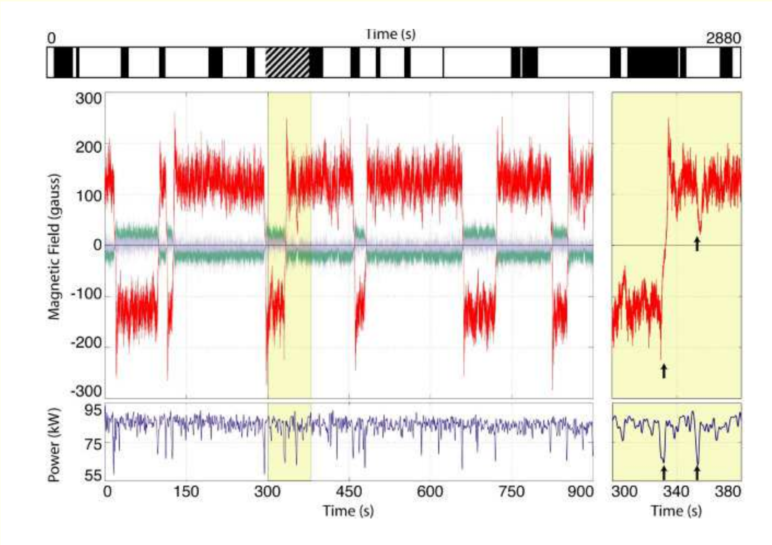
VKS experiment (Von Karman sodium): Helical flow with two poloidal and two toroidal eddies driven by counter-rotating impellers

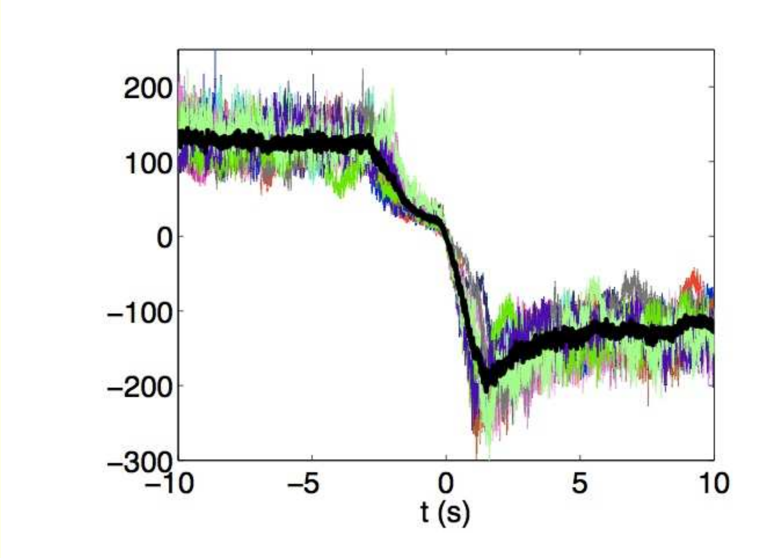




Dynamos: VKS

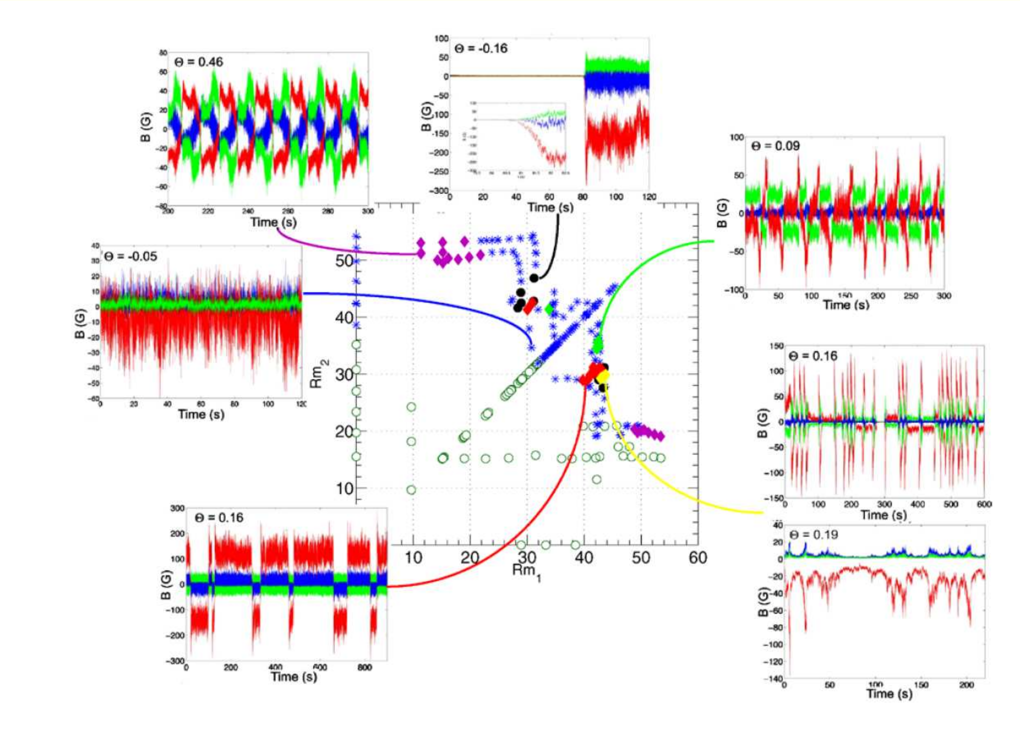
Very nice field reversals (Berhanu et al. 2007), and extremely rich dynamics





Dynamos: VKS

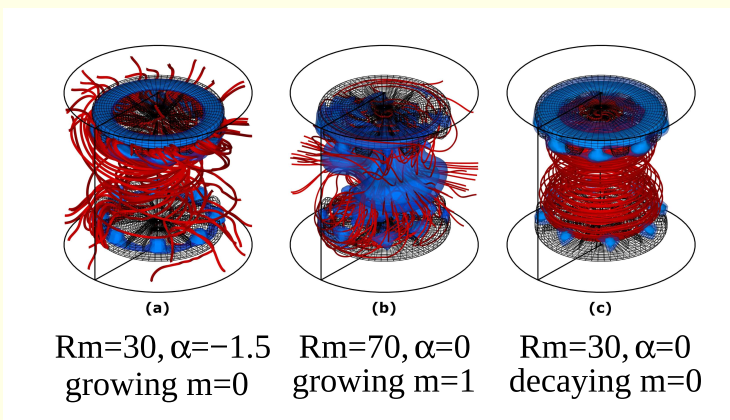
Fantastic dynamic effects (oscillations, reversals, burst....) in dependence on the two propeller rotation rates (Verhille et al., Space Sci. Rev. 2010)

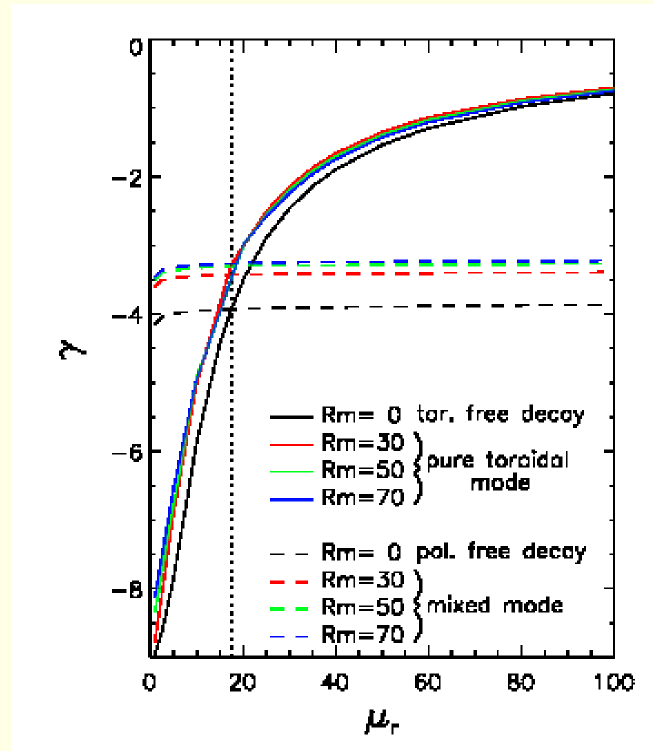


Dynamos: VKS

- Soft-iron impellers play a key role for mode selection $\Longrightarrow$ Dominating toroidal $m = 0$ mode for higher μ_{rel}

- Still, some small amount of helical turbulence is needed for self-excitation

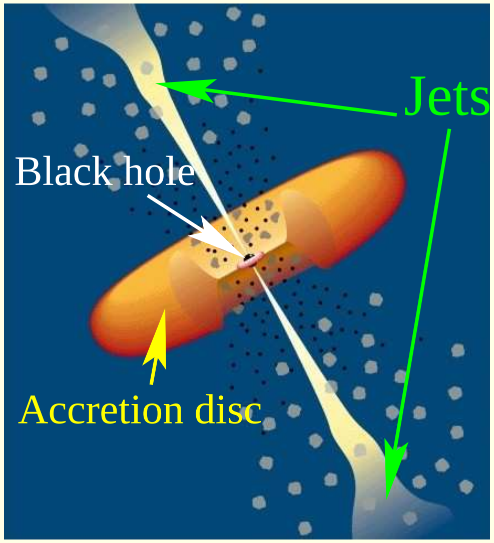




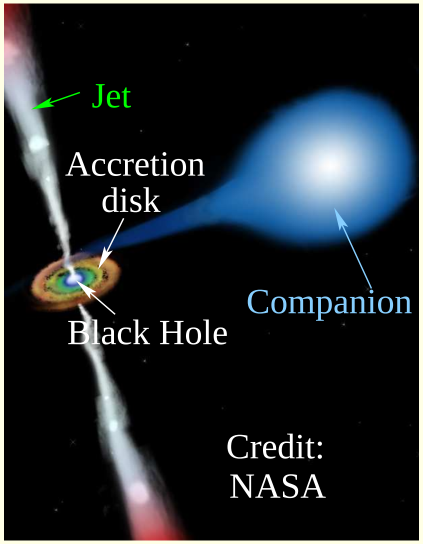
(Giesecke et al., PRL 2010, NJP 2012)

Magnetorotational instability and Tayler instability

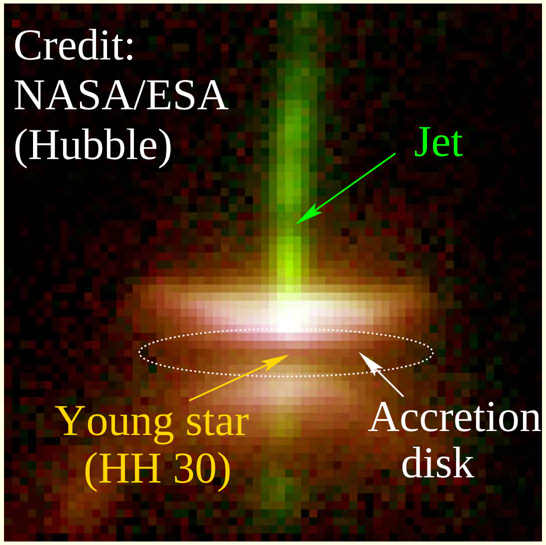
MRI: Accretion disks in the cosmos



Supermassive BH

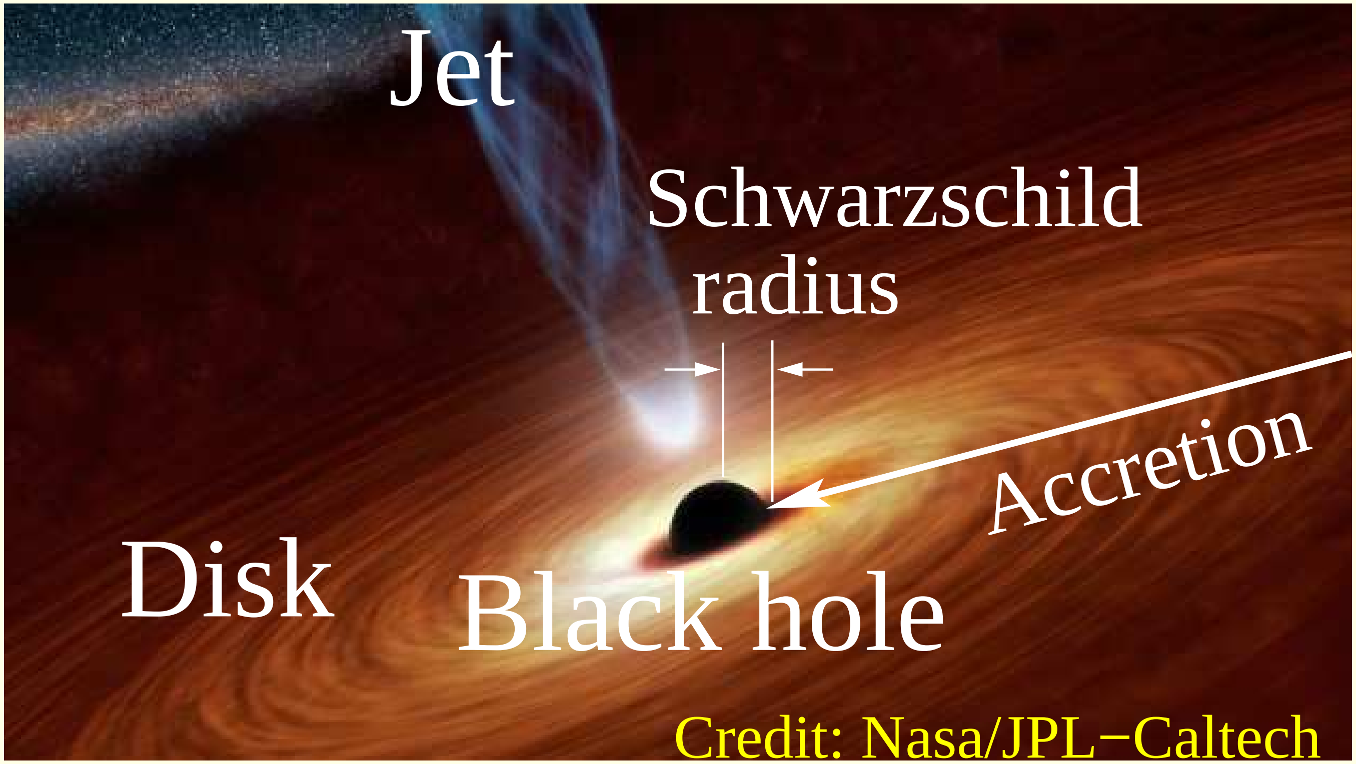


X-ray binaries



Young stars

MRI: The most efficient powerhouse in the cosmos



MRI: The most efficient powerhouse in the cosmos

Which portion of the rest mass is released in the accretion process?

- Schwarzschild radius of a black hole of mass M: $R_S = 2GM/c^2$
- Energy gain (and release) by infalling matter: $\Delta E = GMm/R_S = mc^2/2$
- Compare with:
  - Fusion energy: $\Delta E \sim 10^{-2}mc^2$
  - Fission energy: $\Delta E \sim 10^{-3}mc^2$
  - Chemical energy: $\Delta E \sim 10^{-9}mc^2$

MRI and TI

- Background of **MRI**: How do accretion disks work? Necessary outward angular momentum transport is not explainable by molecular viscosity.

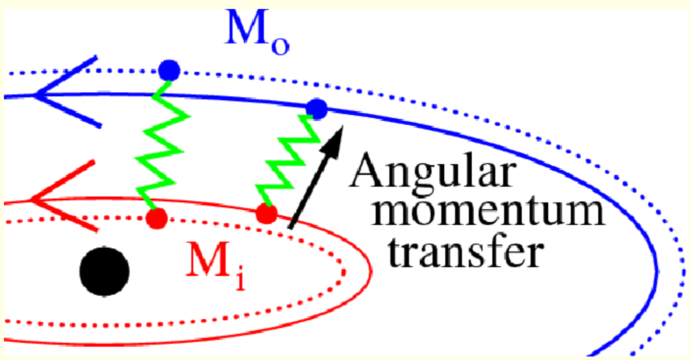
- Turbulence could explain it. However: Kepler-rotation is hydrodynamically stable (angular momentum increases outward)!

- Velikhov 1959: prove of MRI for Taylor-Couette flow. Balbus/Hawley 1991: Revealed the astrophysical relevance of MRI for accretion discs. Recent work on geostrophic MRI (Petitdemange et al.) with possible relevance to the geodynamo...

- **Tayler instability**: Kink type instability of strong azimuthal fields. Possible applications in the Tayler-Spruit dynamo and in galactic jets

MRI: A (somewhat too) simple spring model

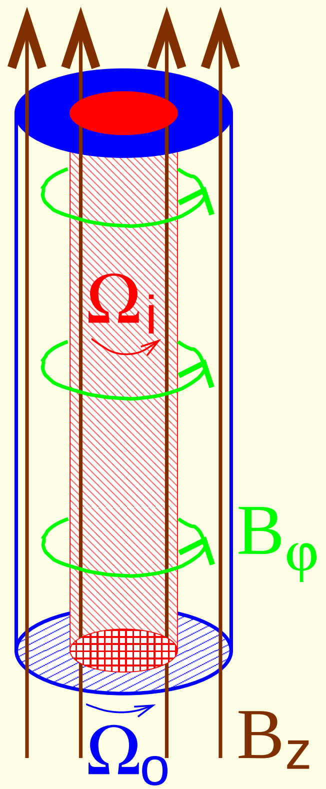
Magnetic field acts similar as a massless spring



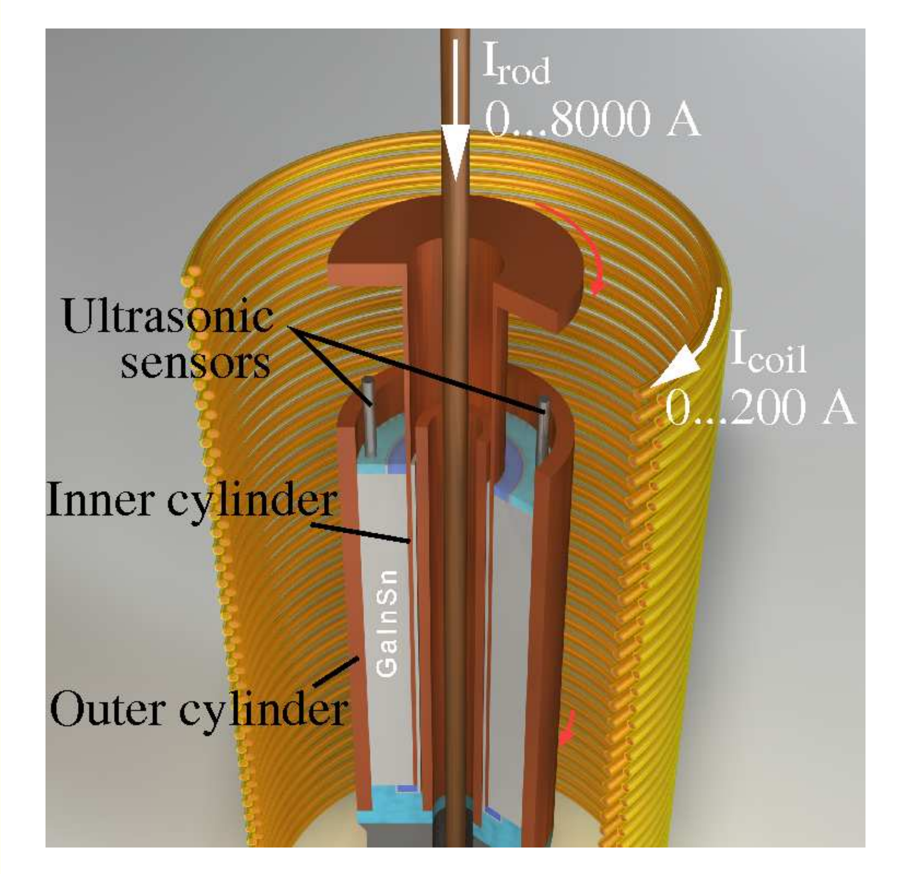
- In Keplerian disks, inner masses orbit more rapidly than outer mass
- Inner masses slow down $\Longrightarrow$ reduce angular momentum $\Longrightarrow$ move to lower orbit
- Outer masses speed up $\Longrightarrow$ increase angular momentum $\Longrightarrow$ move to higher orbit
- Spring tension increases $\Longrightarrow$ run-away process

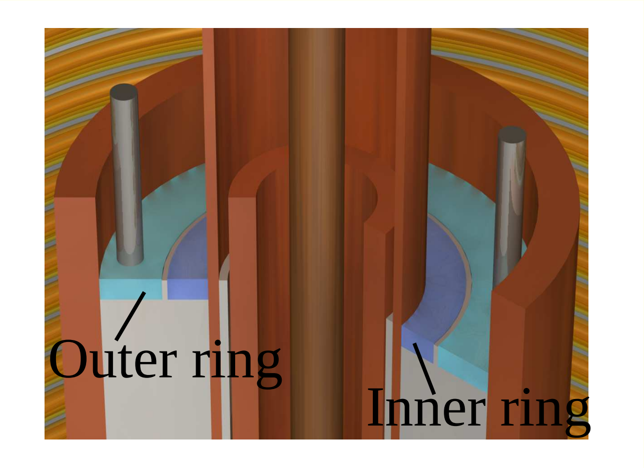
MRI: Standard MRI and helical MRI

- Experiments on MRI with large Rm (pure axial fields) in **Maryland**, Princeton, New Mexico, Moscow
- Hollerbach and Rüdiger (2005): Helical MRI: B_z replaced by $B_z + B_\varphi$: $Re_{crit} \sim 10^3$ instead of 10^6
- Potsdam ROssendorf Magnetic InStability Experiment (PROMISE)
- The "only" Problem: Axial current $\sim$ 5000 Amp.



MRI: PROMISE





Inner rings rotate with the inner cylinder, outer rings with the outer cylinder (to minimize Ekman pumping)

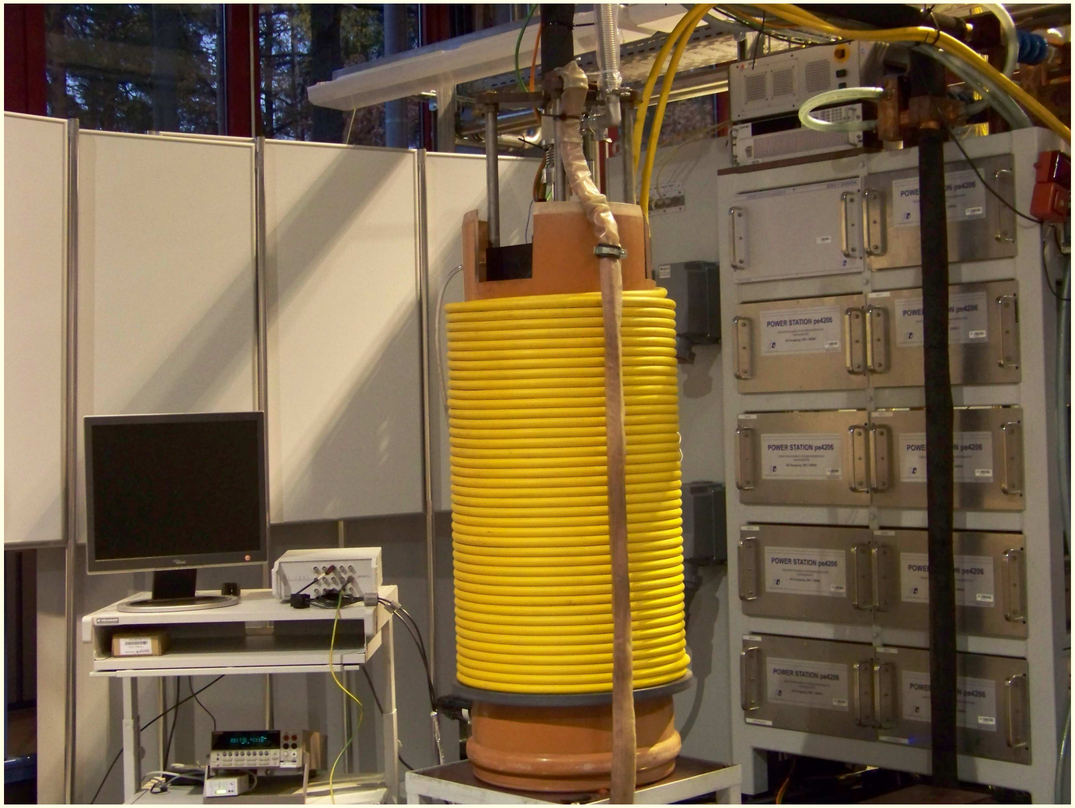
MRI: PROMISE - Copper cylinders

MRI: PROMISE - Coil on a wastewater tube

First layer....

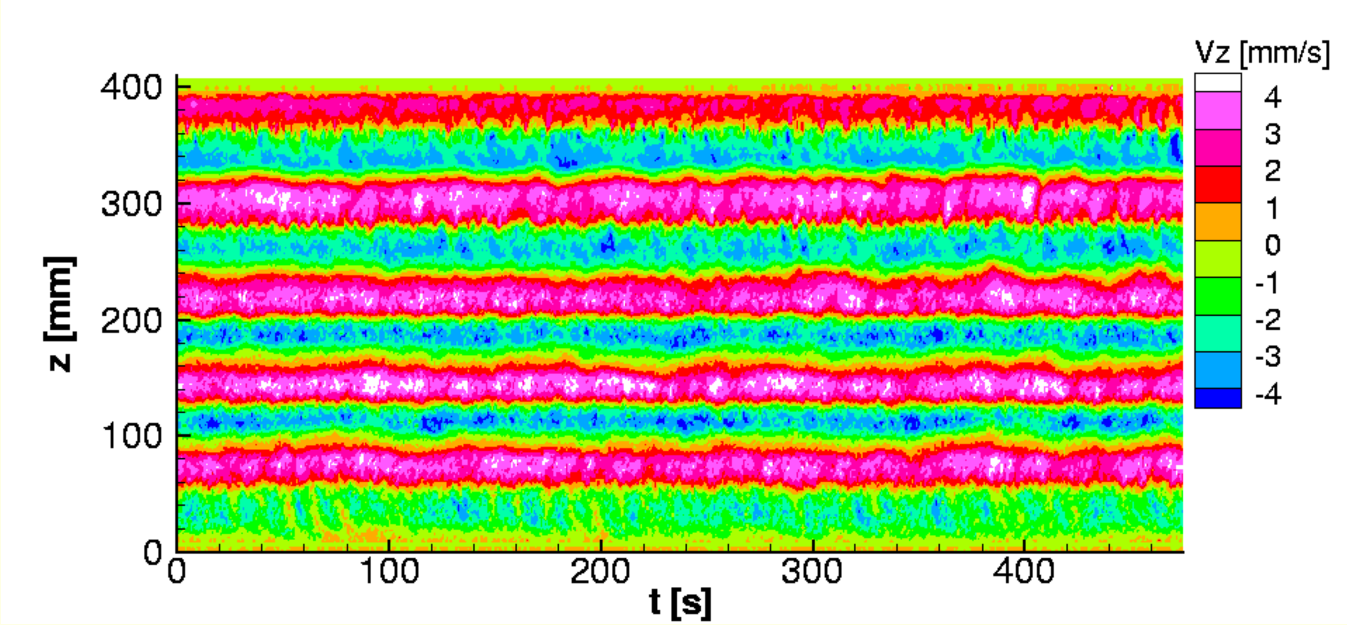
...second layer...done!

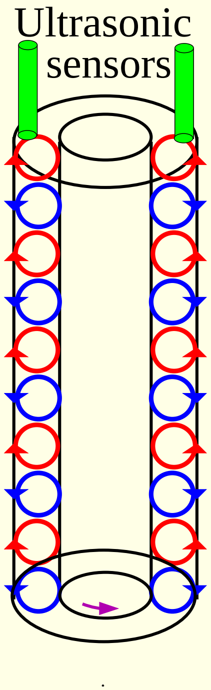
MRI: PROMISE - Present status



MRI: PROMISE - Ultrasonic sensors give axial velocity v_z

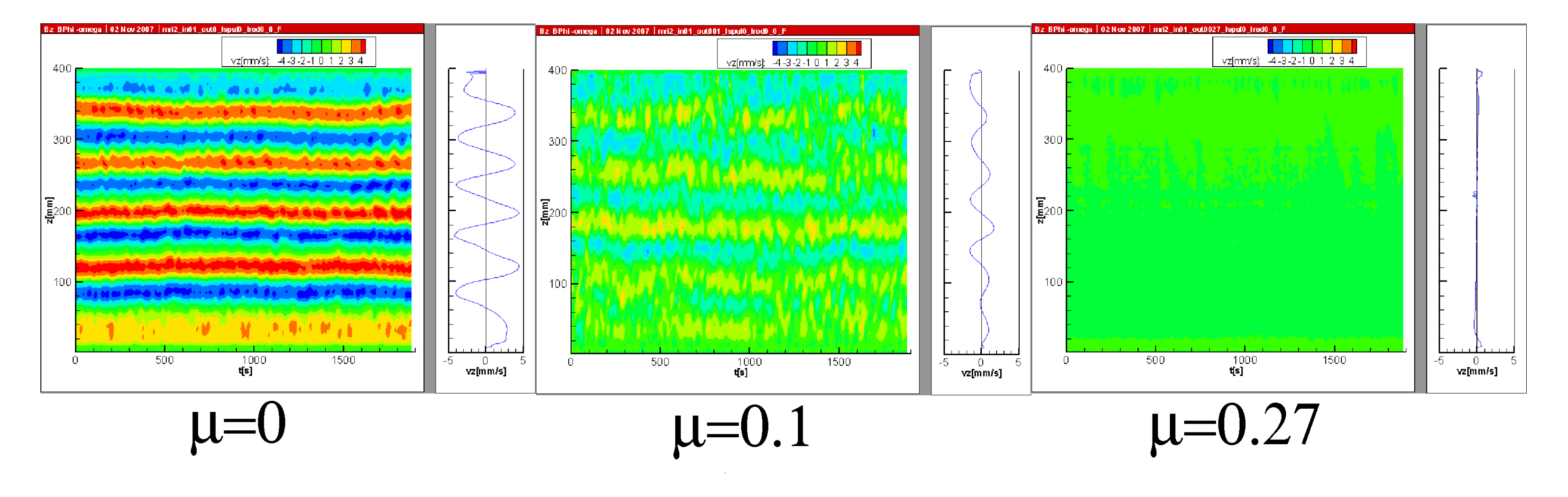
Without magnetic fields: Taylor-Vortex (for outer cylinder at rest)





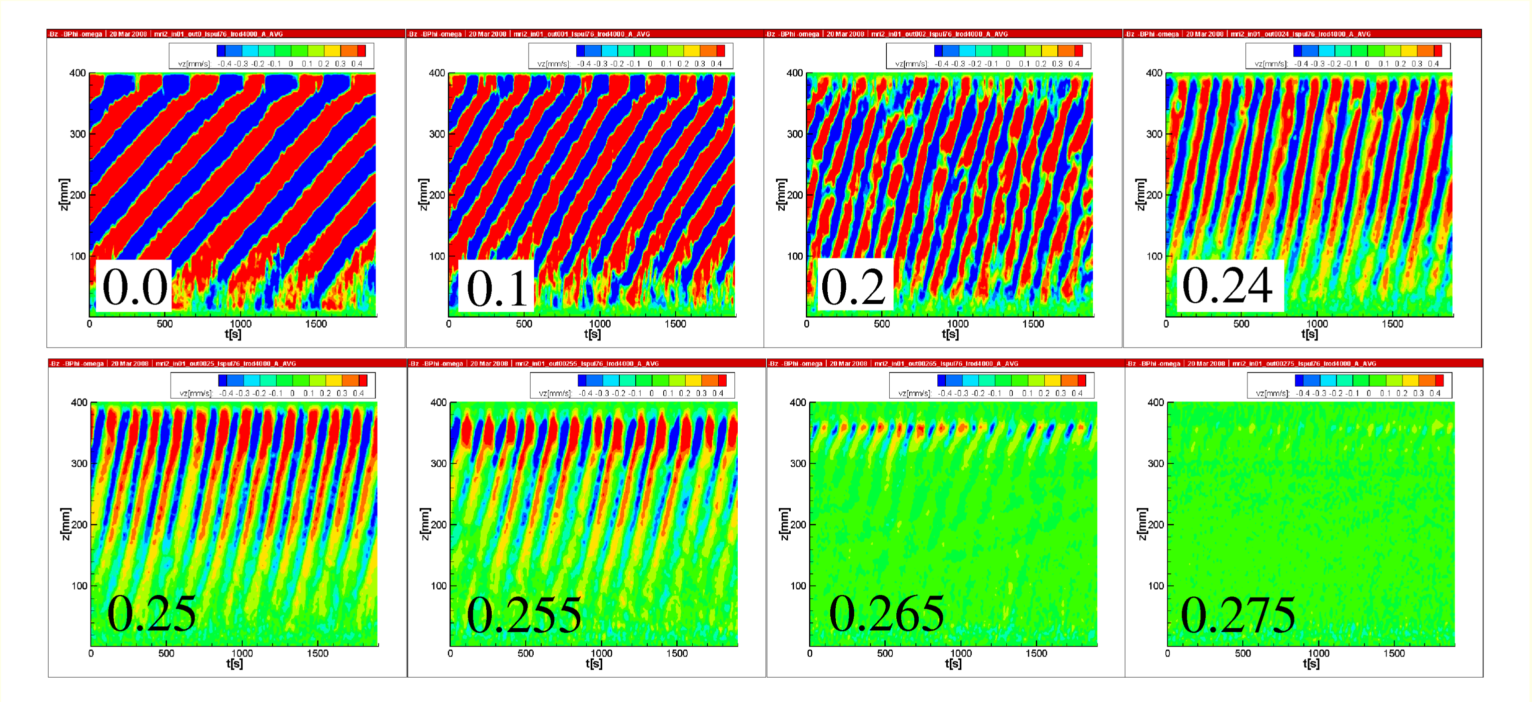
MRI: Tayler vortices disappear at $\mu := f_{out}/f_{in} = 0.25$

$f_{in} = 0.1$ Hz. $I_{coil} = 0$ Amp. $I_{rod} = 0$ Amp



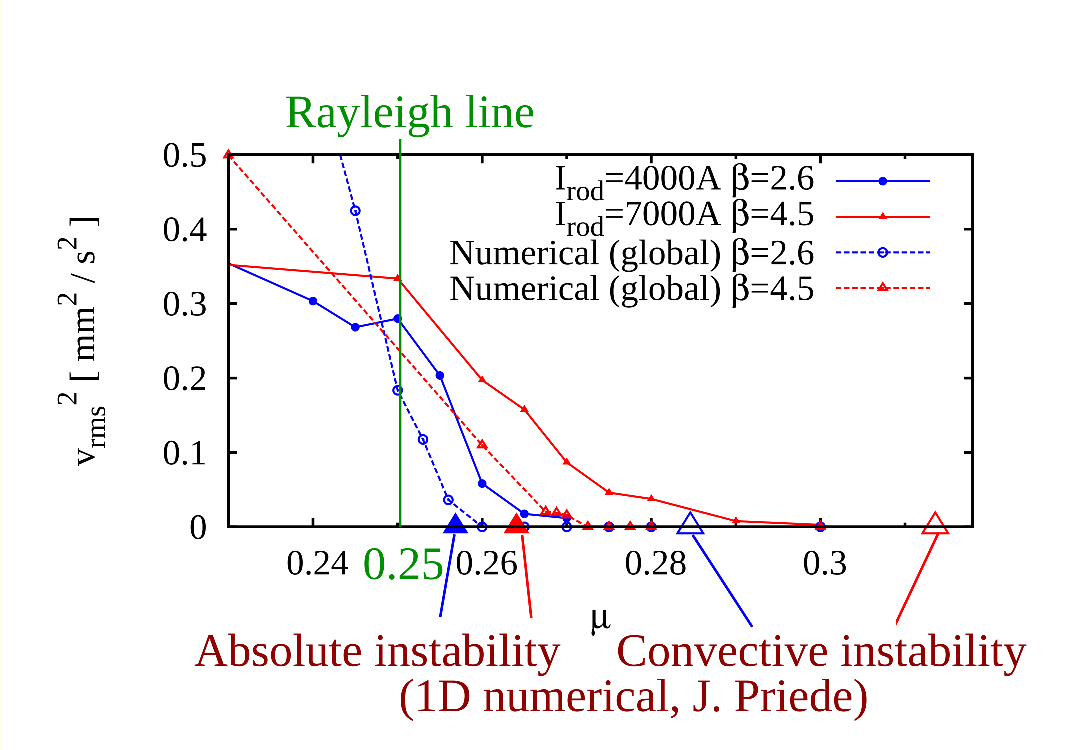
MRI: PROMISE - Increasing $\mu := f_{out}/f_{in}$

$I_{coil} = 76$ Amp. $I_{rod} = 4000$ Amp



Travelling wave extends slightly beyond the Rayleigh line (till $\mu \sim 0.26$)

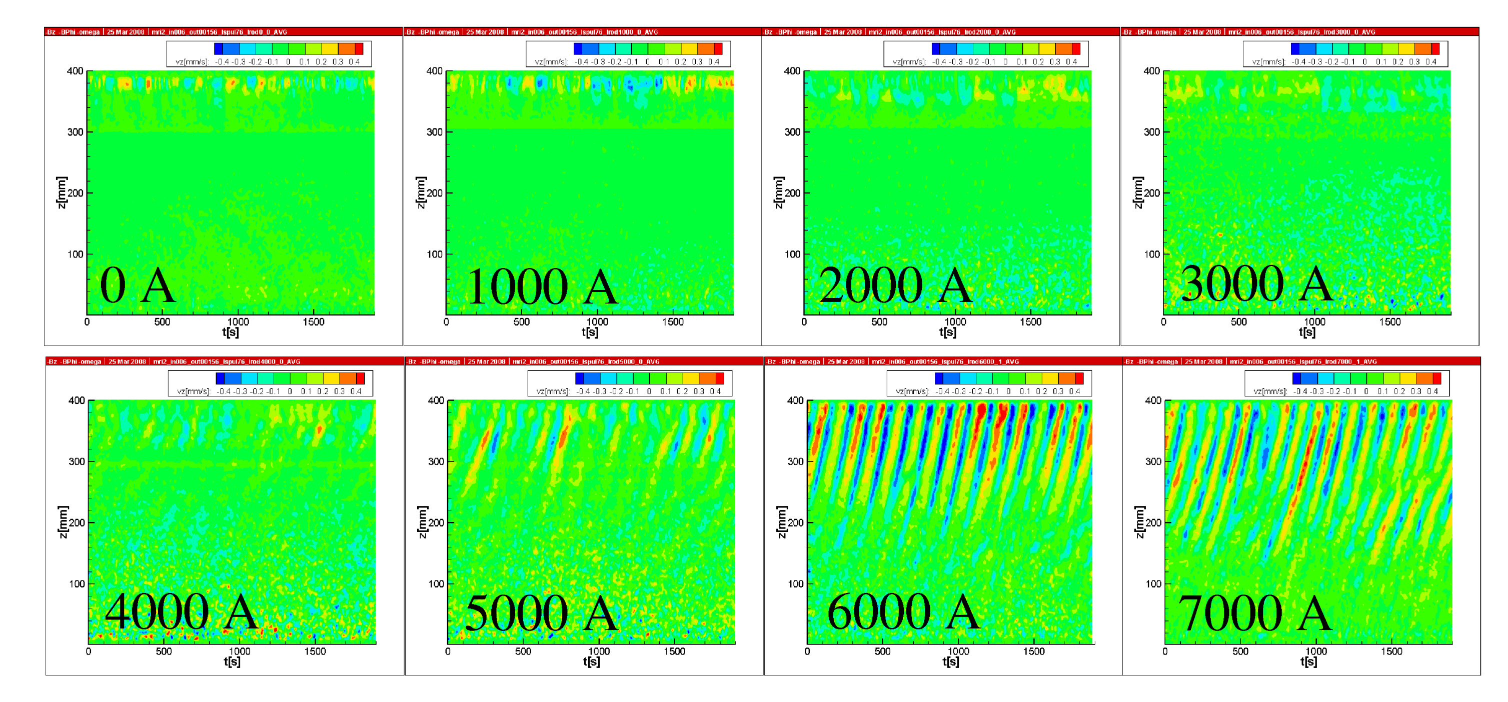
MRI: PROMISE - Increasing $\mu := f_{out}/f_{in}$



Observed mode represents a global, and not only a transient or noise-triggered convective instability ! (Stefani et al., PRE 2009)

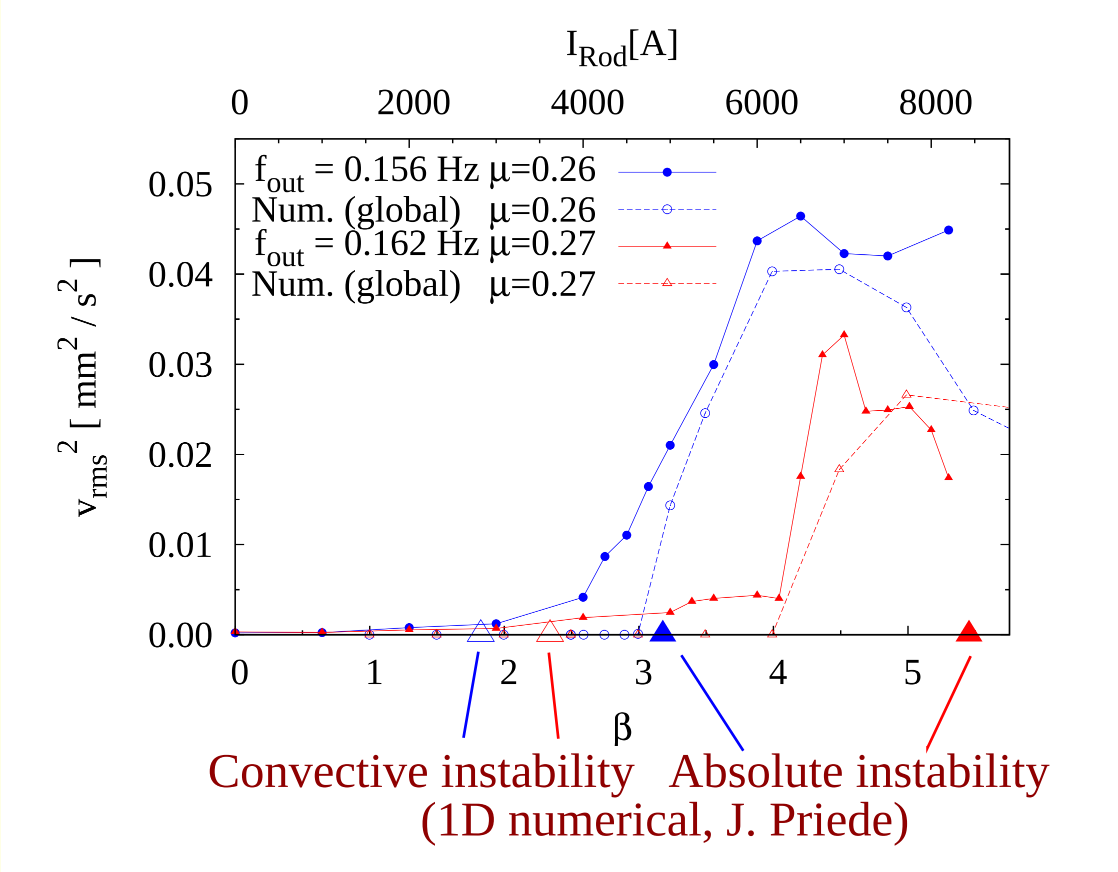
MRI: PROMISE - Increasing I_{rod} (β)

$f_{in} = 0.06$ Hz. $\mu = 0.26$, $I_{coil} = 76$ A



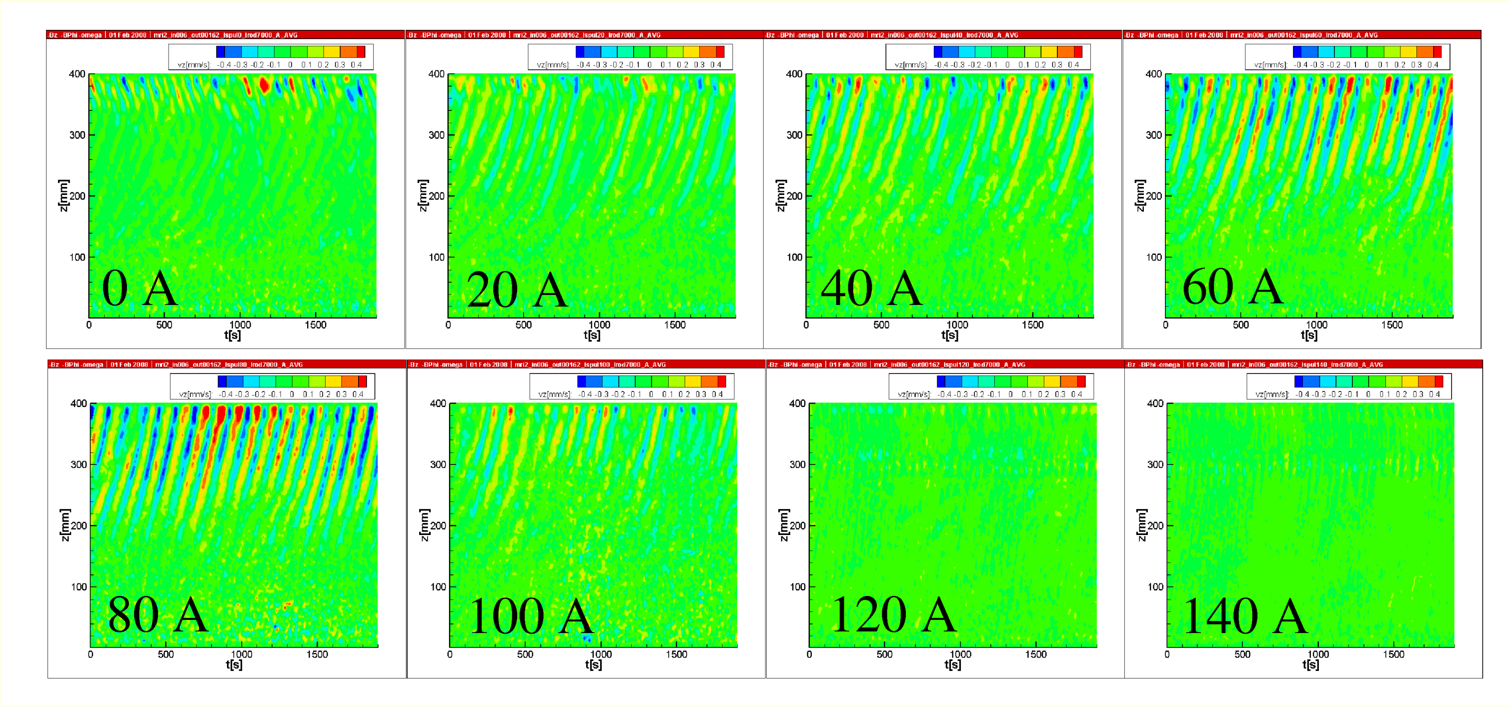
MRI appears only beyond a critical value of I_{rod}

MRI: PROMISE - Increasing I_{rod} (β)



MRI: PROMISE - Increasing I_{coil} (Ha)

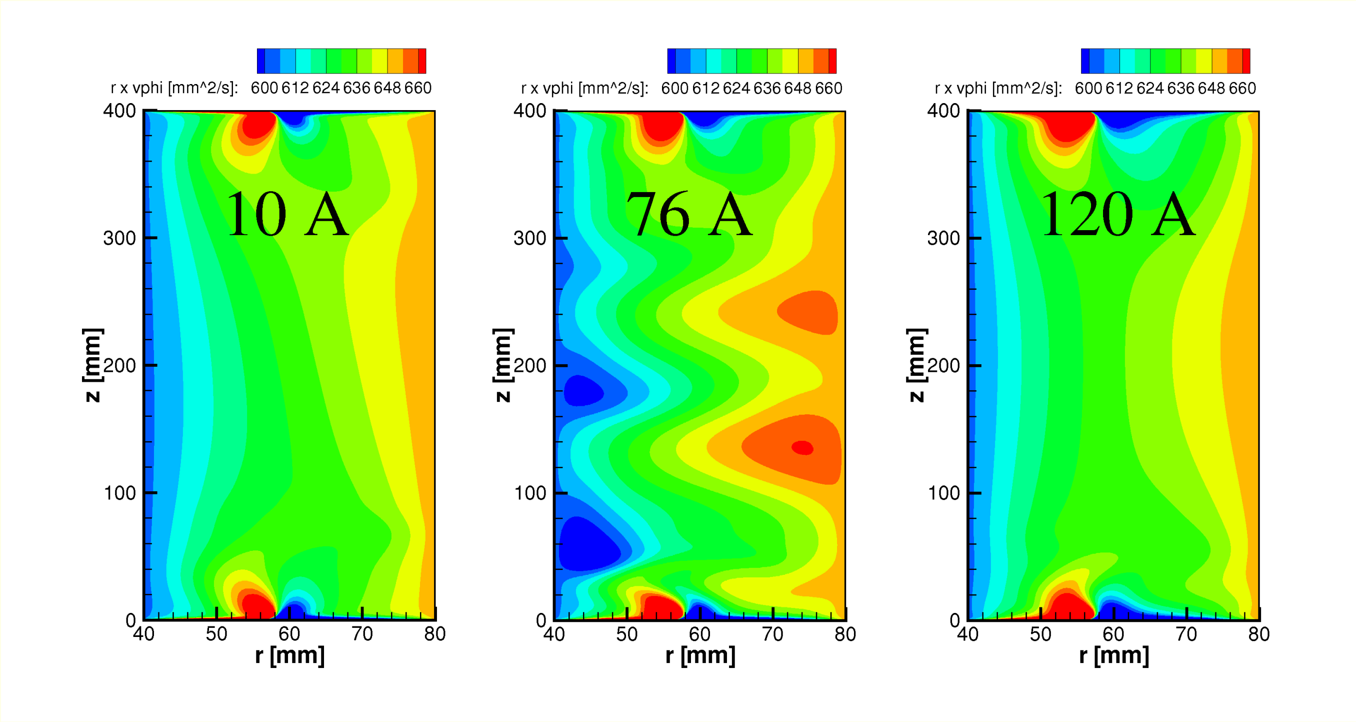
$f_{in} = 0.06$ Hz. $\mu = 0.27$, $I_{rod} = 7000$ A



MRI appears only in a finite window of I_{coil}

MRI: PROMISE - Increasing I_{coil} (Ha)

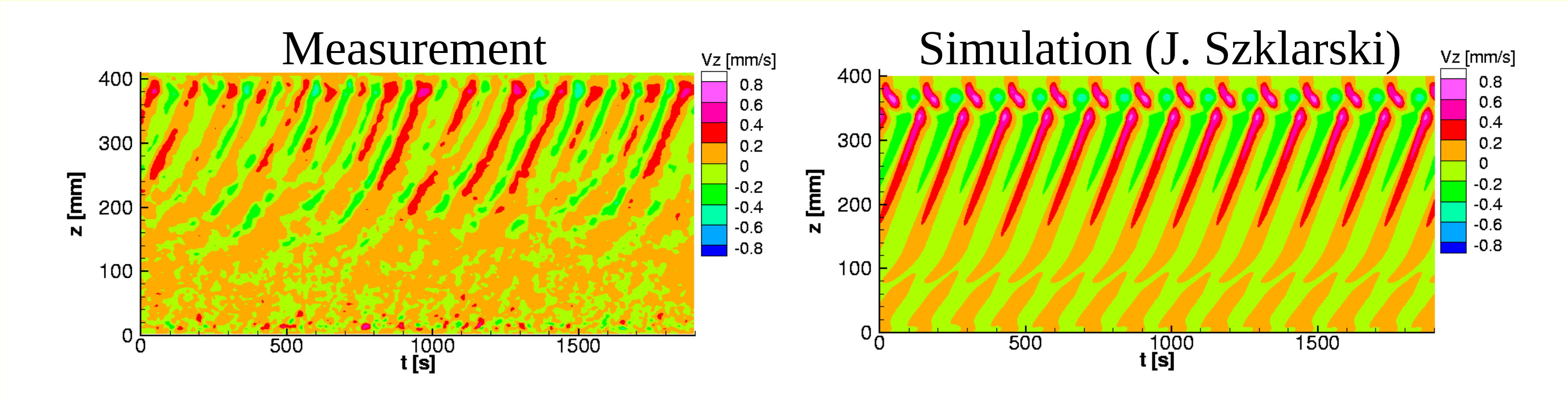
$f_{in} = 0.06$ Hz. $\mu = 0.27$, $I_{rod} = 8000$ A



Fingering of angular momentum. Simulation by Jacek Szklarski.

MRI: PROMISE - Comparison measurements/numerics

$f_{in} = 0.06$ Hz. $\mu = 0.26$, $I_{coil} = 60$ A. $I_{rod} = 6000$ A



MRI: Azimuthal MRI (AMRI)

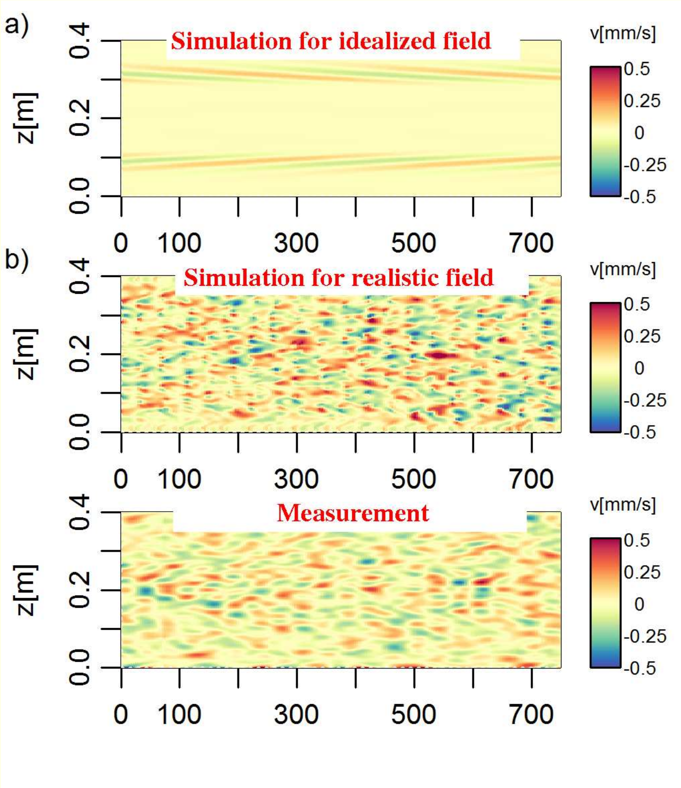
- Non-axisymmetric $m = 1$ MRI mode in the presence of a purely (or strongly dominant) azimuthal external magnetic field

- Ogilvie and Pringle, MNRAS 1996

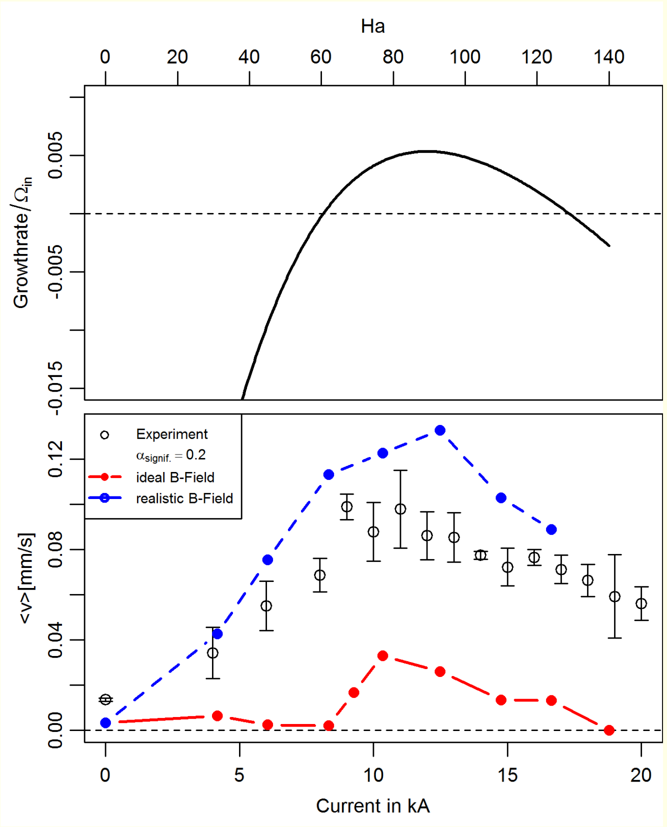
- Hollerbach, Teeluck, Rüdiger, PRL 2010: Extension of AMRI to the inductionless case with similar scaling as HMRI ($Re \sim 1000$, $Ha \sim 100$)

- Why is the scaling so similar? $\longrightarrow$ Kirillov, Stefani, Fukumoto: ApJ 2012

MRI: AMRI-Experiments at PROMISE

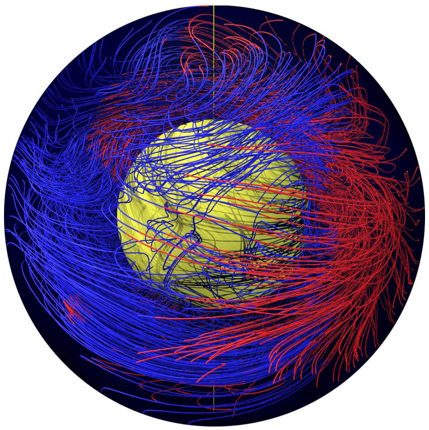


Seilmayer et al. arXiv:1311.7223

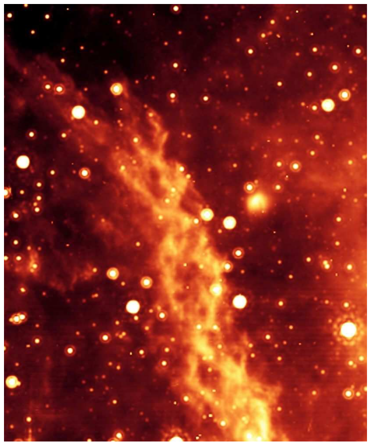


Tayler instability (TI)

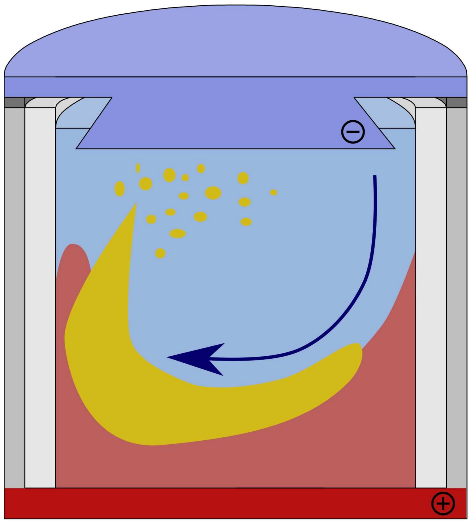
Kink-type instability of strong azimuthal fields: Possible role for stars, jets, and ...liquid metal batteries batteries



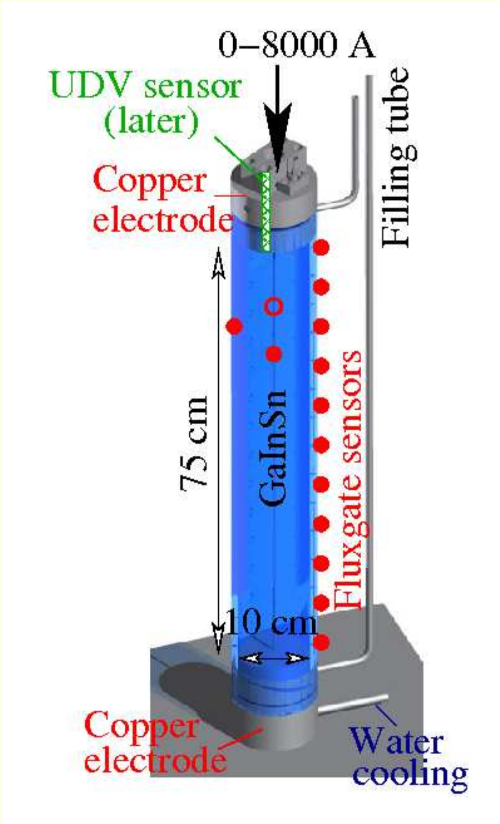
Courtesy: Rainer Arlt (AIP)



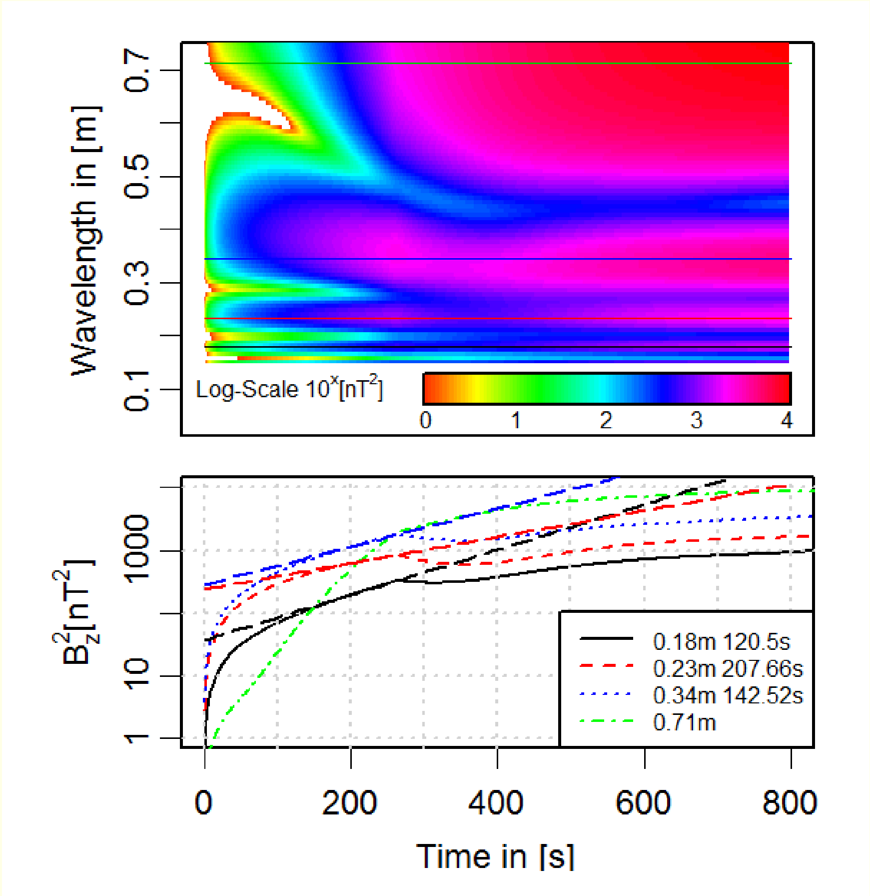
Morris, Nature 2006



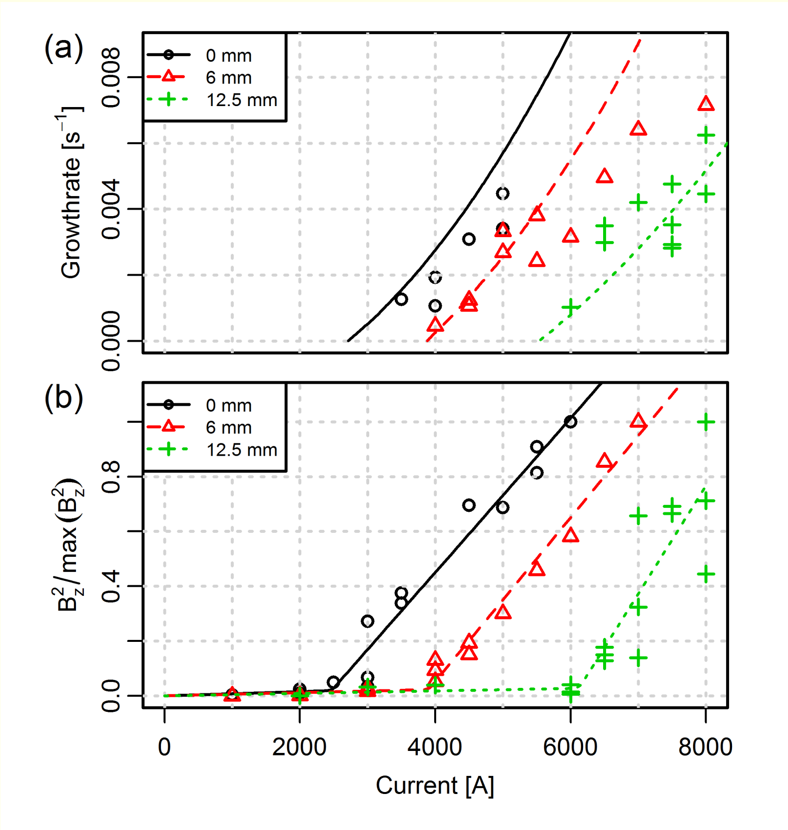
TI: Experimental setup

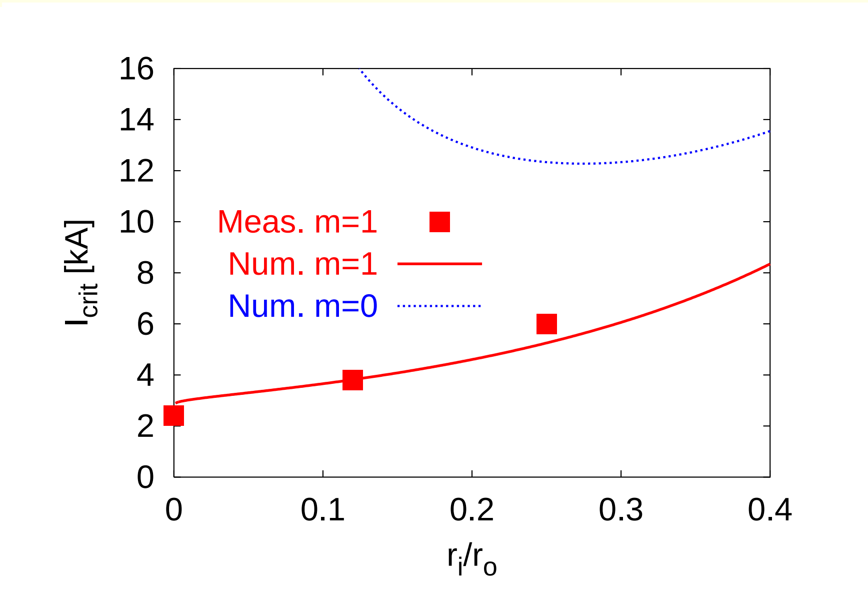


TI: Complicated interplay with convection



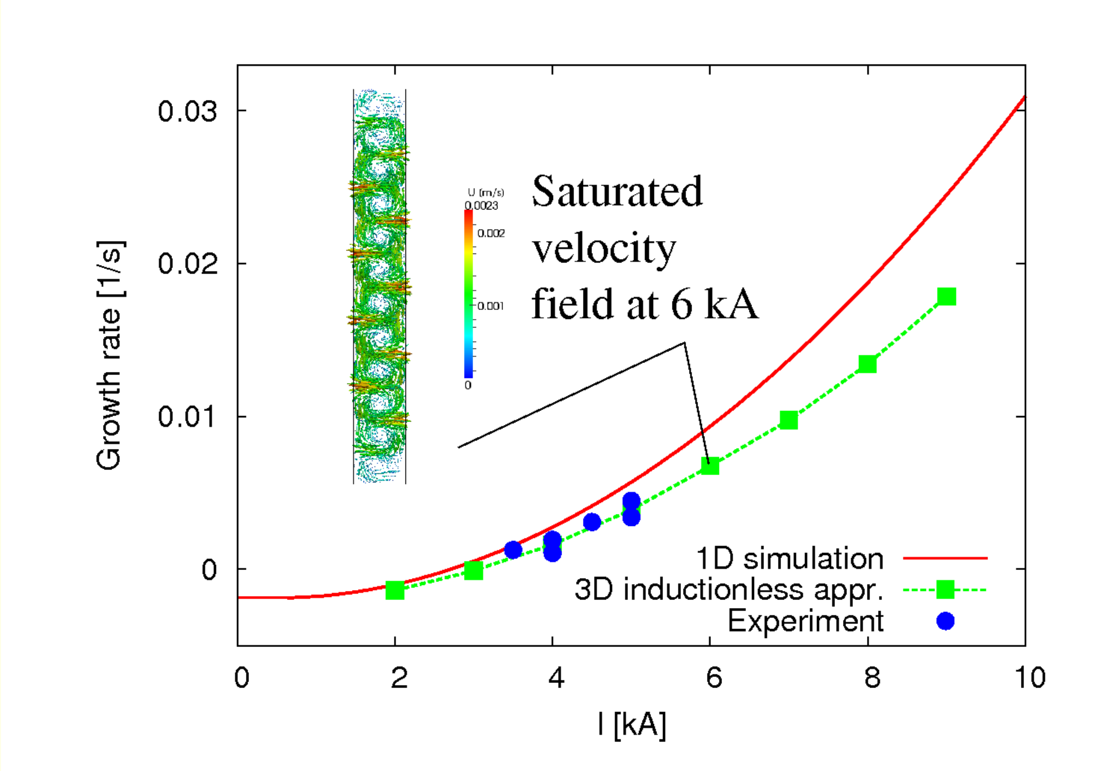
TI: Growth rates, saturation levels, critical current





Good agreement with numerical predictions of the kink (m=1) mode (Seilmayer et al., PRL 2012)

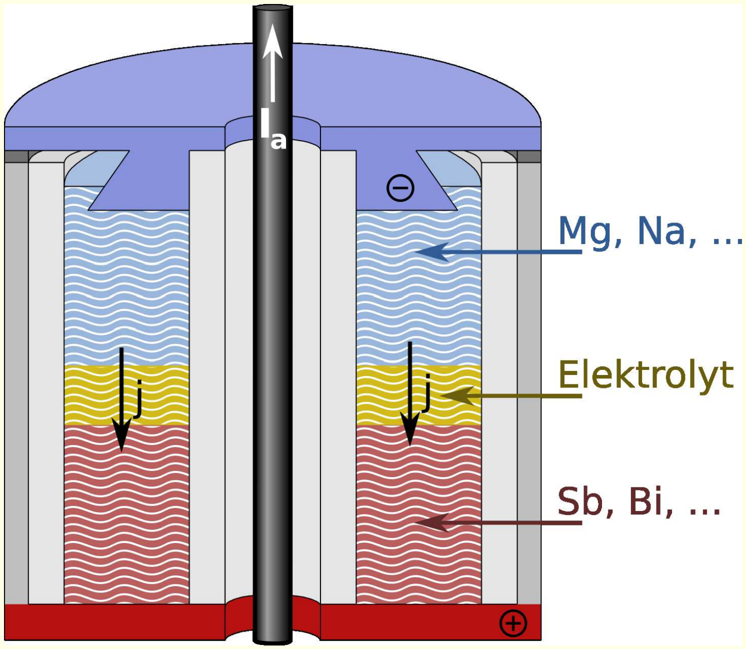
TI: Simulation with OpenFoam+Biot-Savart



Weber et al., New J. Phys. 2013

TI: How to avoid the TI in liquid metal batteries?

- D. Sadoway (MIT): Self-assembling battery (half-metal, electrolyte, metal)
- Advantage: High currents, huge capacity
- Problem: Tayler instability!!!
- Solution: Hole in the center, guiding the current back



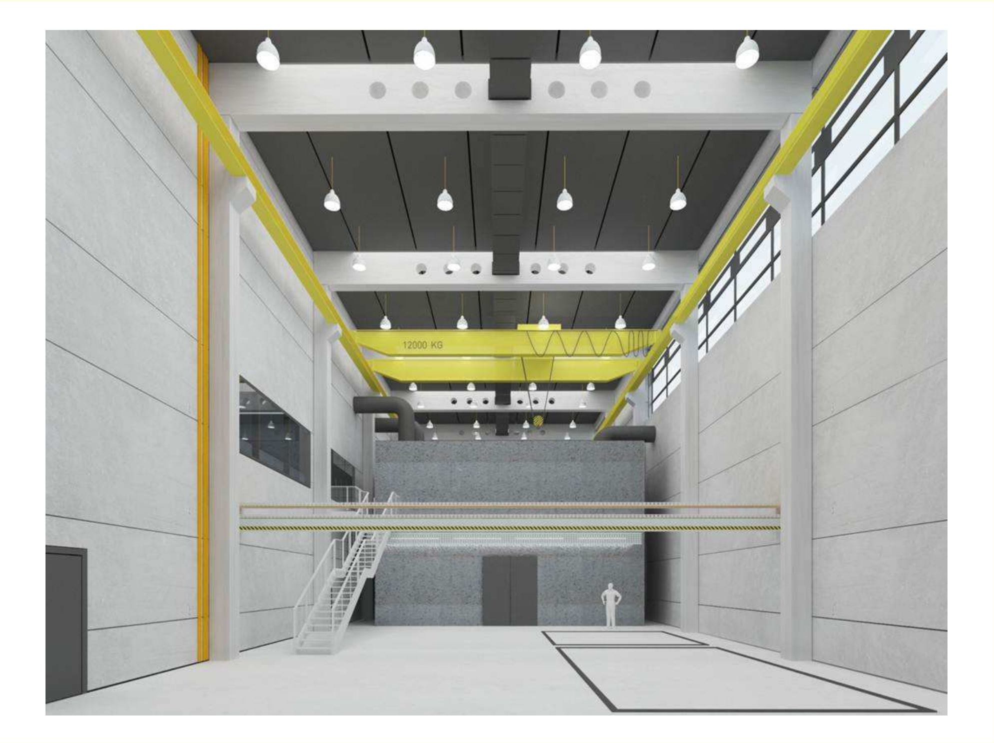
Prospects

DRESDYN

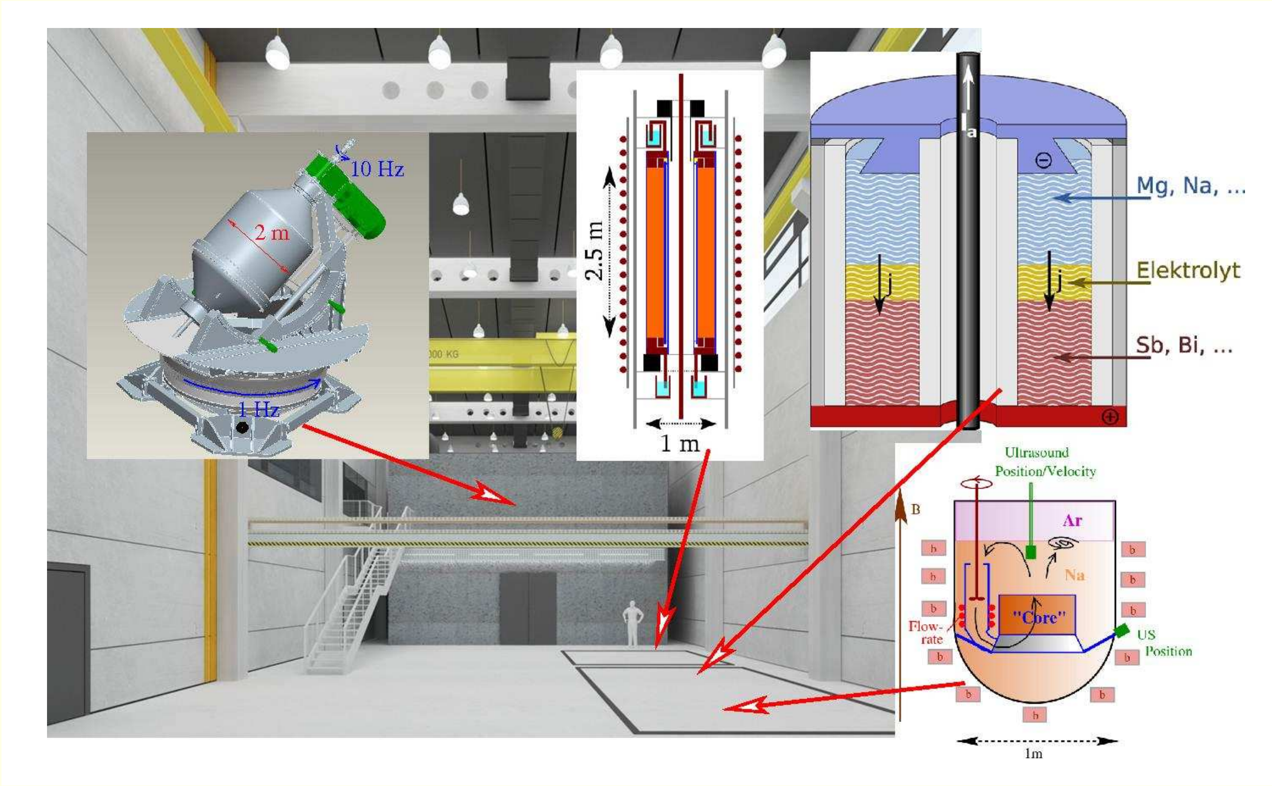
DRESDYN

- DREsden Sodium facility for DYNamo and thermohydraulic studies
- An infrastructure project initiated on occasion of the transition of the Rossendorf institute from Leibniz community to Helmholtz community
- Various experiments, total sodium inventory: appr. 12 tons

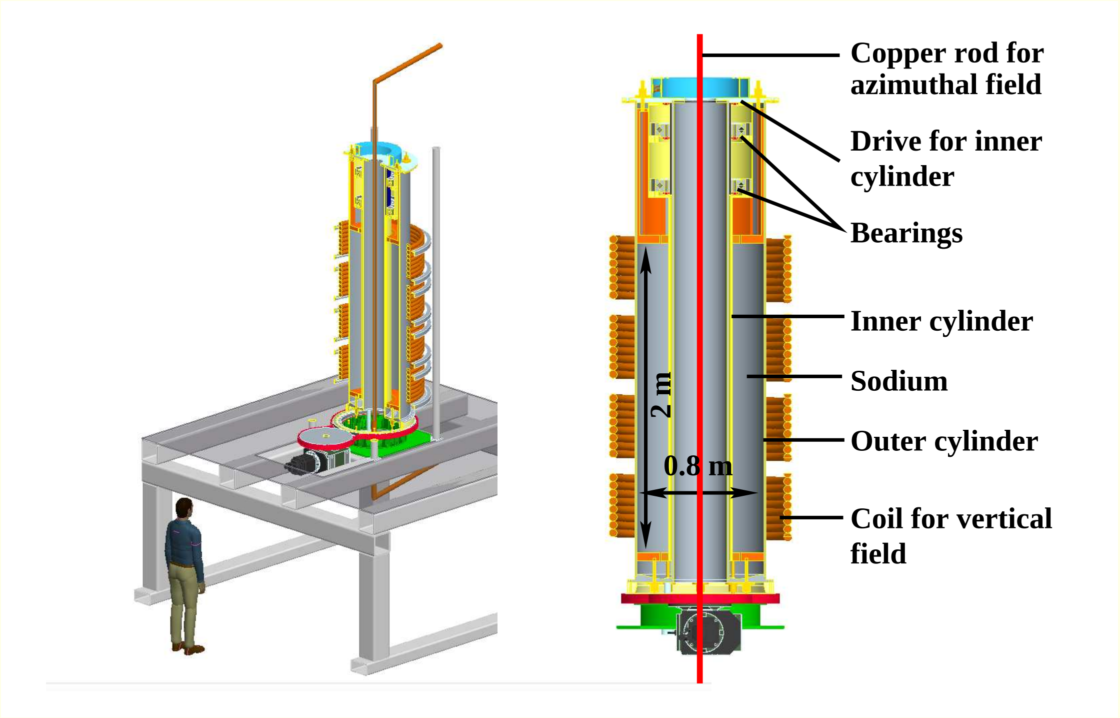
DRESDYN - Plan of the building



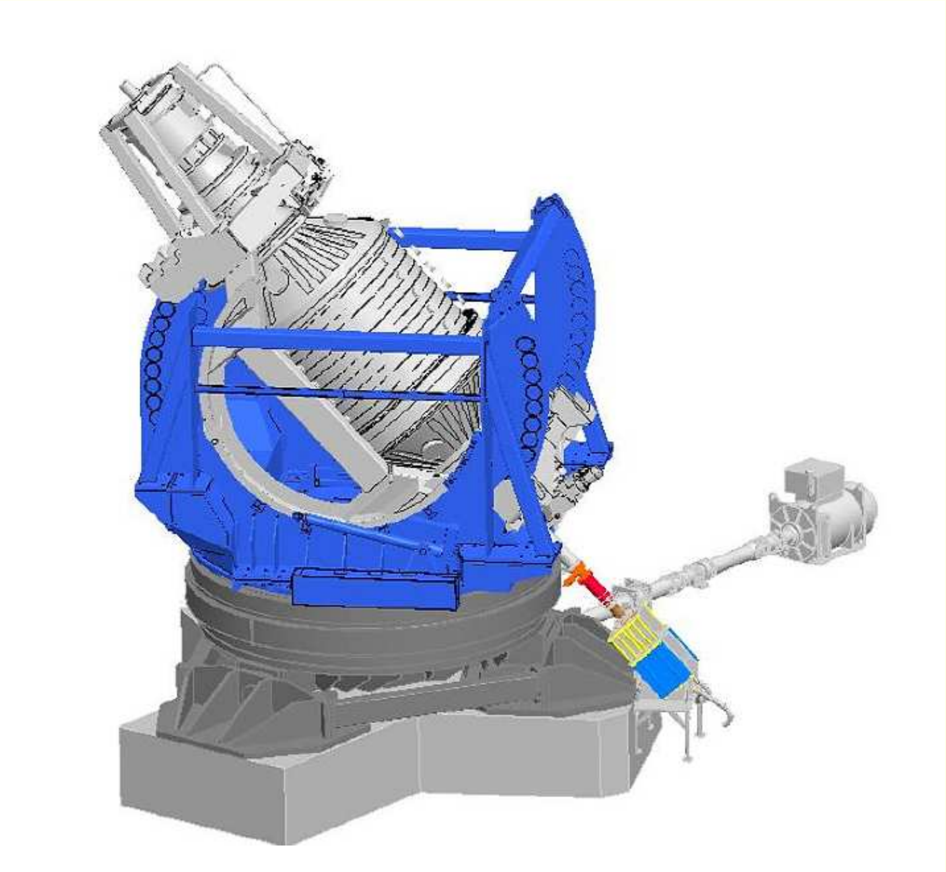
DRESDYN - The interior



DRESDYN - Combined MRI+TI experiment



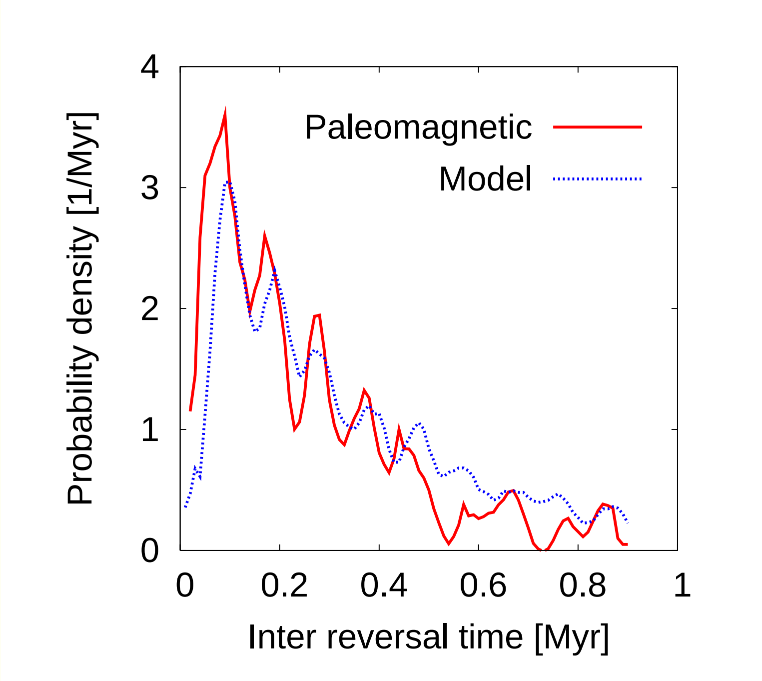
DRESDYN: Precession - Plans for the "big one"



DRESDYN: Precession experiment

- Precession is discussed as a (complementary) energy source of planetary dynamos

- Some evidence: influence of Milankovic cycle on geomagnetic field reversals (Consolini, De Michelis 2003): possible link to climate (ice ages)!



DRESDYN: Precession experiment

- Former dynamos: Inner stainless steel cylinder (Riga), Many spin generators (Karlsruhe), Decisive role of high-permeability impellers (VKS)

- Ambitious goal: Construct a perfectly homogeneous dynamo! Active volume: 2 m height, 2 m diameter, 8 tons of liquid sodium

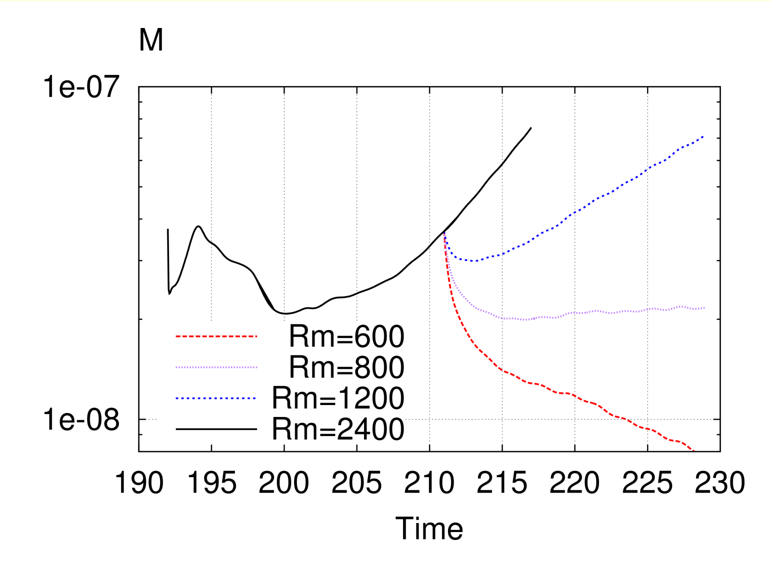
- J. Léorat (Meudon): Water experiment in cylinder (ATER)

- A. Tilgner: Phys. Fluids 2005, $R_m^{crit} \sim 200$ (based on unstable modes)

- A. Krauze: Magnetohydrodynamics 2010: $R_m^{crit} \sim 600$ (for a cube)

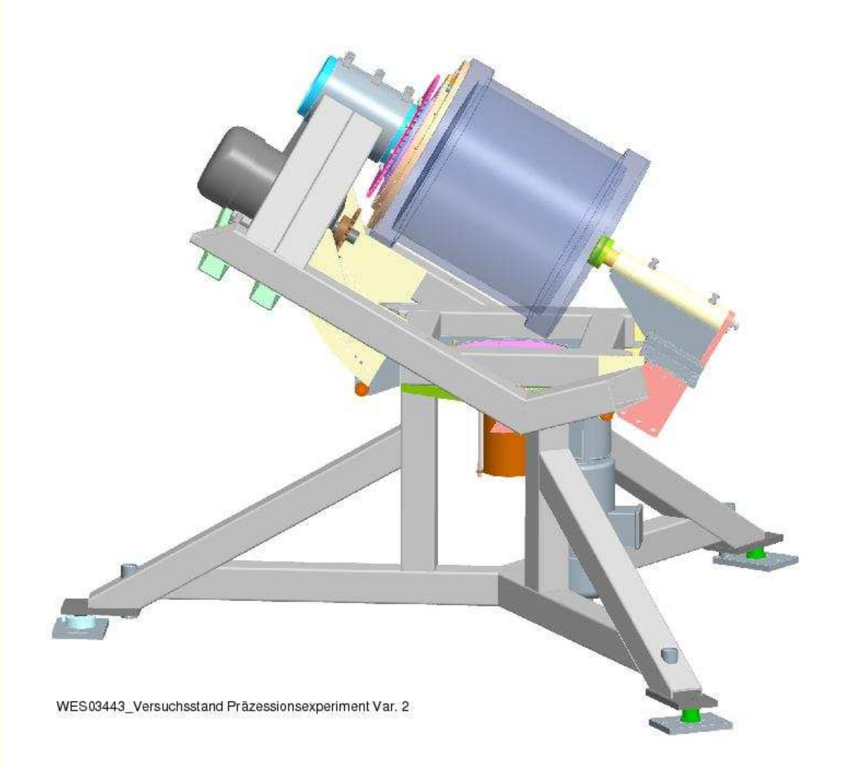
DRESDYN: Precession experiment

C. Nore, J. Léorat et al.: Phys. Rev. E 2011, R_m^{crit} around 750 (for cylinder and $Pm \sim 1$)

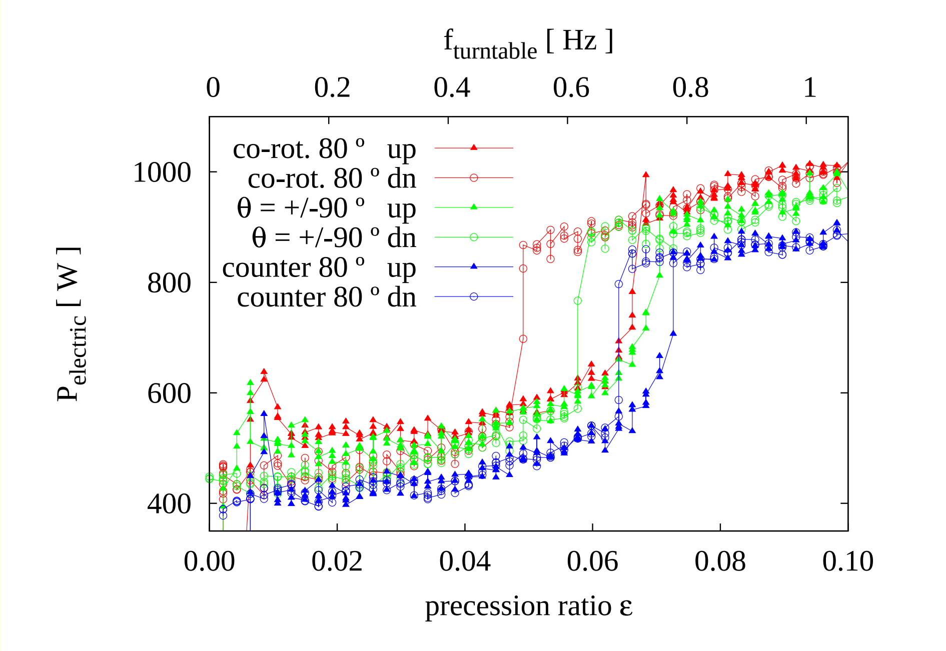


DRESDYN: Precession - Water pre-experiment

- $H = D = 0.32$ m, i.e. scale 1:6
- Rotation up to 10 Hz, precession up to 1 Hz
- To be measured: Flow, motor powers, torques for various precession ratios and angles

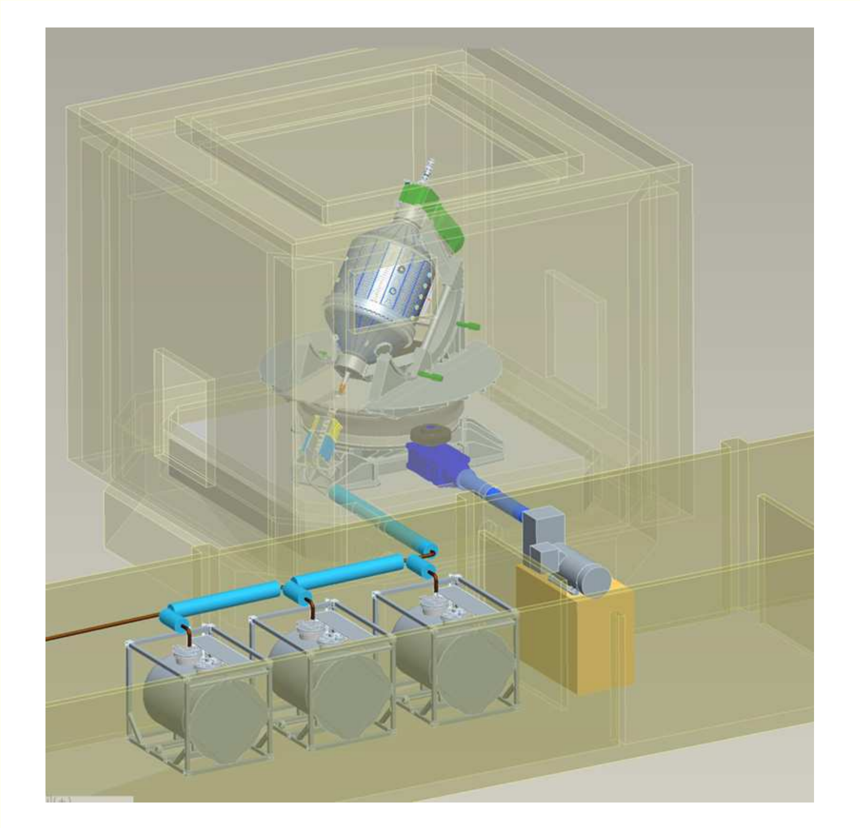


DRESDYN: Sharp transition to turbulence

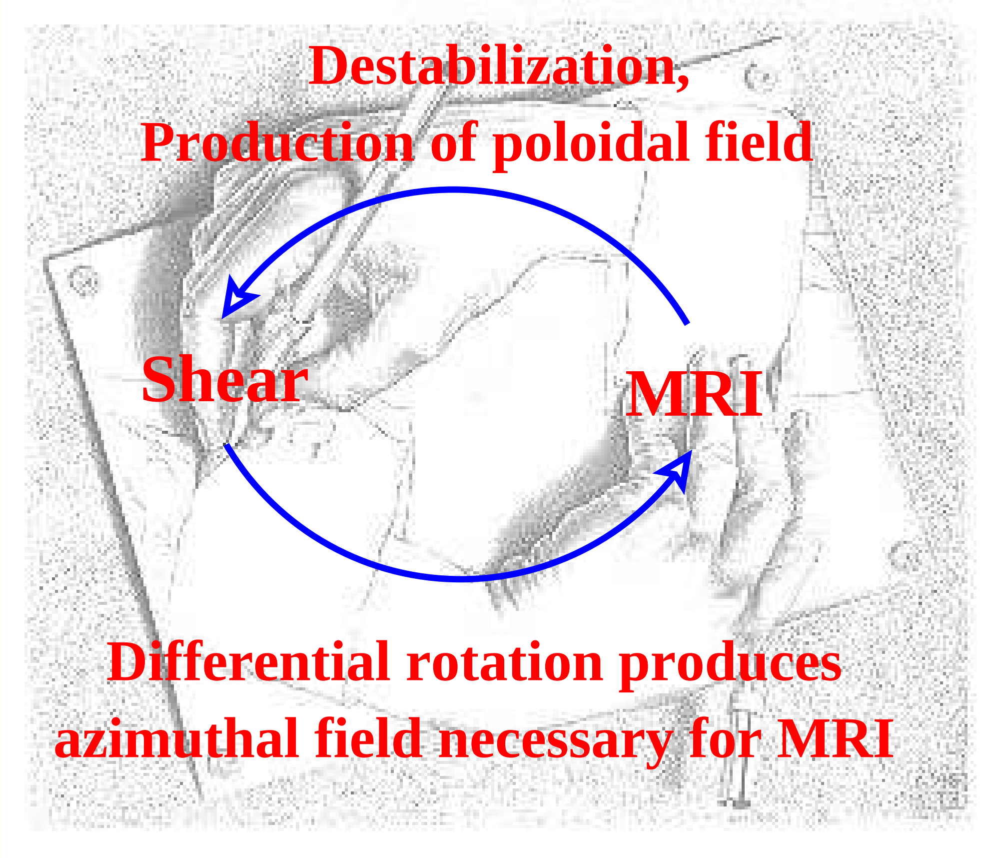


Turbulent scaling for $\Omega_p/\Omega_r \sim 0.07$: $P \sim 300$ W; scaled by $6^5 \Longrightarrow P_{large} \sim 2$ MW !!! Laminar scaling better...

DRESDYN: Precession - Containment and tanks



A dream: Combining MRI and dynamo



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- A. Gailitis et al.: Rev. Mod. Phys. 74 (2002), 973-990; F. Stefani et al.: ZAMM 88 (2008) 930-954; Theor. Comp. Fluid Dyn. 23 (2009) 405-429; Mahyd. 48 (2012) 103