Survey of experimental results

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Do we need experiments?

- Proofs of theory
- Checks of numerical simulations.
- Studies in different regimes
- Real models of natural objects
- Inputs for theories or simulations
- Improvement in technology
- Discoveries
- …

Outline

1. Introduction : some physical properties
2. Historical approach to experimental dynamos
3. 1999: Two successful experiments
4. A new generation of experimental dynamos...

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The magnetic Reynolds number

$$Re_m = \frac{UL}{\eta} = \mu\sigma UL$$

Necessary condition for dynamo action :

Re_m >~50

- μ is difficult to change (Martin et al, 2000; Frick et al, 2002)
- $\sigma_{Na} = 3\ \sigma_{Ga} = 10\ \sigma_{Hg}$
- σ_{Na} decreases with T
- At T ≈ 100 C, $\mu\sigma_{Na} \approx 10$
- For L = 1m, $\tau_{diff} \approx 0.1$ s

Size L and velocity U should be as large as possible

The magnetic Reynolds number

$$\mathrm{Re_m} = \frac{\mathrm{UL}}{\eta} = \frac{\mathrm{UL}}{\nu}\frac{\nu}{\eta} = \mathrm{Re\,P_m}$$

- For liquid metals, $P_m \approx 10^{-6}$
- Liquid metal dynamo occurs for large Re ($>10^6$)
- "Turbulent" dynamos
- β effect (effective η increases with turbulence).
  (Reighart and Brown, 2001)

Velocity / Size

- Velocity is limited by the available power.

$$\mathrm{Po} \propto \rho\eta^3 \frac{\mathrm{R}_\mathrm{m}^3}{\mathrm{L}}$$

For liquid sodium:
$\rho\eta^3 = 1$

Pour Rm = 50, L = 1 m, Po ≈ 100 kW (Nataf, 2003)

The problem is to cool down the experiment (0.1K/s)

- Large L is necessary.
- Sodium is cheap (< 10 €/l) and light (r < 1000).
- Sodium is dangerous (reductor, water => explosion H2).
- Large experiments are expansive.

Experiments ; necessary conditions

- Rm >≈ 50 imposes the use of sodium
- U > 5m/s, which means a power of a few hundreds KW (cooling unit too)
- L > 1m, which means a few tons of liquid sodium

An adequate velocity field
(in space and time)
to start and maintain a dynamo

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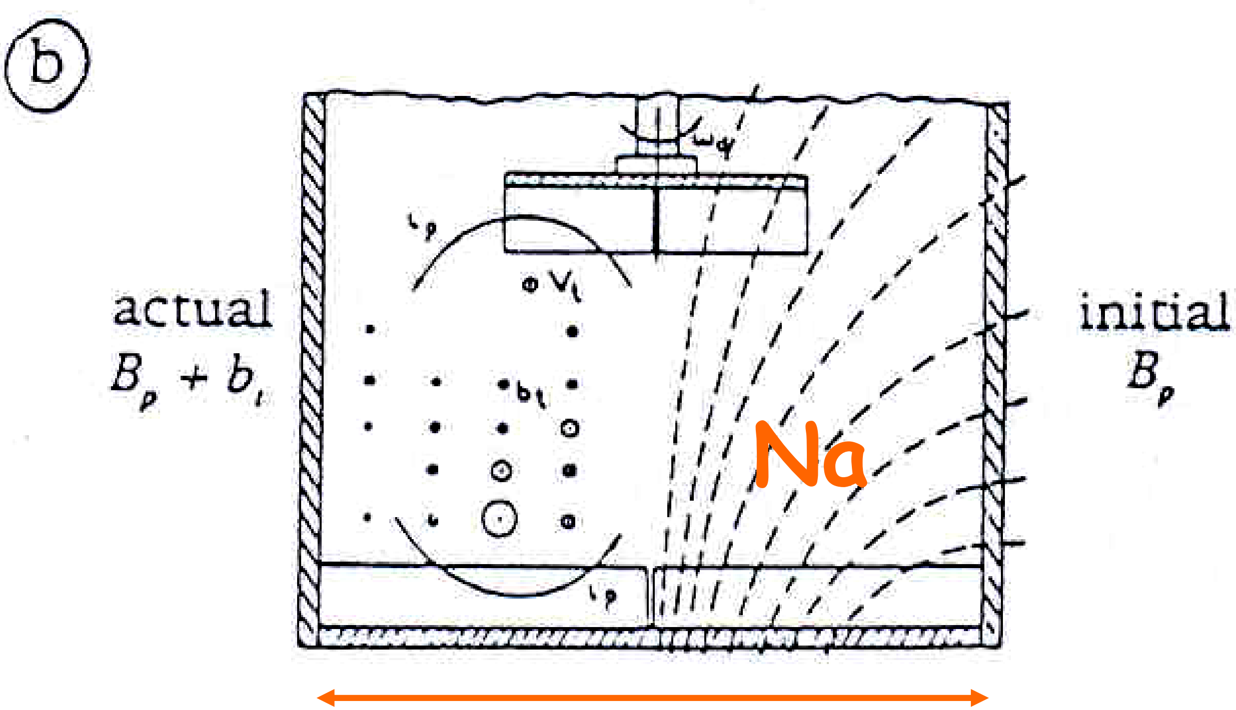
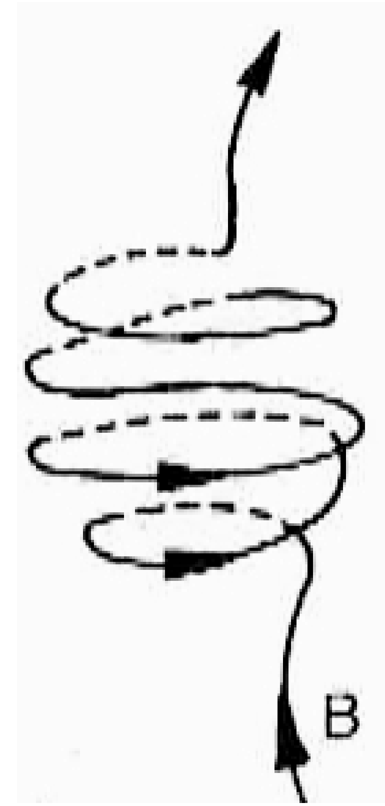
(Lehnert,1958)





« ω effect »

$b_t/B < 0.25$

40 cm

58 litres of sodium.

$b_{pr}/B < 0.1$

$\Omega < 500$ rpm

Rm < 5

(Lowes and Wilkinson,1963; 1968)

(Herzenberg, 1958)

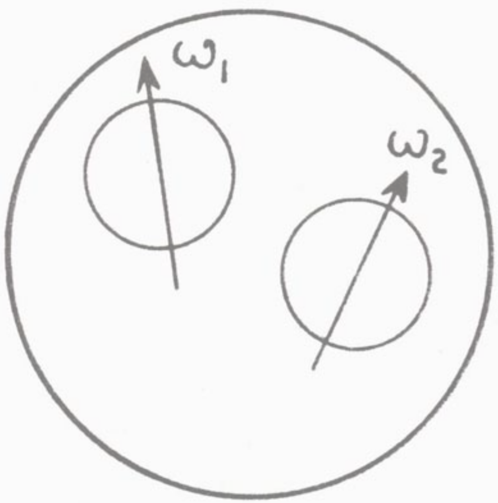


Fig. 1. The Herzenberg dynamo

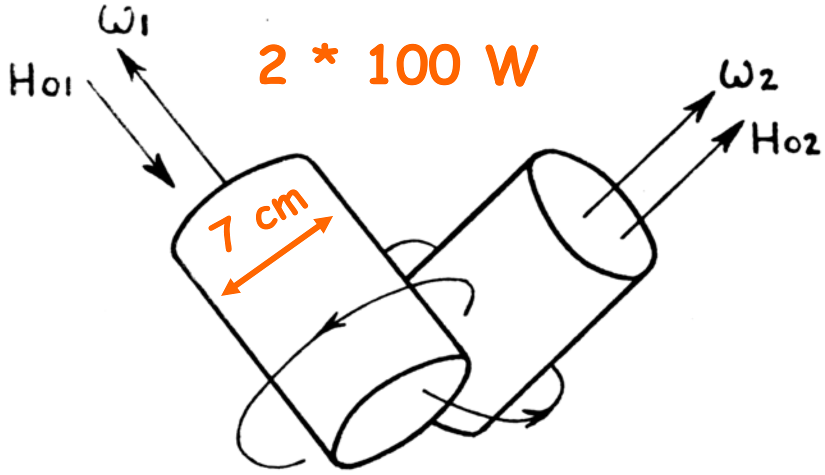


Fig. 3. Schematic diagram of our dynamo model

Ferromagnetic materials ($\mu > \mu_0$)
+ Mercury

(Lowes and Wilkinson,1963; 1968)

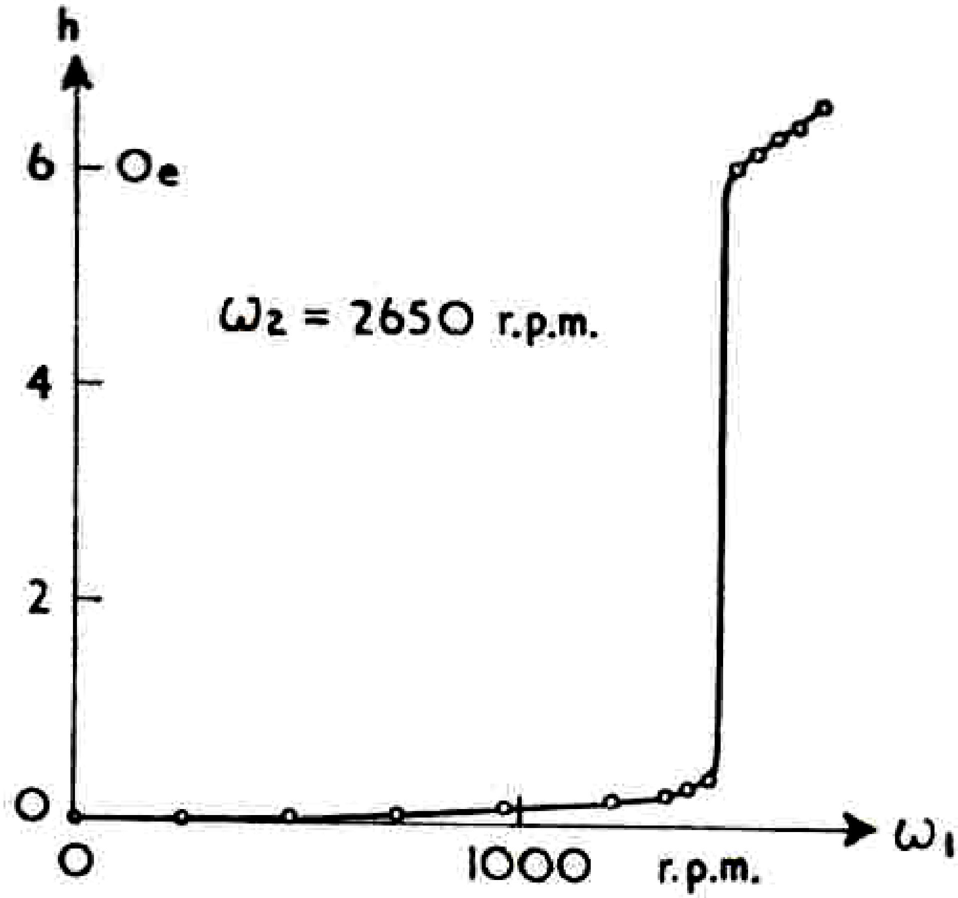
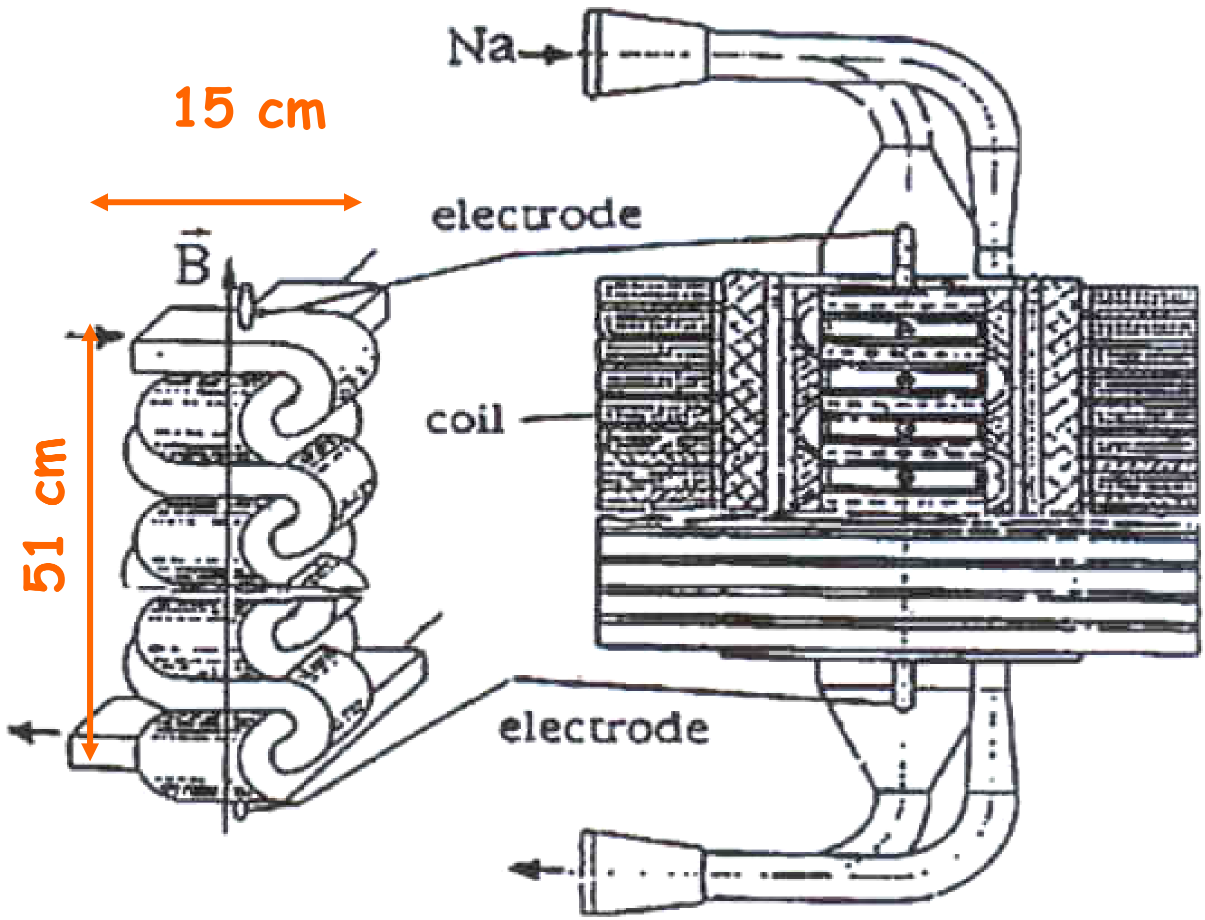


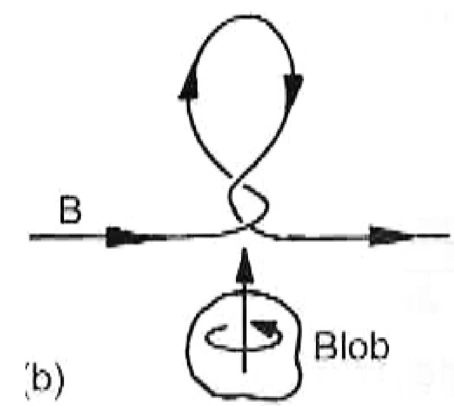
Fig. 4. External induced field from modified model as velocity is increased

$\mu_r \sim 200$

$Re_m \sim 200$

(Steenbeck et al.,1967)





« α **effect** »

U = 0-11 m/s

(Steenbeck et al.,1967)

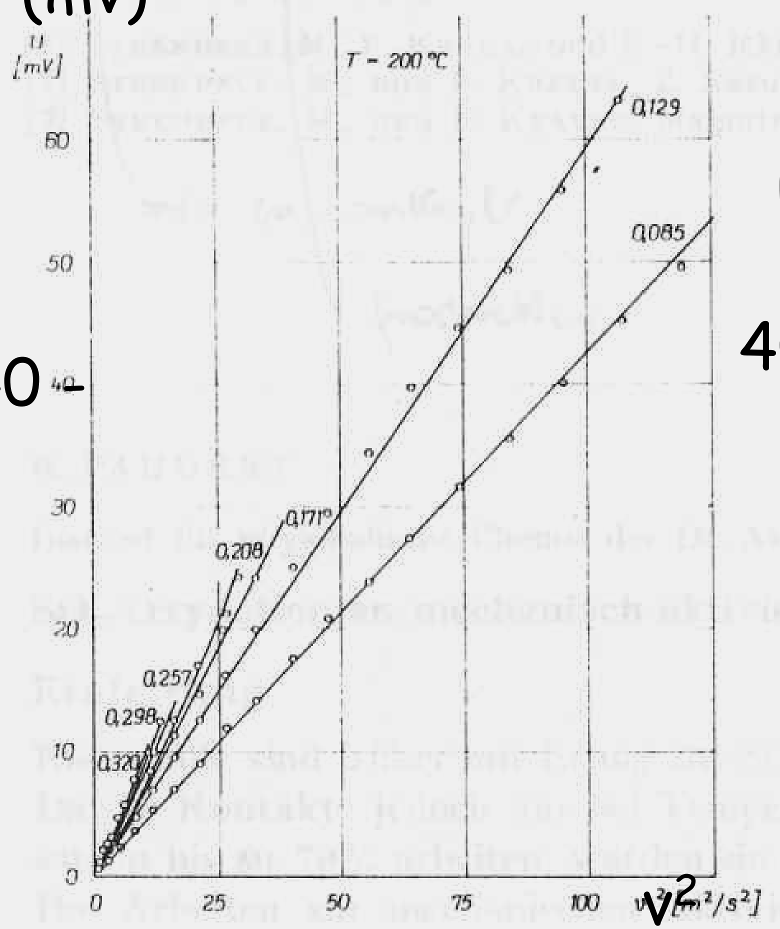


Abb. 3. Quadratische Abhängigkeit des α-Effektes von der Geschwindigkeit (Angabe der magnetischen Feldstärke in Tesla)

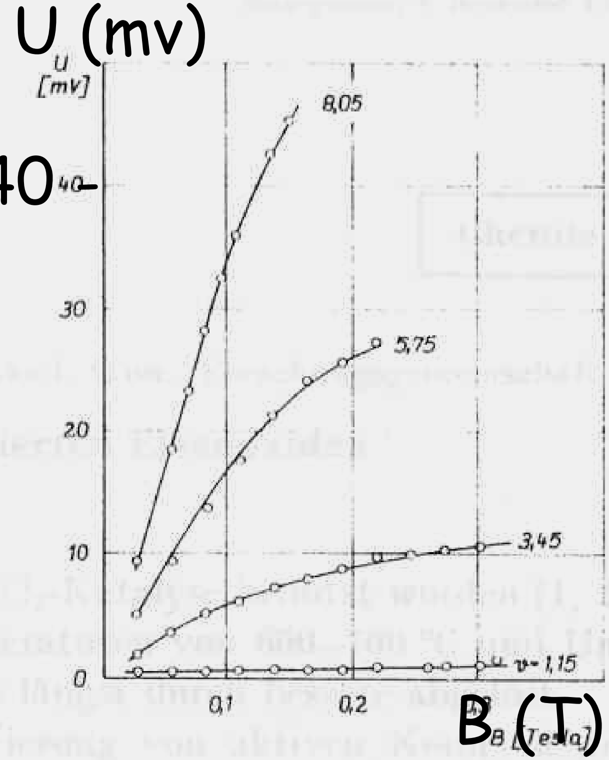
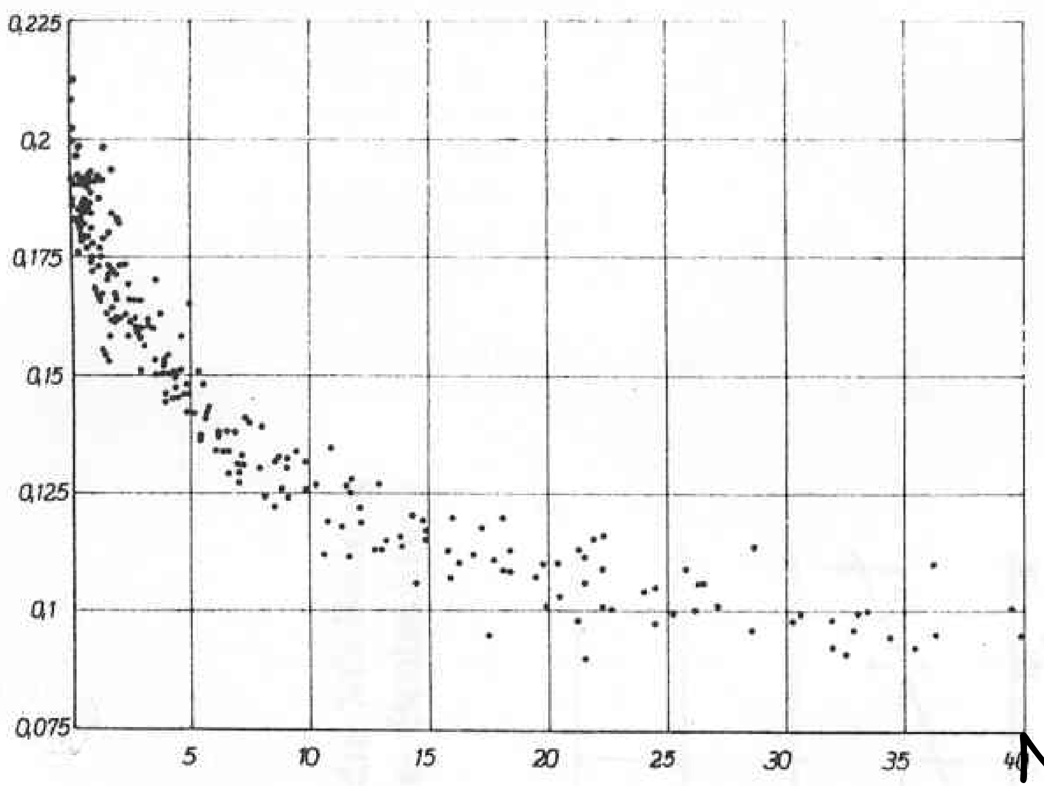


Abb. 4. Abhängigkeit des α-Effektes von der Stärke des Magnetfeldes (Angabe der Geschwindigkeit in m/sec)

$U \propto v^2 B$

(Steenbeck et al.,1967)

U/U_{theo}



$N = \sigma l B^2/\rho v$

Abb. 5. Das Verhältnis der gemessenen Spannung zu der nach Formel (1) berechneten in Abhängigkeit von der STUART-Zahl $N = \frac{B^2 l \sigma}{\varrho v}$

$U_{theo} \propto \mu_0 \sigma v^2 B l^2$

(Gans,1970)

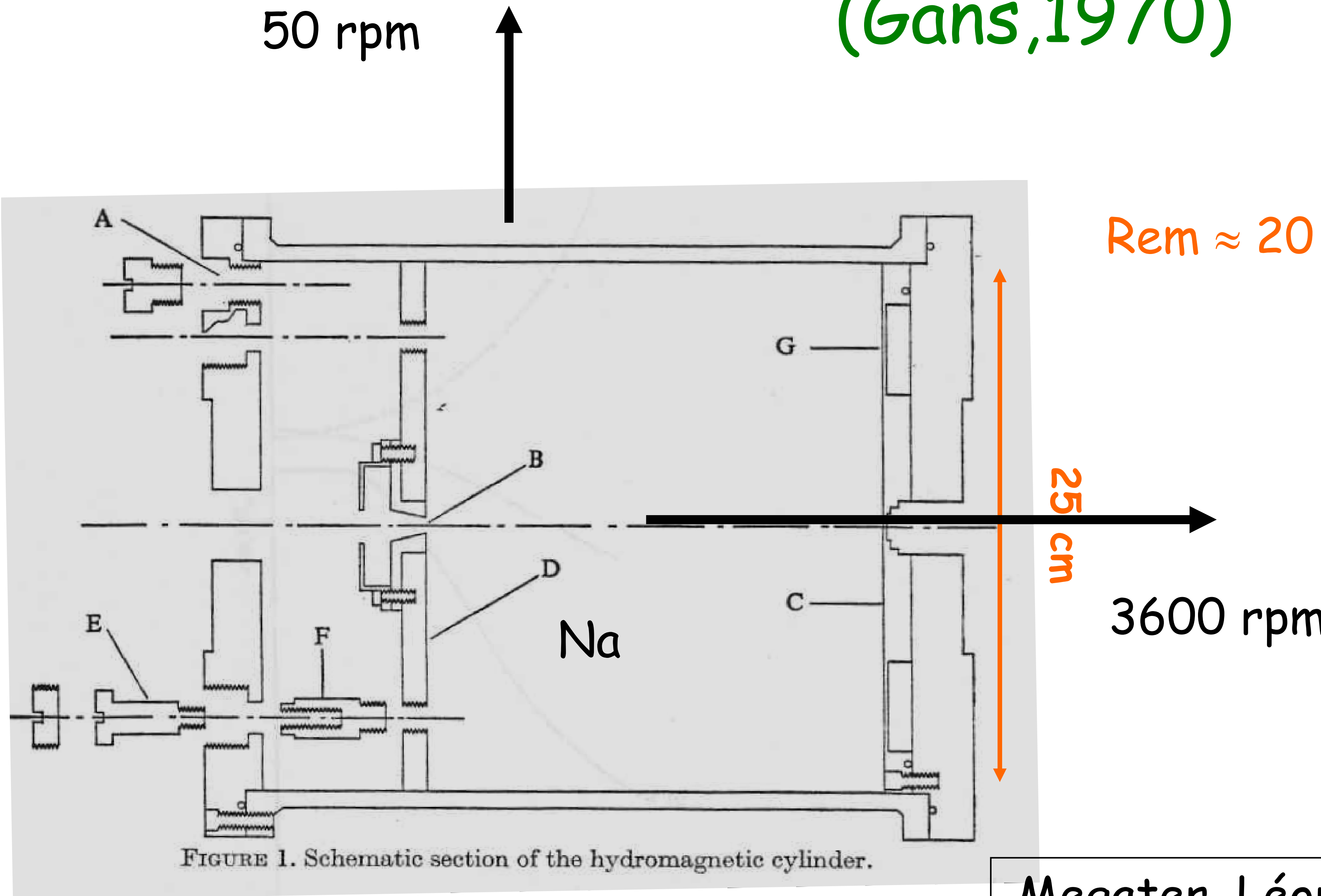


FIGURE 1. Schematic section of the hydromagnetic cylinder.

Megater, Léorat

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The Riga dynamo

(Ponomarenko,1973) dynamo

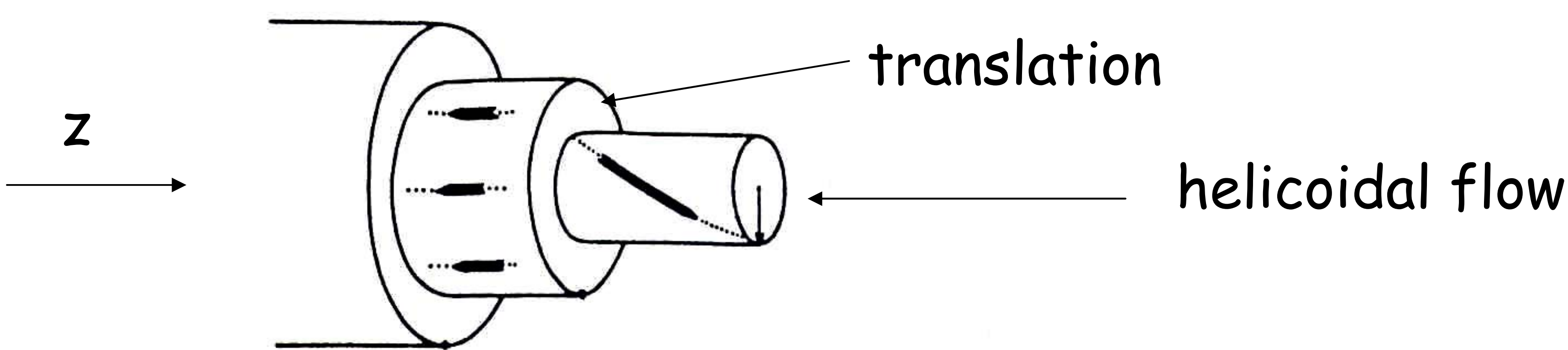


Figure 2. Theoretical model: two coaxial cylinders moving as solid bodies inside a motionless shell.

At rest

Kinematic approach,
With infinite geometry.

$$B \propto \exp(ikz)\,\exp(i\omega t)$$

First attempt

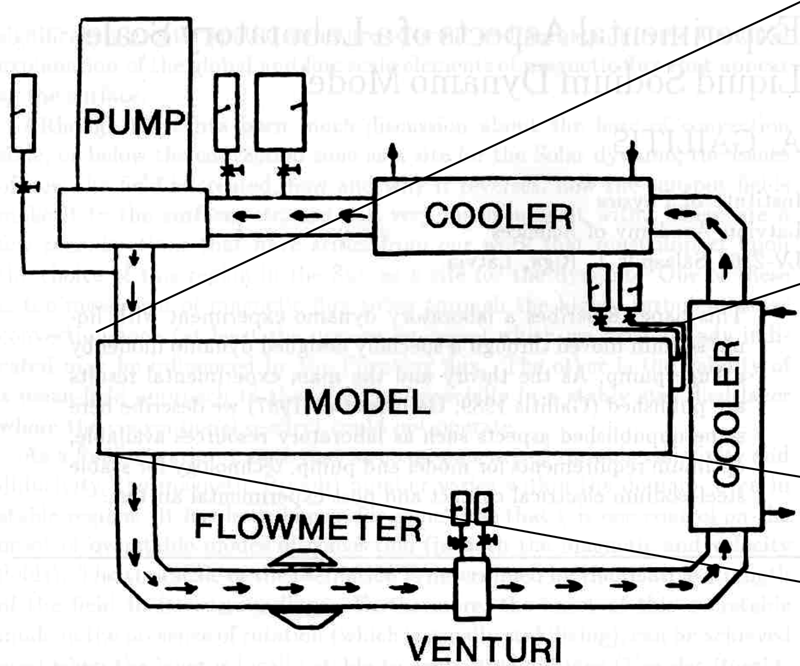


Figure 1. Test loop with pump CEMP 3/1200: device at the Efremov Institute of Electrophysical Apparatus, St. Petersburg, Russia. The reported test was carried out there in 1986.

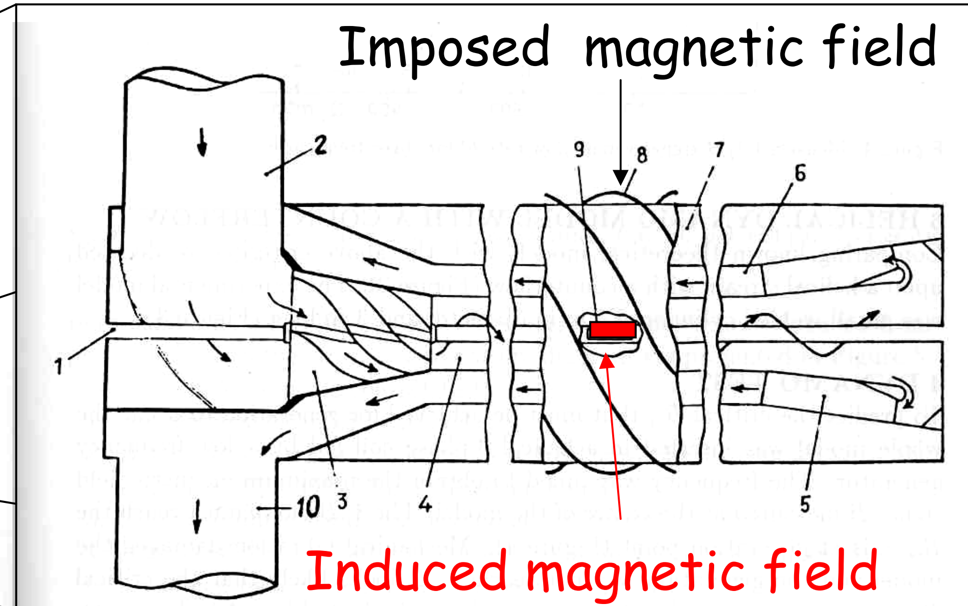


Figure 3. Experimental model. 1–Measuring channel. 2–Sodium entrance. 3–Helical labyrinth. 4–Main channel. 5–Reverse system. 6–Counterflow channel. 7–Immobile sodium. 8–Helical coil for outside excitation. 9–Coil, measuring transverse field. 10–Sodium exit.

Leningrad, 1987

(Gailitis et al., 1987, 1989); (Gailitis 1992).

First attempt; results.

(Gailitis et al., 1987, 1989);
(Gailitis 1992).

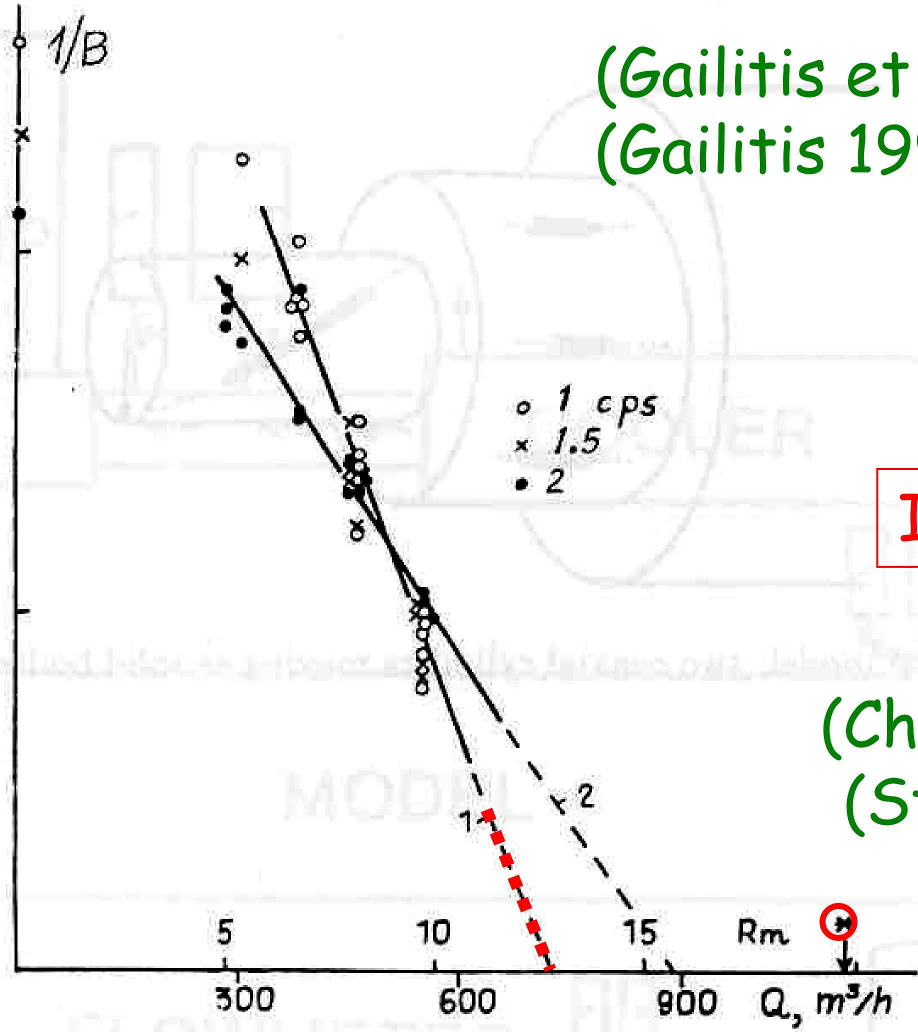


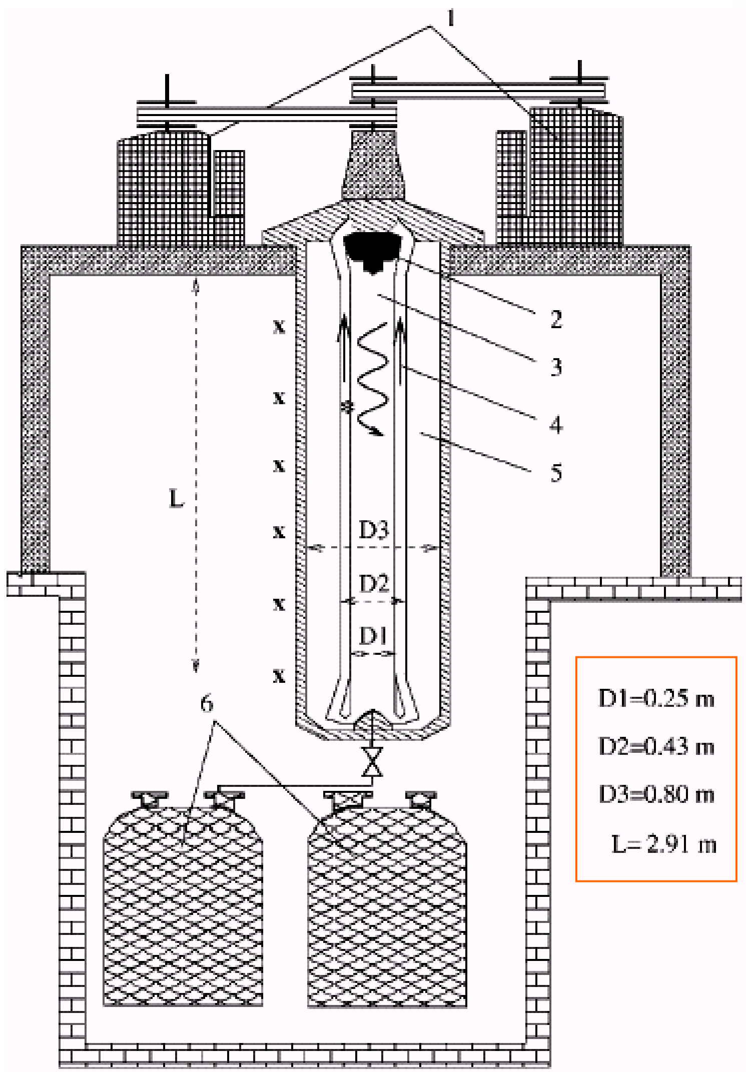
Figure 4. Measured $1/B$ signal versus flow rate Q for three frequencies.

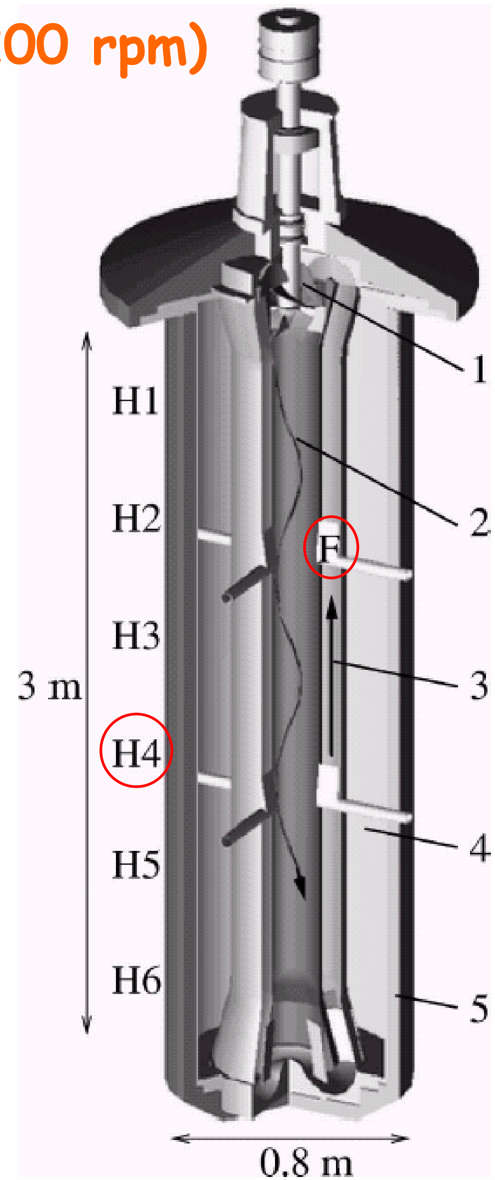
Improvements:

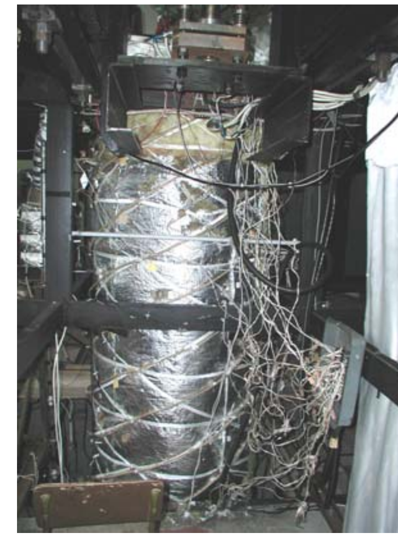
(Gailitis, 1996);
(Christen et al., 1998)
(Stefani et al.,1999)

Riga Dynamo

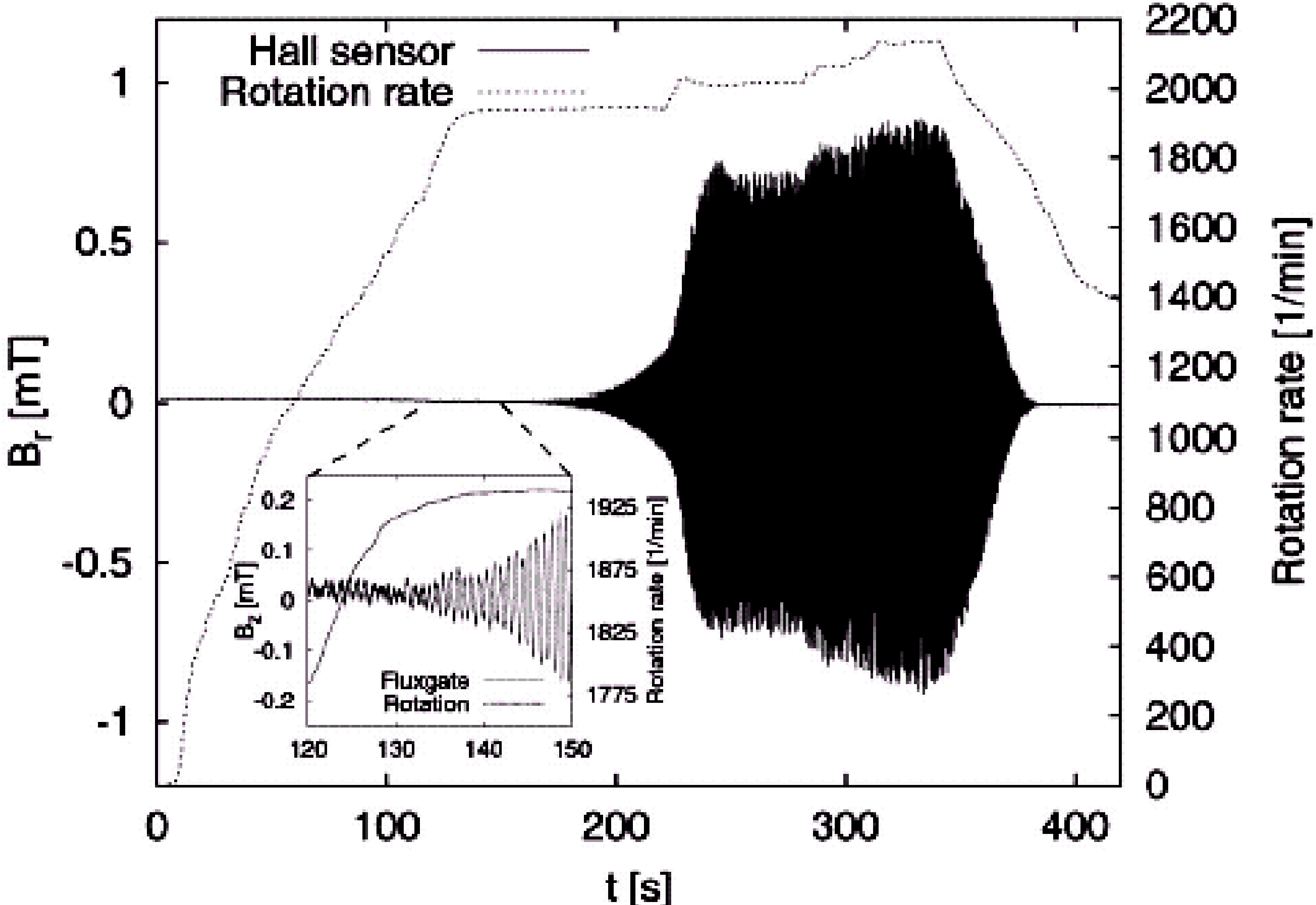
(120 kW, 1500 litres Na, 2200 rpm)





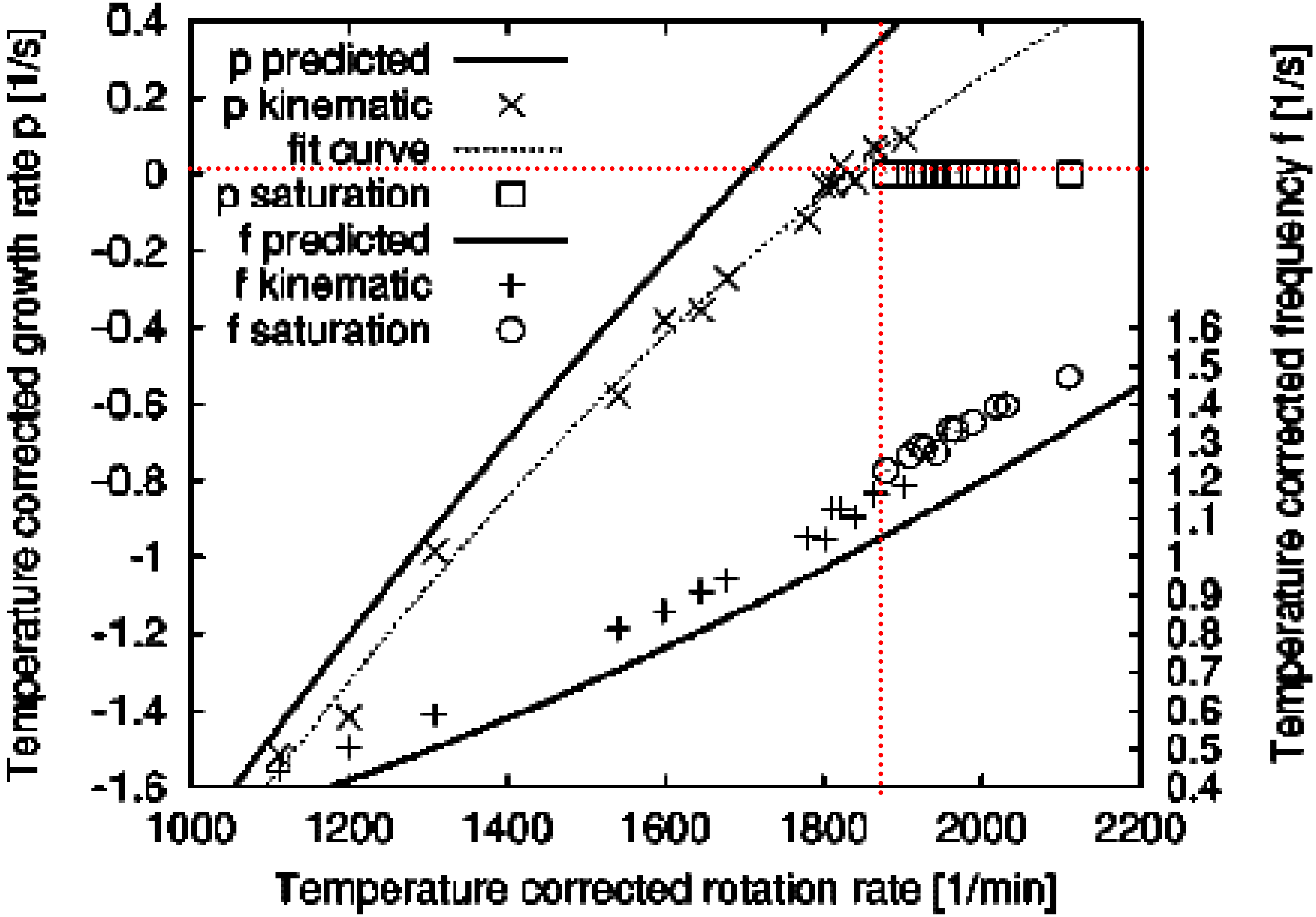


Riga; growth of the magnetic field



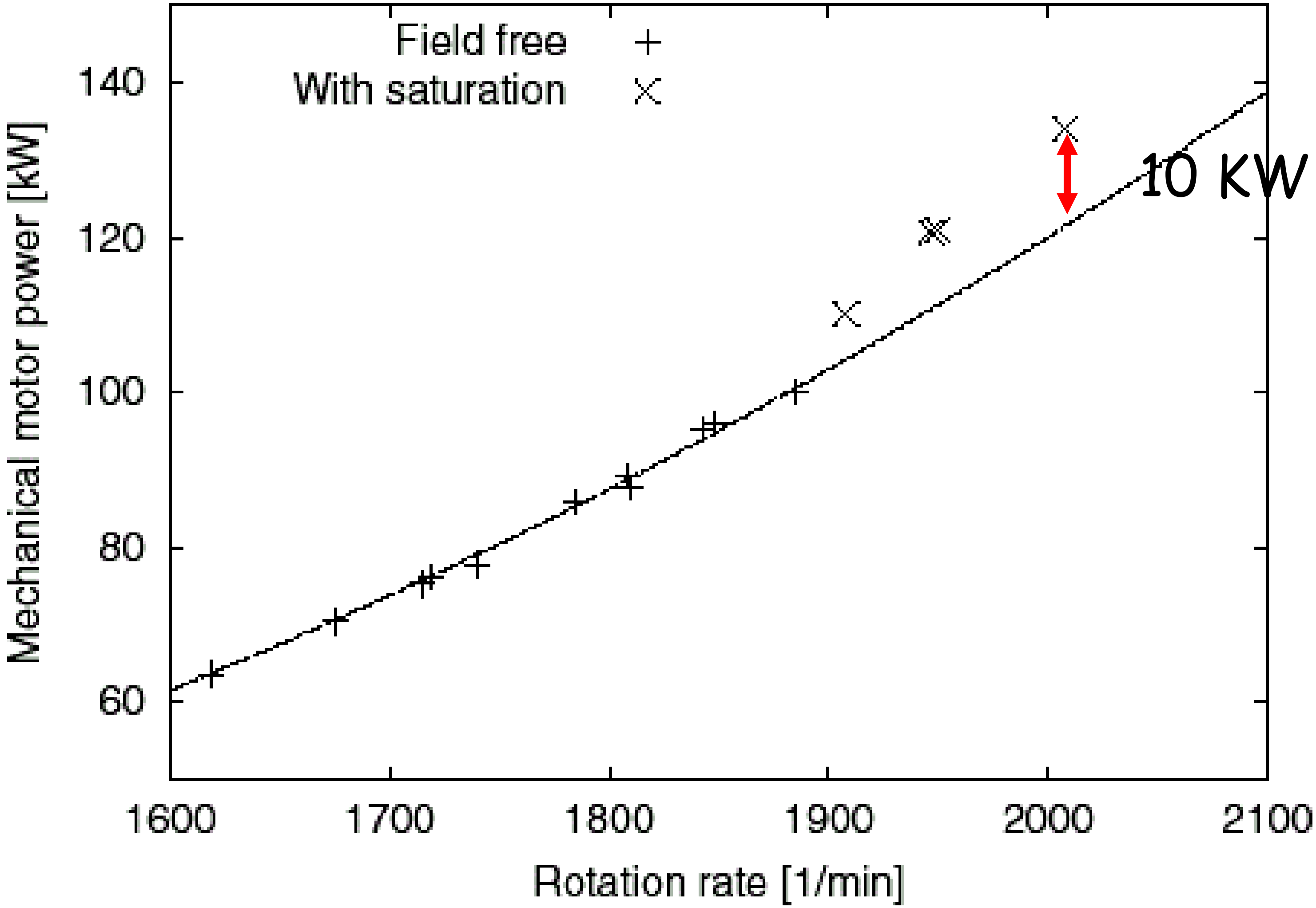
(Gailitis et al., 2001)

Riga; comparison Num./Exp.



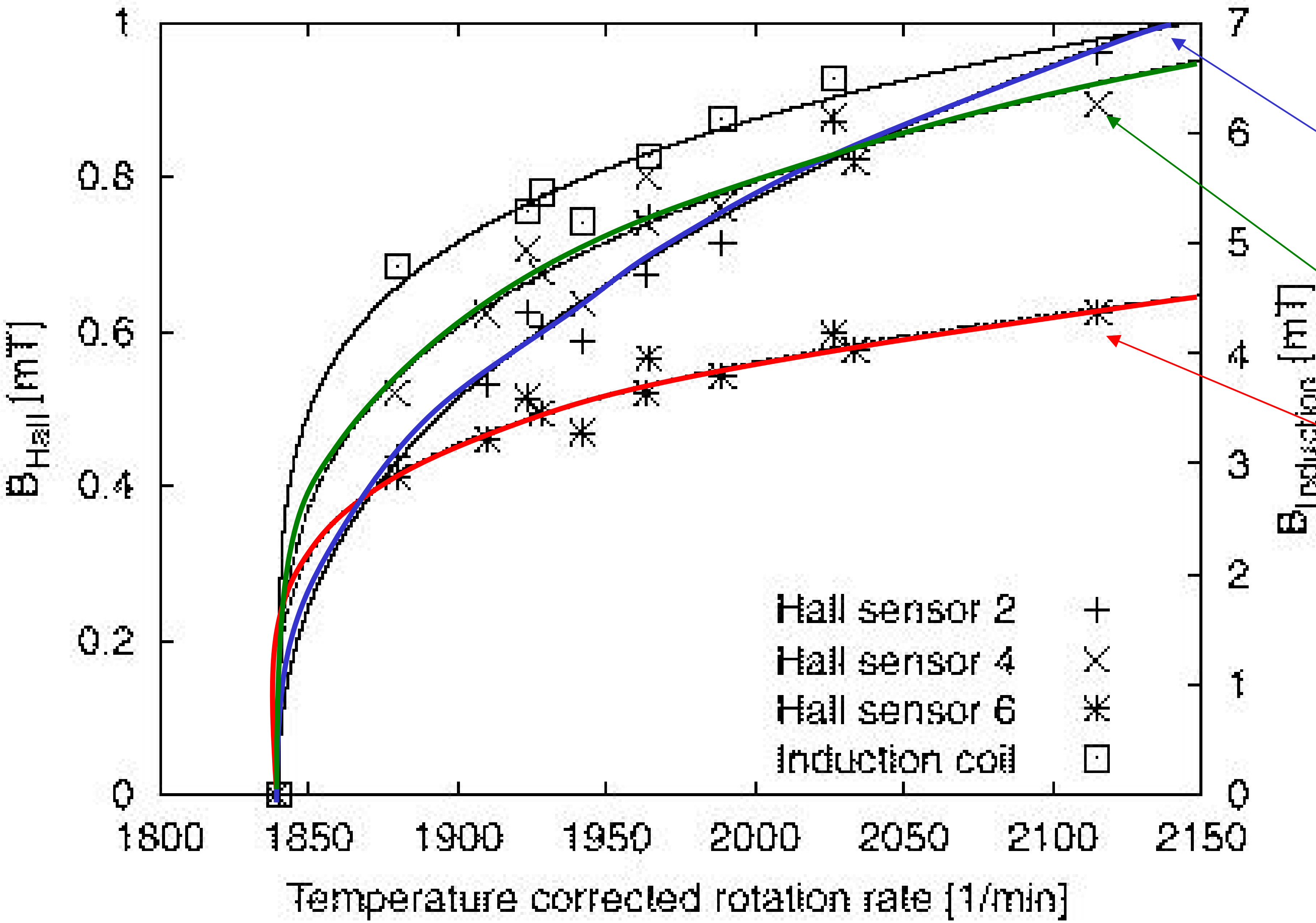
(Gailitis et al., 2002)

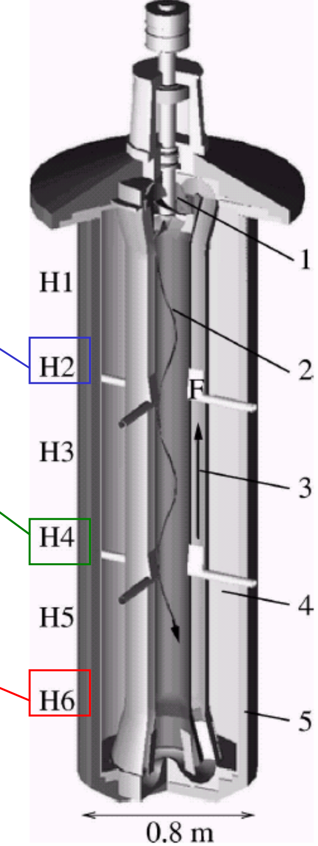
Riga: Motor power measurements



(Gailitis et al., 2001)

Riga: Saturation

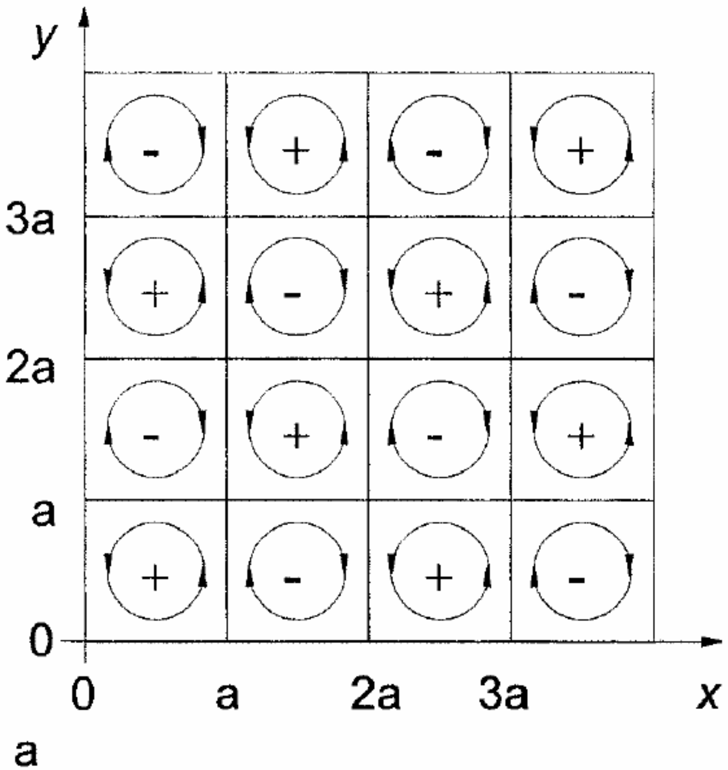




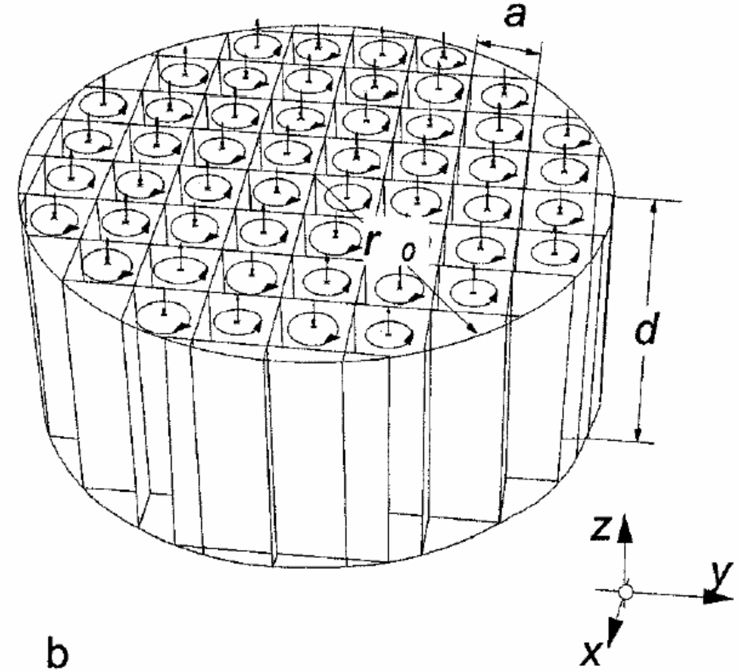
(Gailitis et al., 2001)

The Karlsruhe dynamo

(G.O.Roberts,1972) dynamo



$$\mathrm{Re}_{m,H}\,\mathrm{Re}_{m,C} > 8\pi^2$$

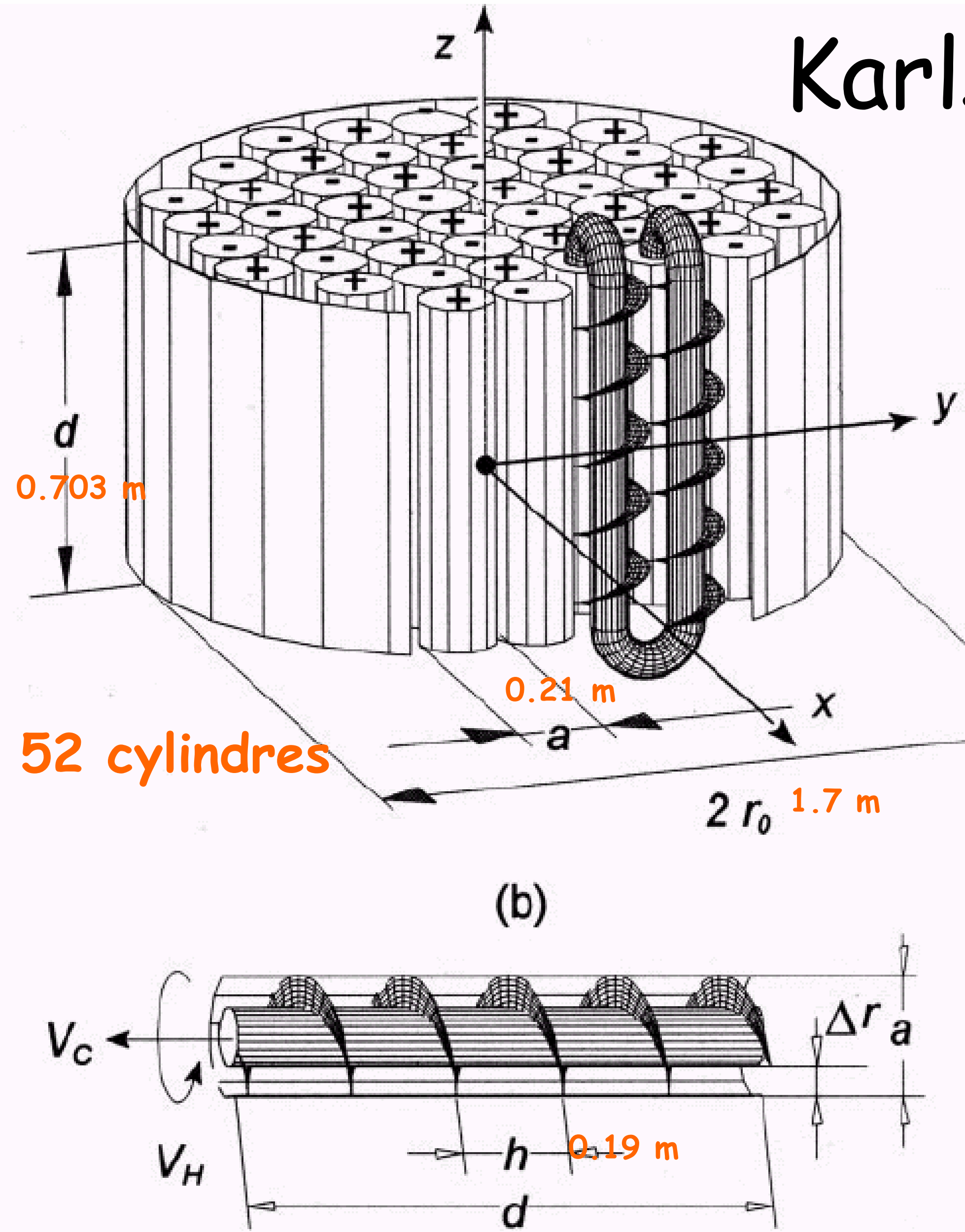


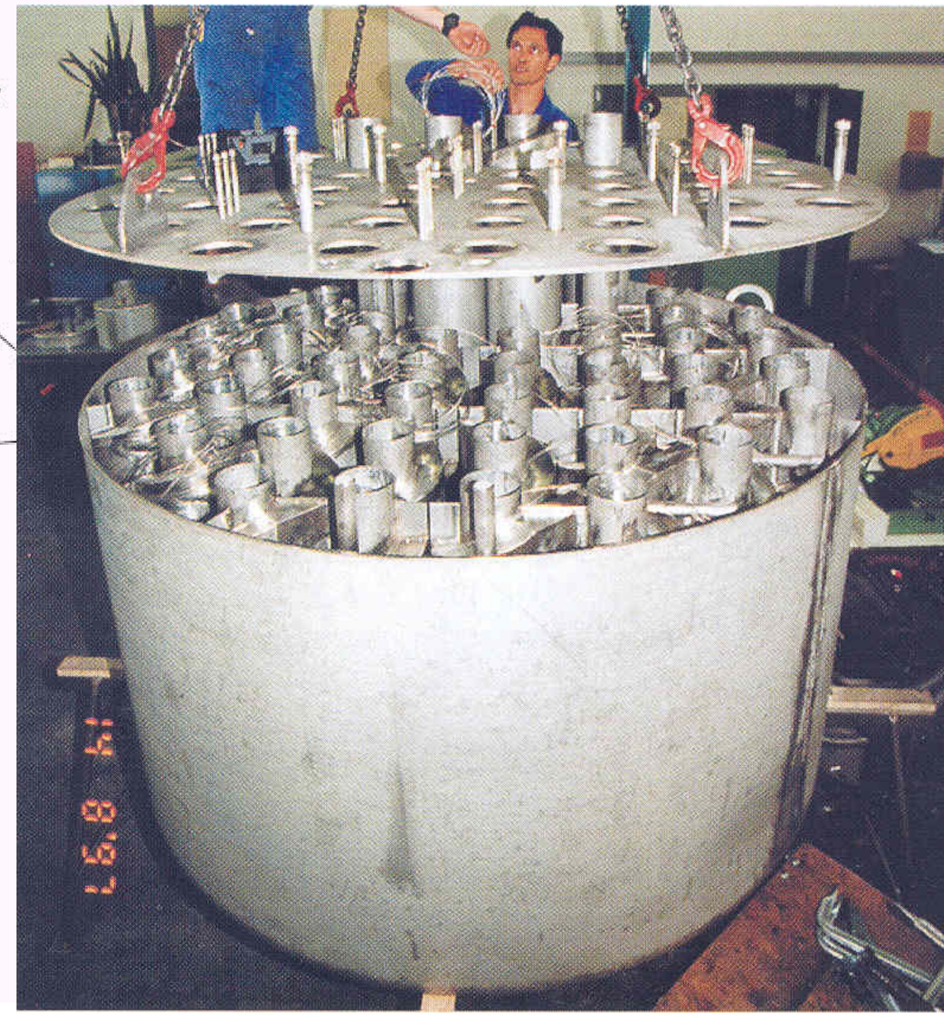
(Busse,1992): $r_0, d, a/r_0 \ll 1$

$$\mathrm{Re}_{m,H}\,\mathrm{Re}_{m,C} > \frac{16a}{\pi r_0}\left[1+\left(\frac{3.83d}{\pi r_0}\right)^2\right]$$

Karlsruhe: the set up

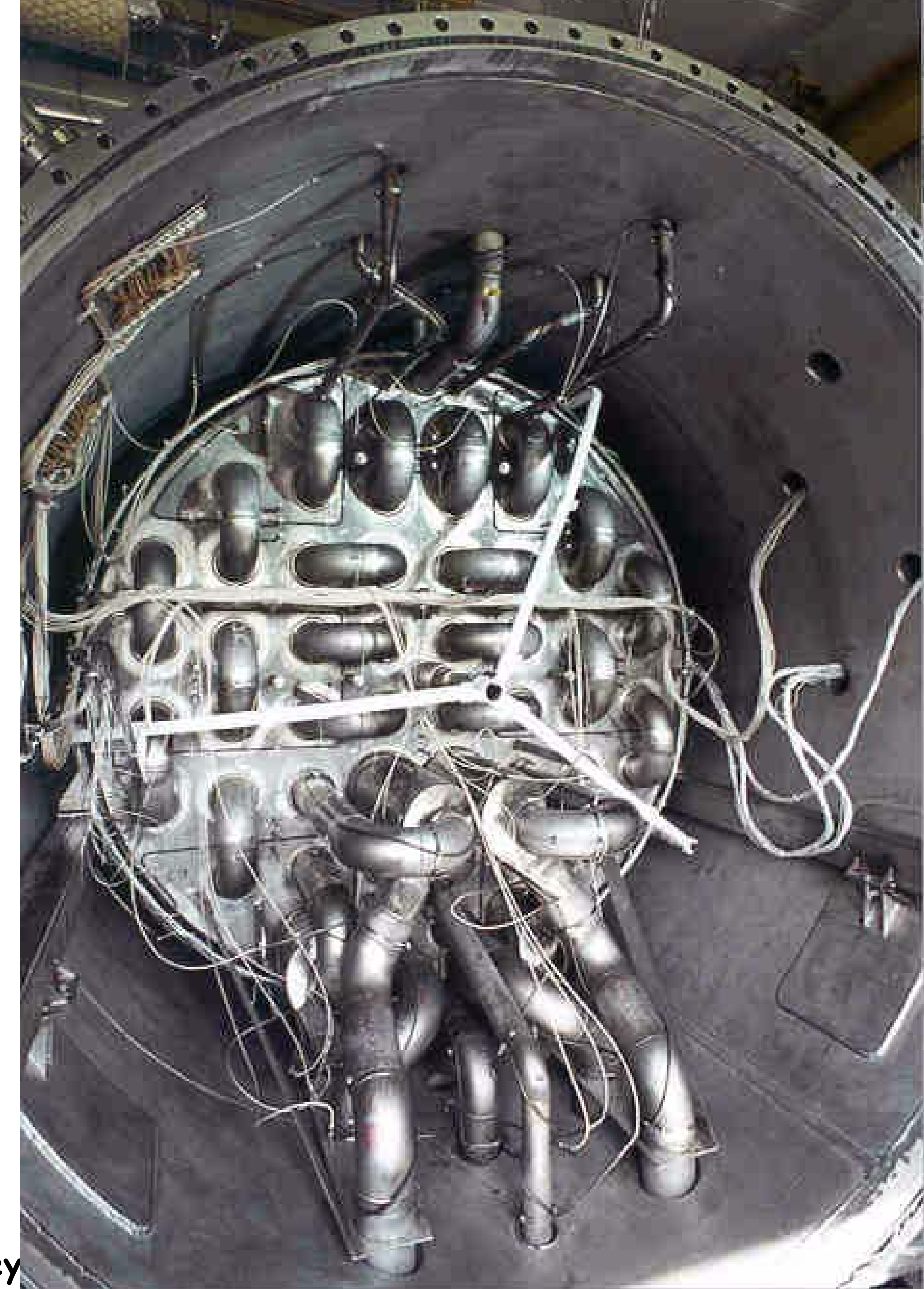
(1600 litres Na, 630 kW)



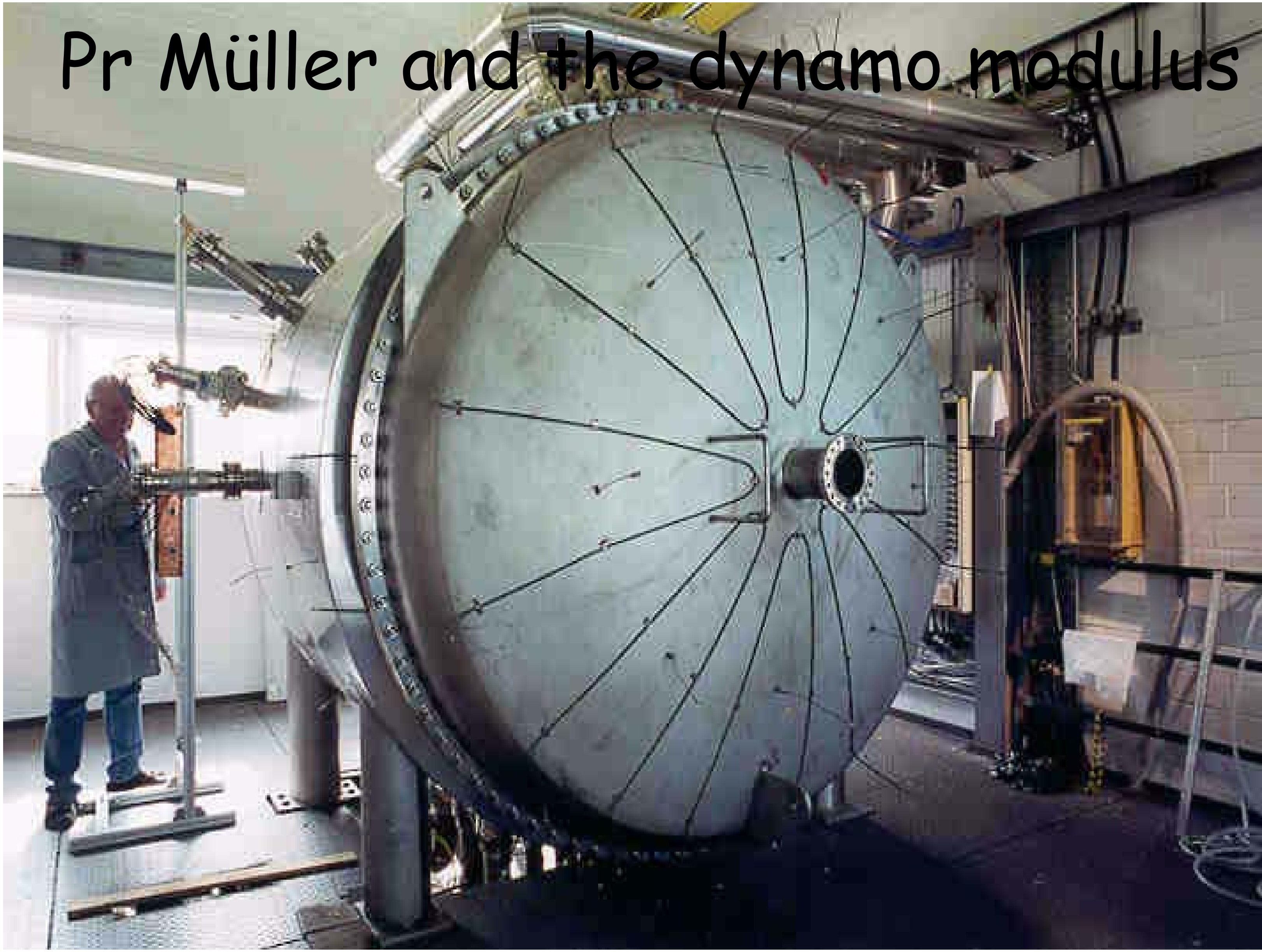


V_C or V_H up to 120 m^3/h

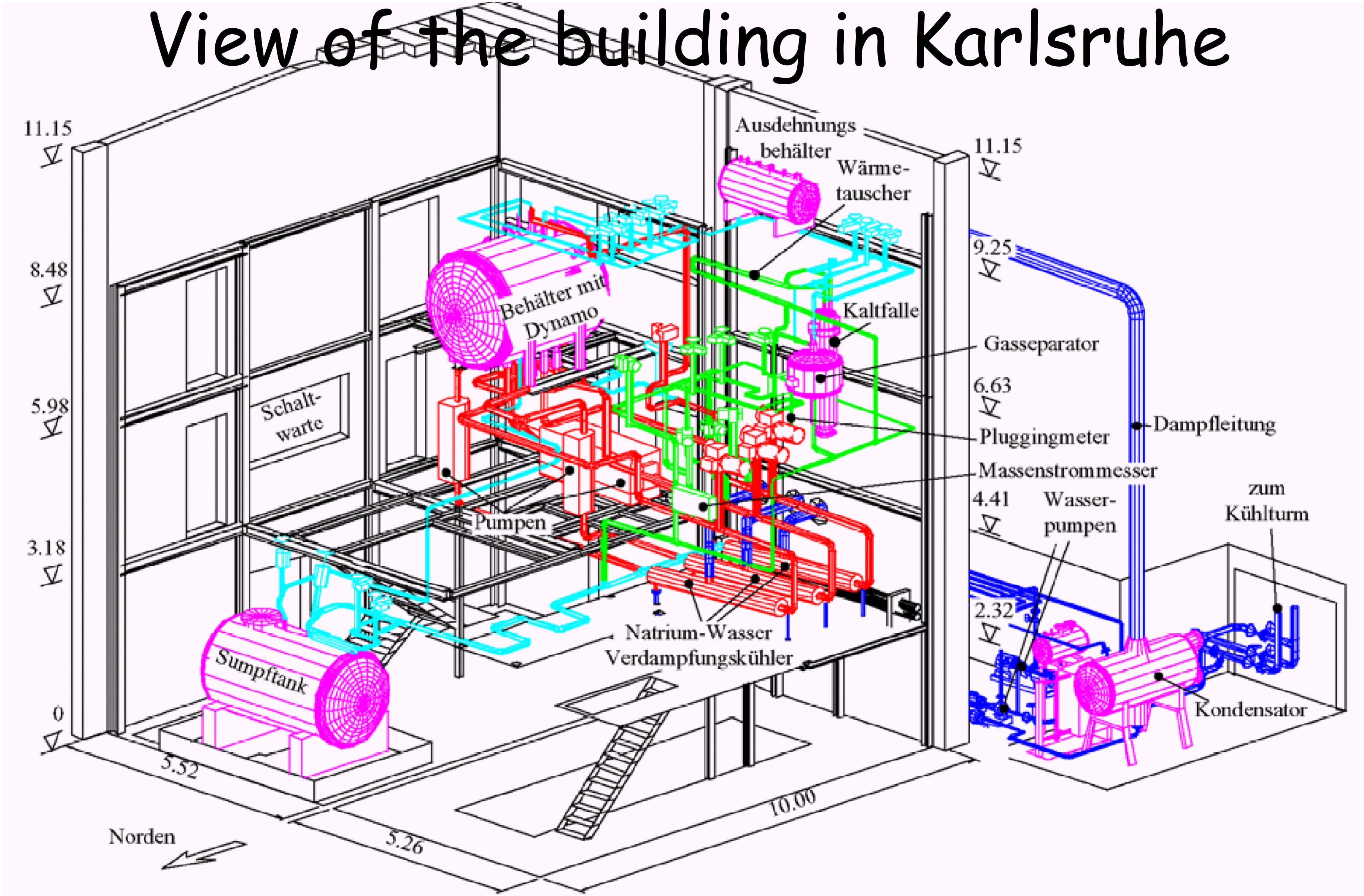
Dynamo modulus in Karlruhe



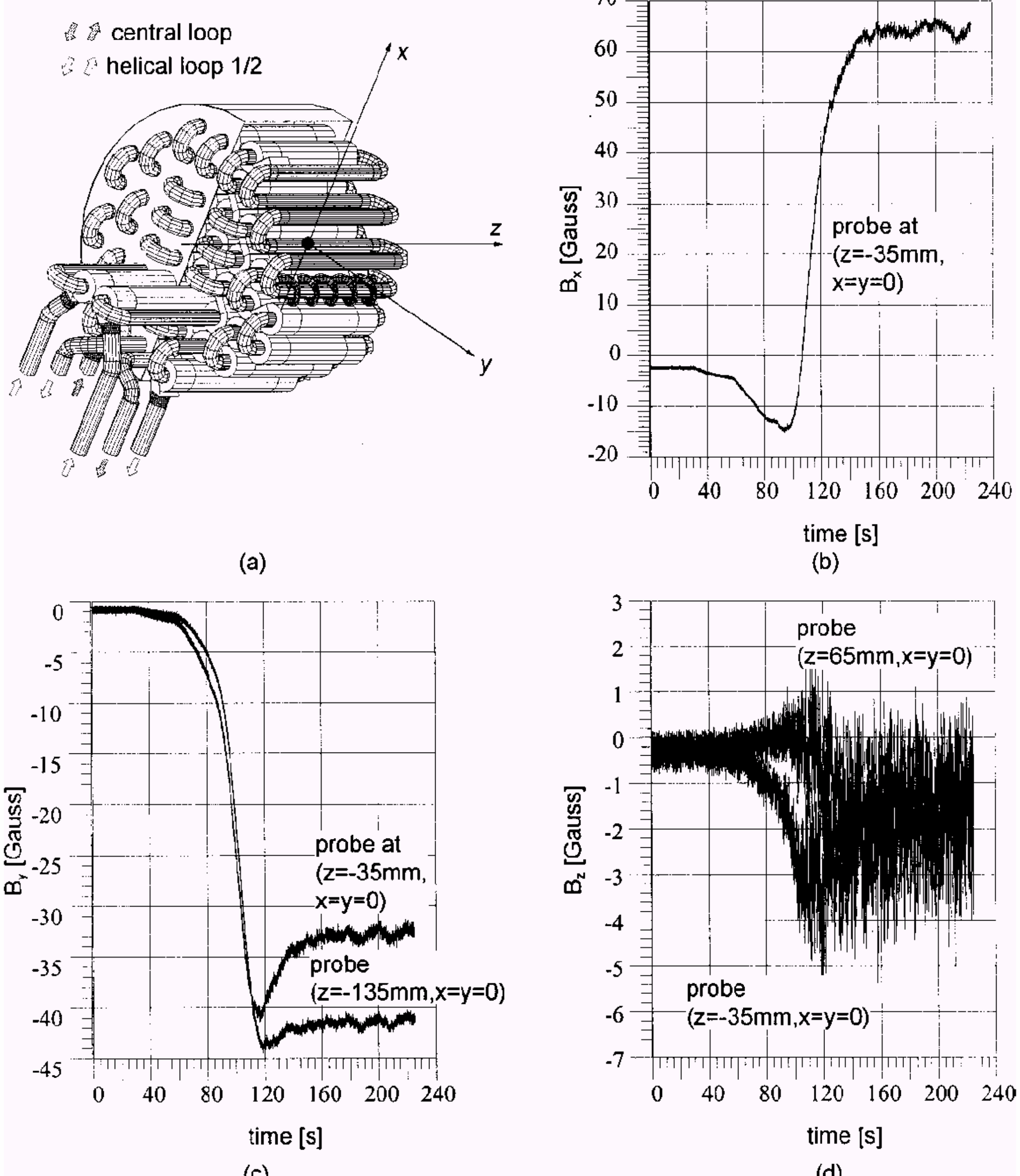
Pr Müller and the dynamo modulus



View of the building in Karlsruhe



http://www.ubka.uni-karlsruhe.de/vvv/fzk/6223/



Dynamo effect in Karlsruhe experiment

(Müller and Stieglitz, 2000)

(Stieglitz and Müller, 2001)

Stability diagram in Karlsruhe dynamo

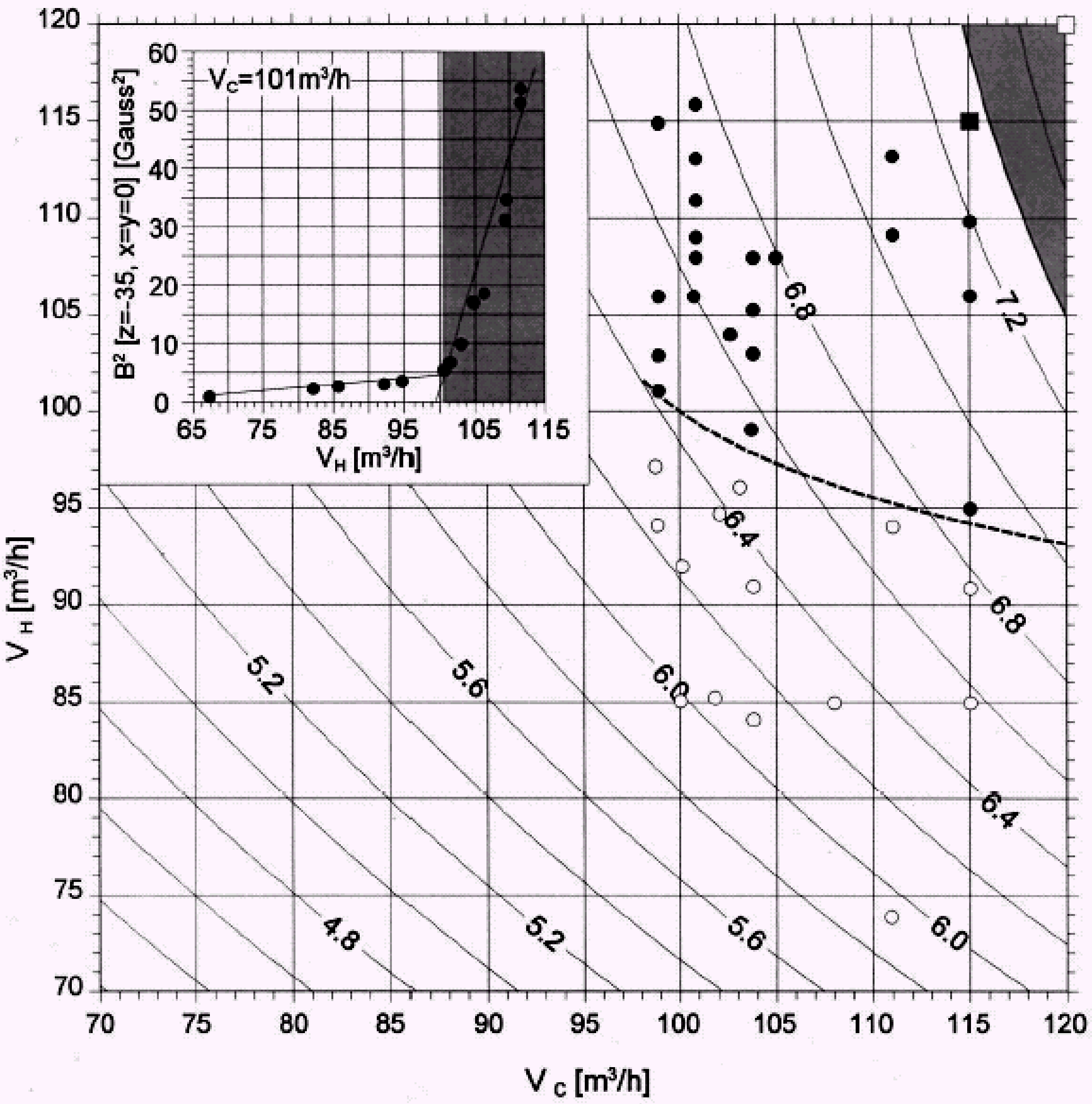
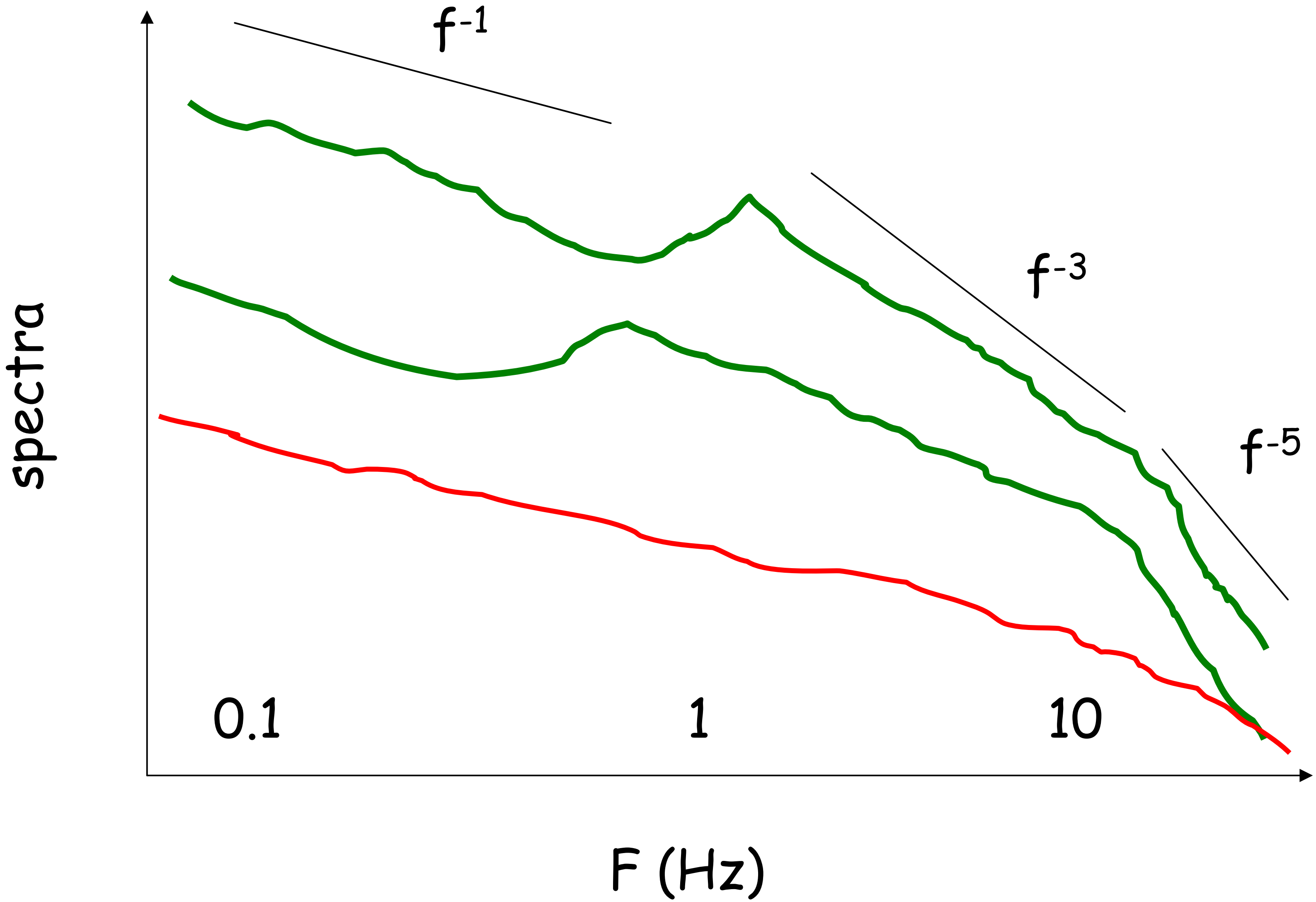


FIG. 3. Stability diagram for the onset of dynamo action as a function of the central flow rate V_C and the helical flow rates V_H. The filled dots denote experimentally measured dynamo action, open dots denote nondynamos. The dashed line indicates the experimentally obtained marginal stability curve, defined by a regression of the steep increase of the magnetic energy ($\sim B^2$) with V_H (see subgraph in the upper left). The gray-marked domain specifies the calculated flow rate domain for the existence of a dynamo by Rädler *et al.*[11,12] The isolines show the values of a combined modified magnetic Reynolds number according to the mean-field model of Rädler *et al.*[11] The symbols □ and ■ indicate Tilgner's[9] calculations for onset of dynamo action.

(Stieglitz and Müller, 2001)
(Rädler et al, 1998)
(Tilgner, 1997)

B-spectra in Karlsruhe



Two succesful experimental dynamos

- Good prediction of the onset with laminar (average) flow and ideal boundary conditions.
- Kinematic and mean field approaches.
- Saturation mechanism ? (Tilgner et Busse, 2002) Motions of the liquid sodium initially at rest.
- (Pétrélis et Fauve, 2001) claim that a turbulent scaling is in agreement with the experiment whereas a laminar scaling predict a field orders of magnitude too small.

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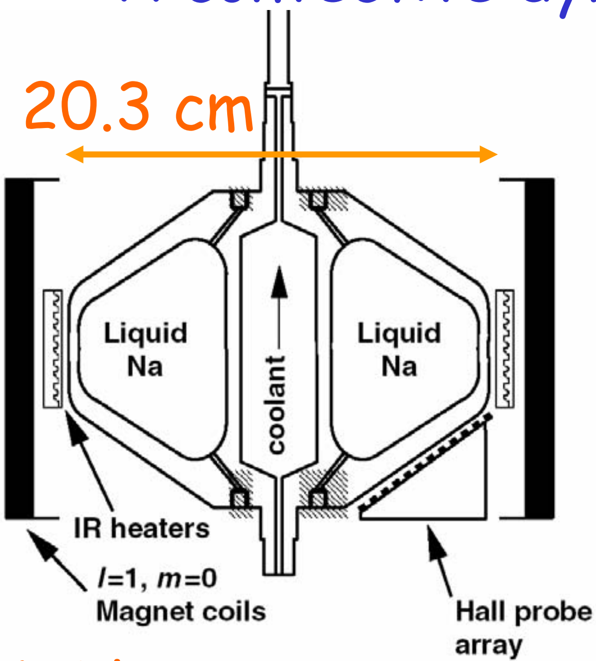
The Maryland group

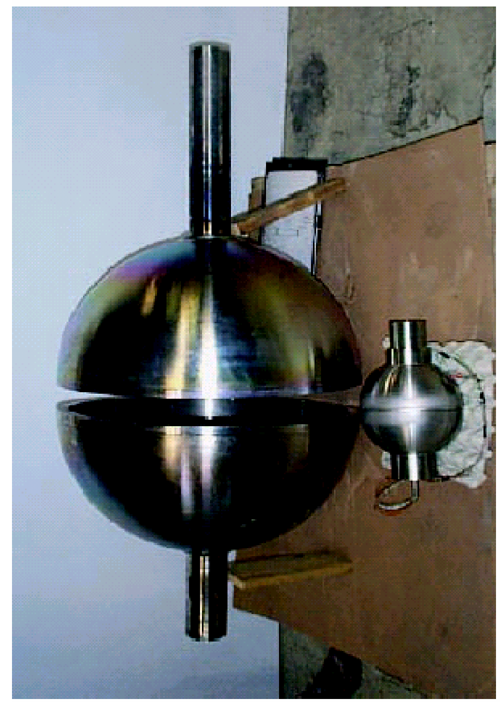
(Shew et al.,2002)

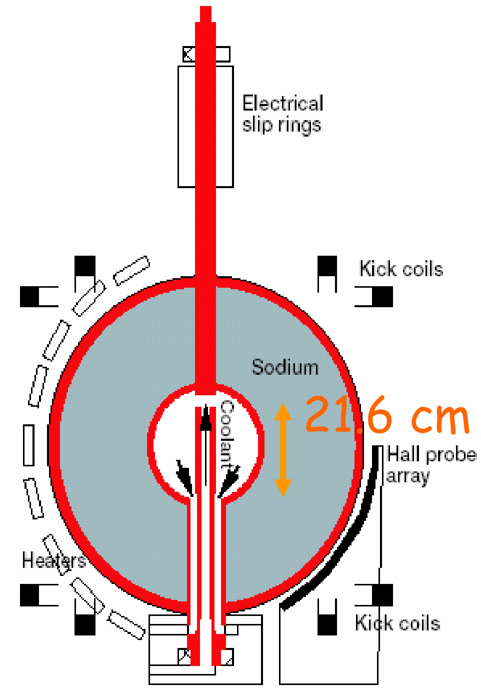
A convective dynamo?

6000 rpm, E ~ 10-8, Λ ~ 1, Rm < 10

20.3 cm







1.5 litres

6000 rpm   Rm<8

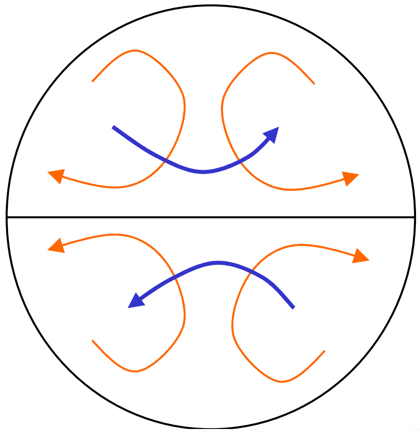
(Lathrop et al., 2001)

90 litres

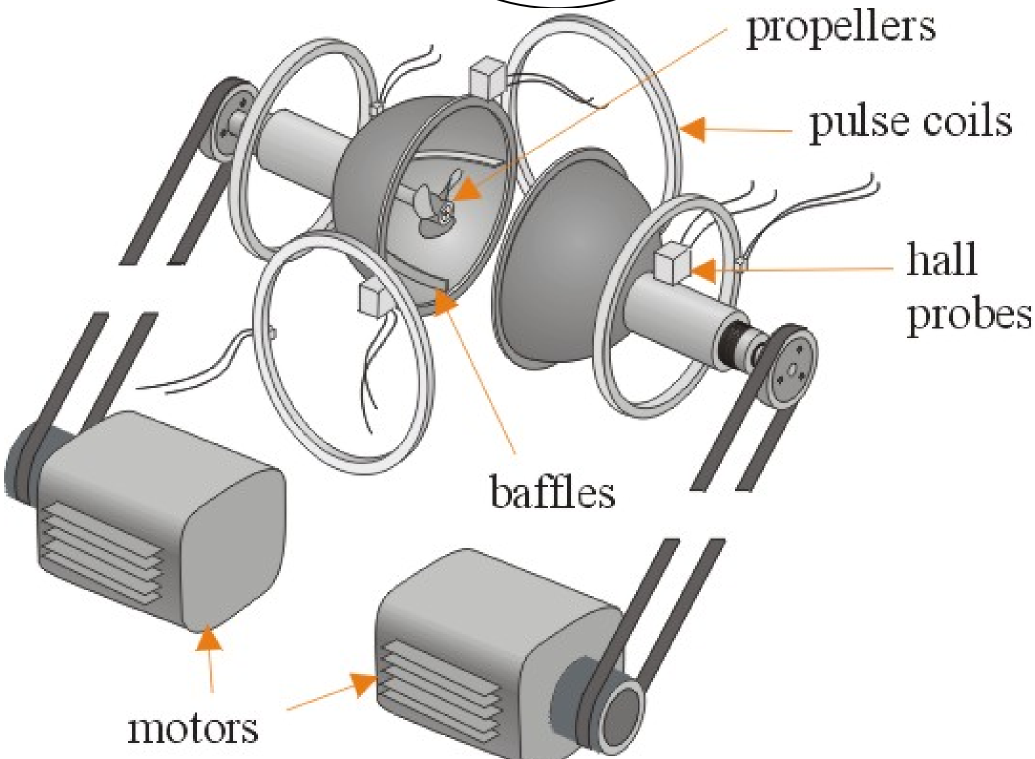
61 cm

(Aubert el al.,2001) predict if R=1 m and 100kW of heat, $Re_m = 1$

Mechanically forced motions



S2T2 kinematic model
(Dudley and James, 1989)
$R_{mc} = 55$



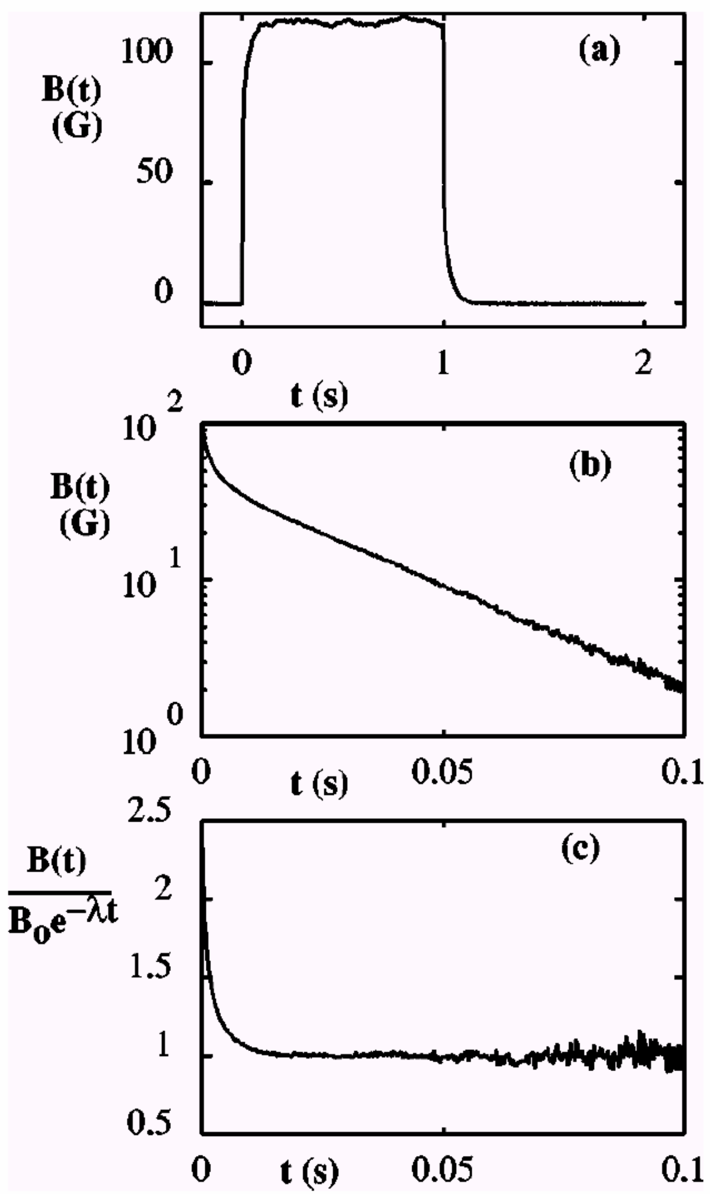
2 * 7.4 kW

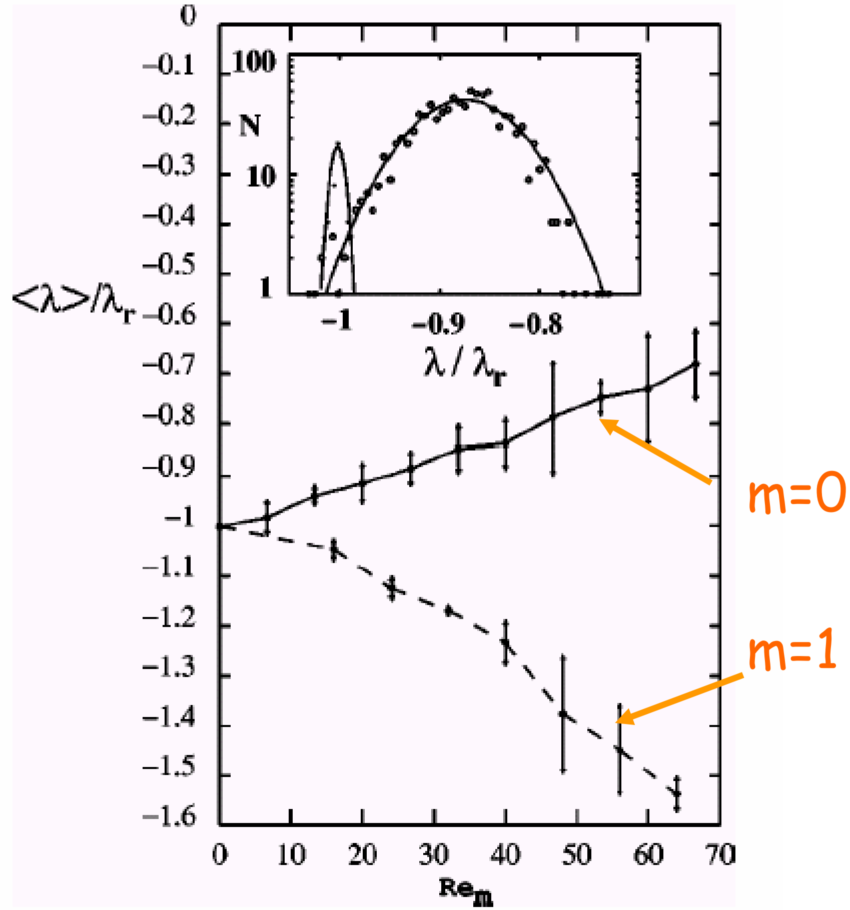
15 litres

D = 31.2 cm

(Lathrop et al., 2001)

Decay rates





(Peffley et al., 2001)

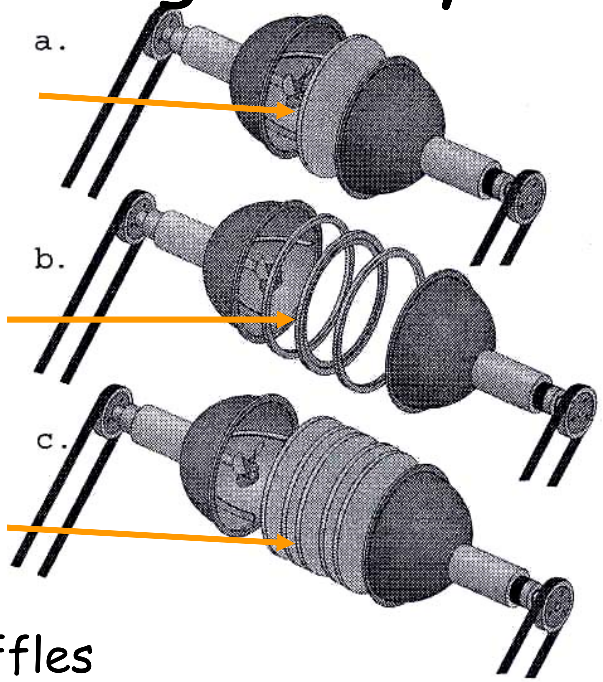
$R_{mc} \sim 200$?

"Hunting for dynamos"

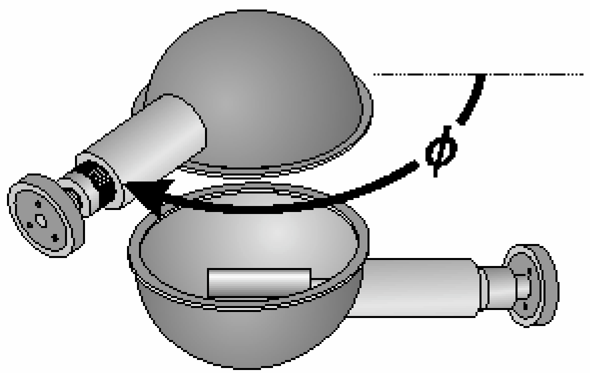
1 Cu plate

3 Cu rings

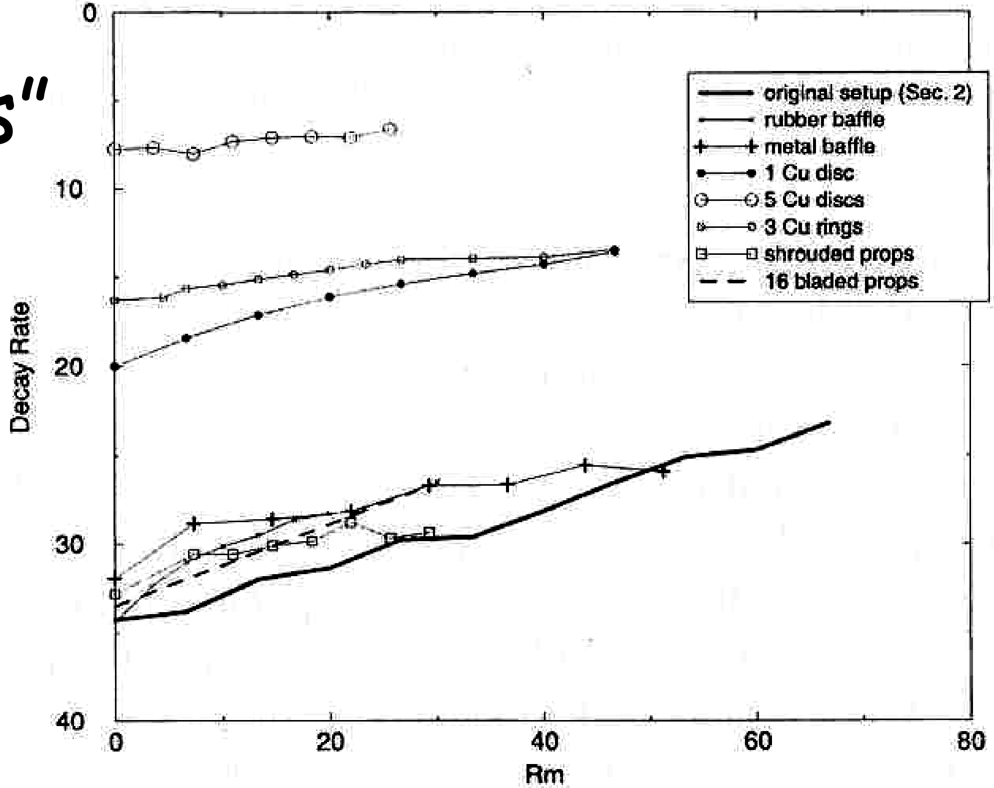
5 Cu plates



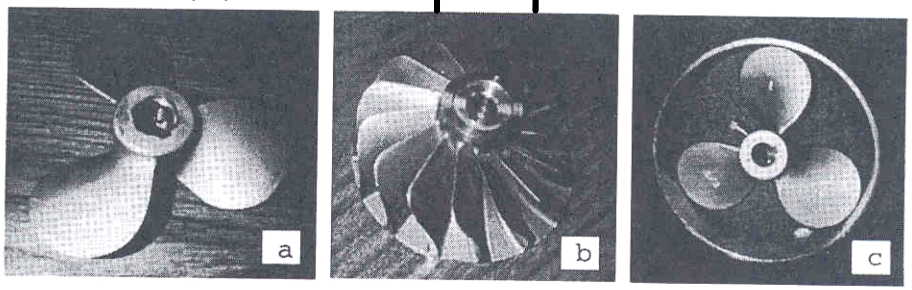
+ baffles



Herzenberg type



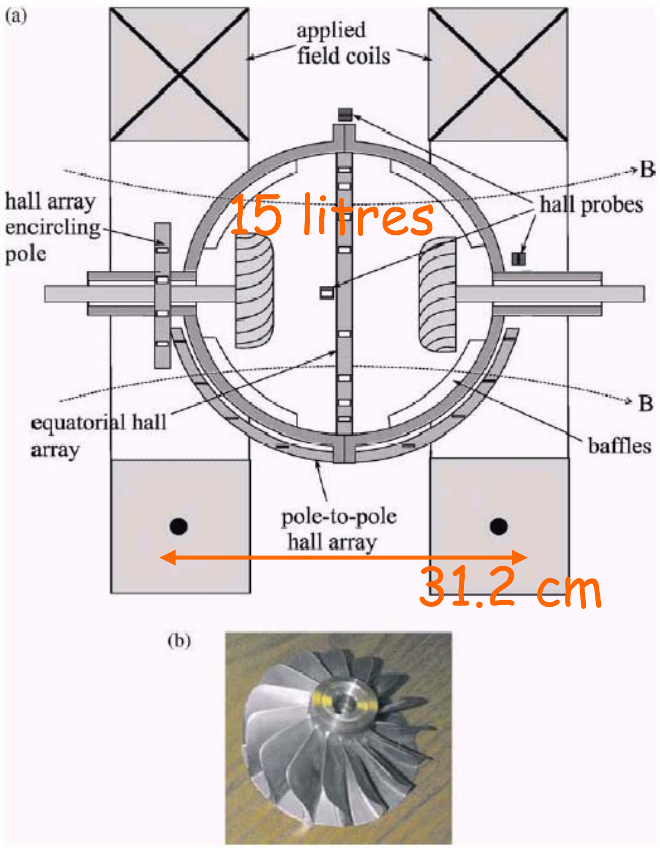
Different propellers



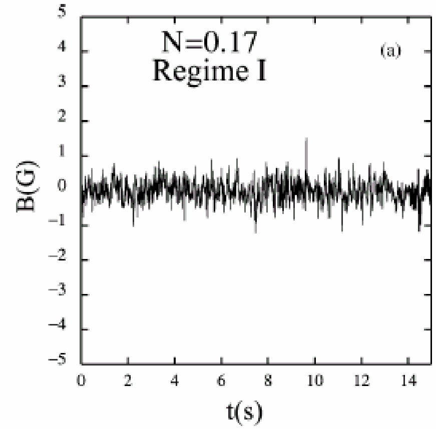
BEST

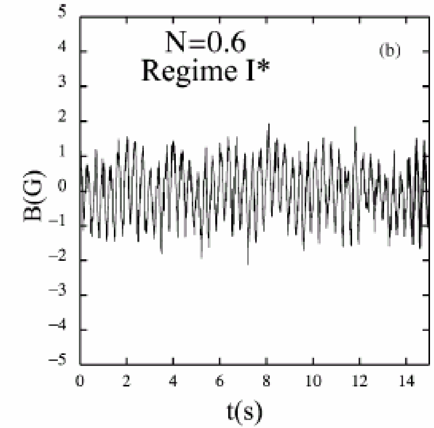
(Shew et al., 2002)

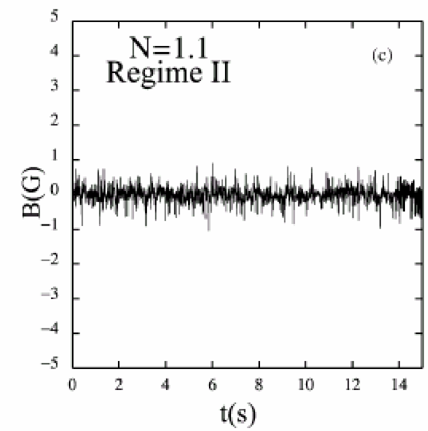
MHD Turbulence



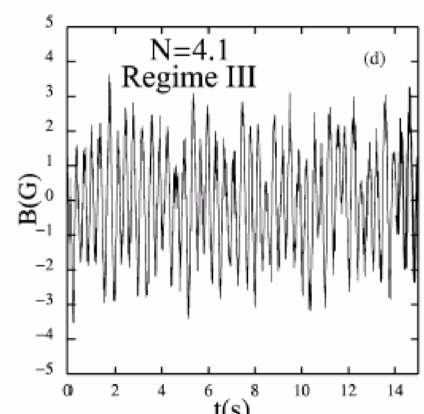
$N = \sigma l B^2/\rho v$

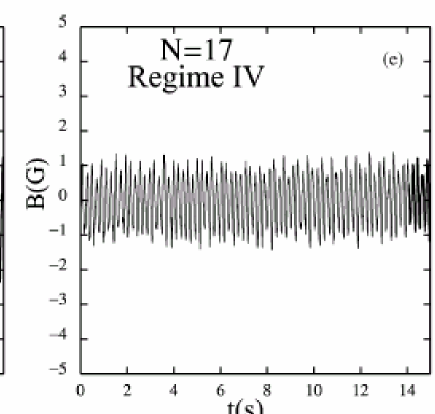






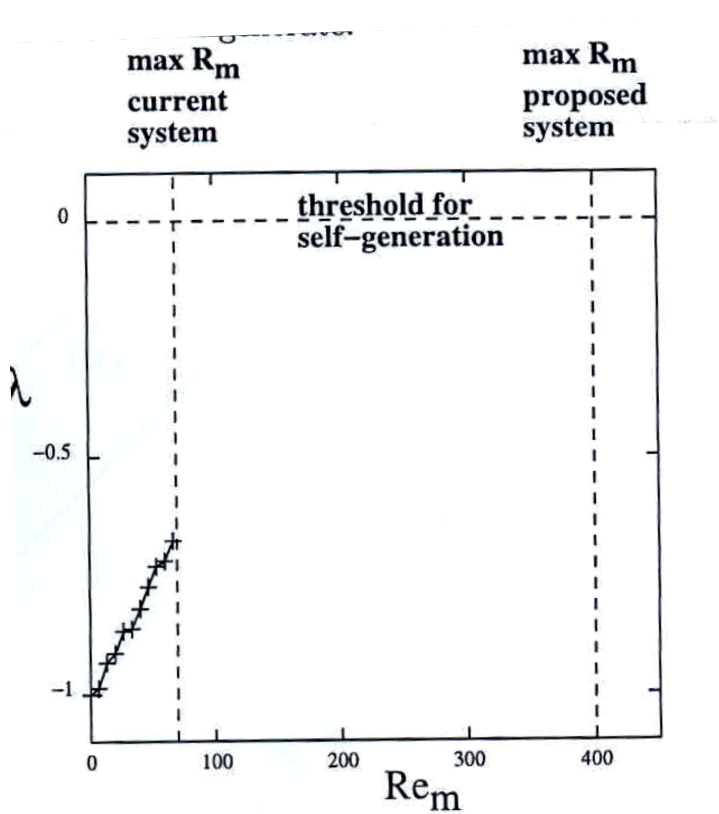
Re_m=7.5
600 rpm
var B

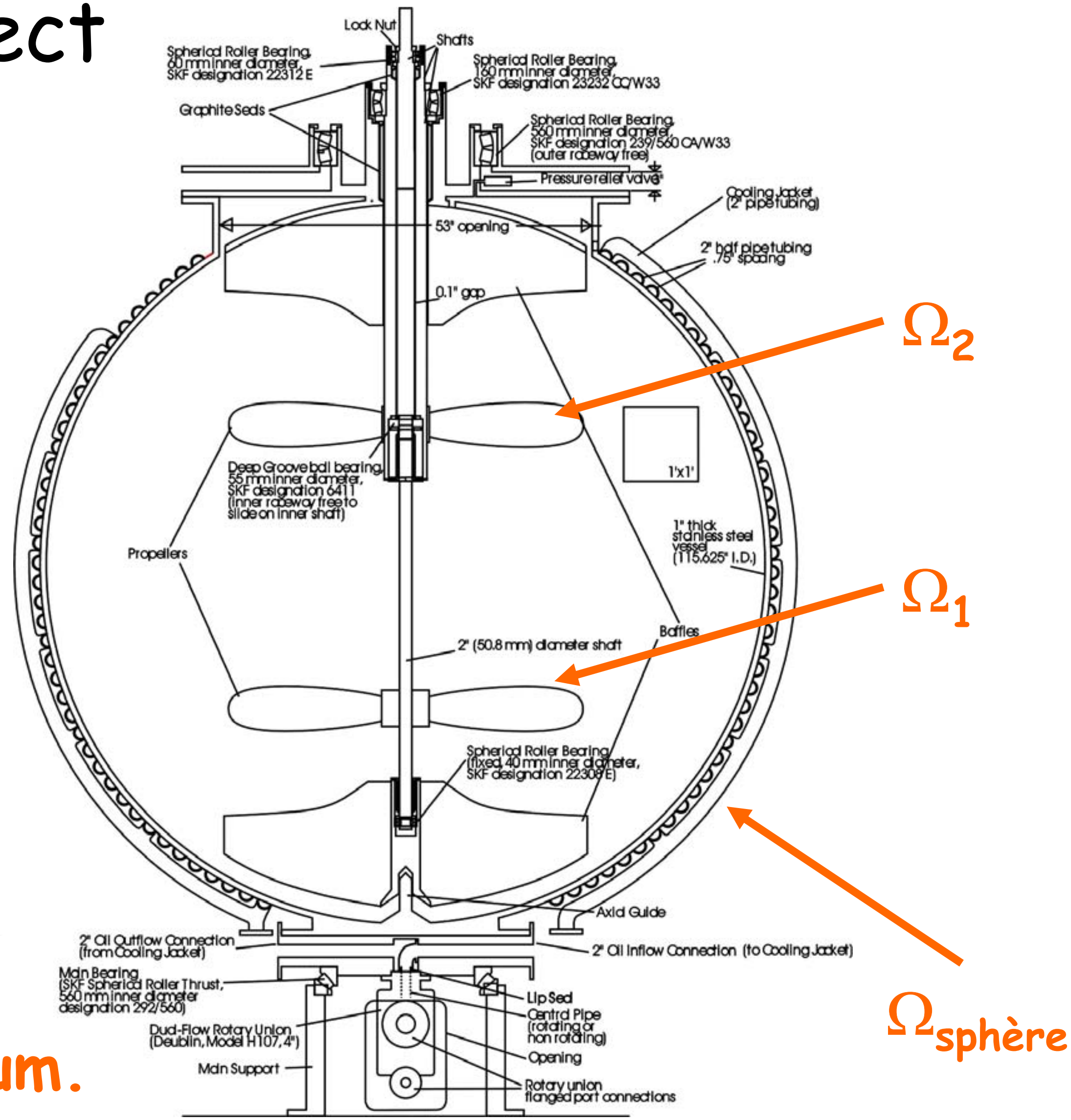




(Sisan et al., 2003)

The maryland project

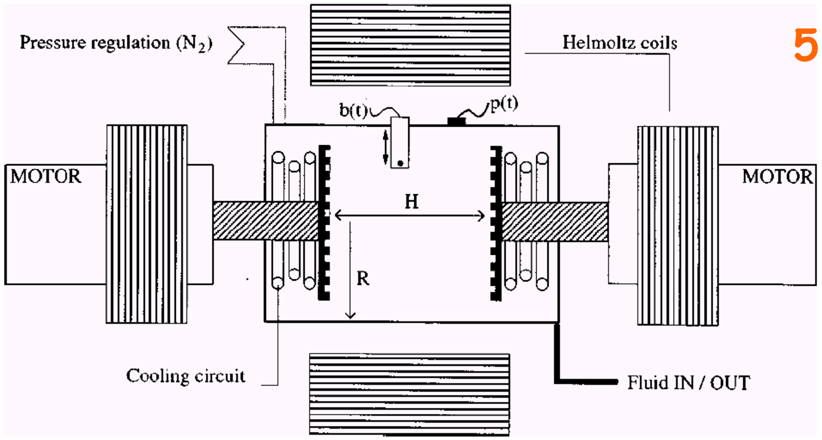




D=3m, 15 tonnes Sodium.
260 kW * 3= 780 kW.
Rem < 400.

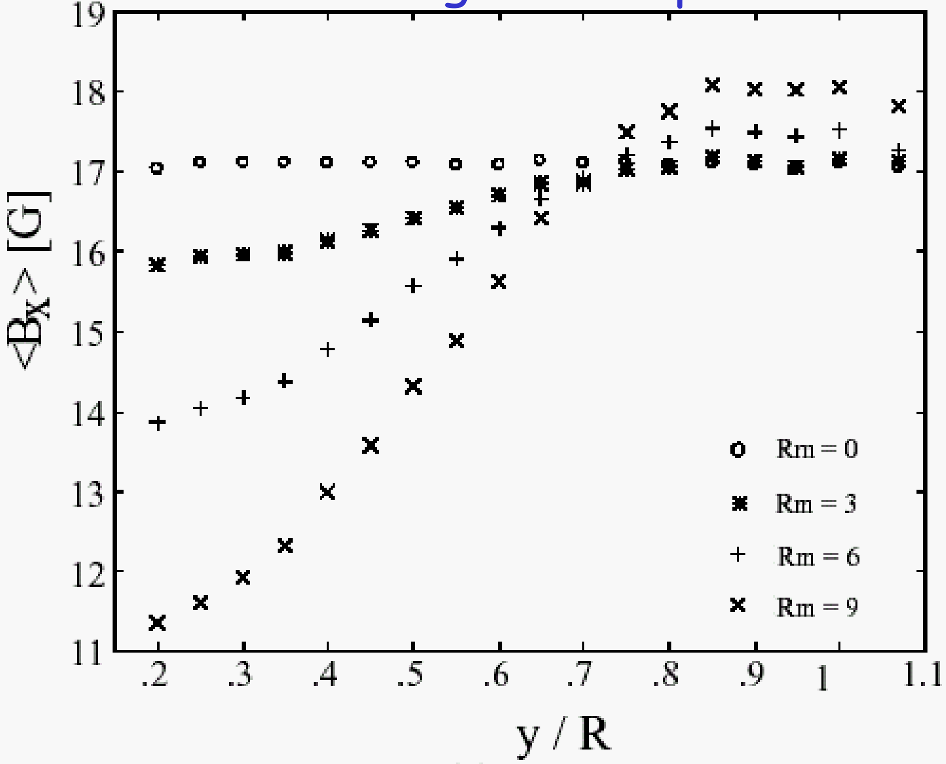
(Lathrop, 2003)

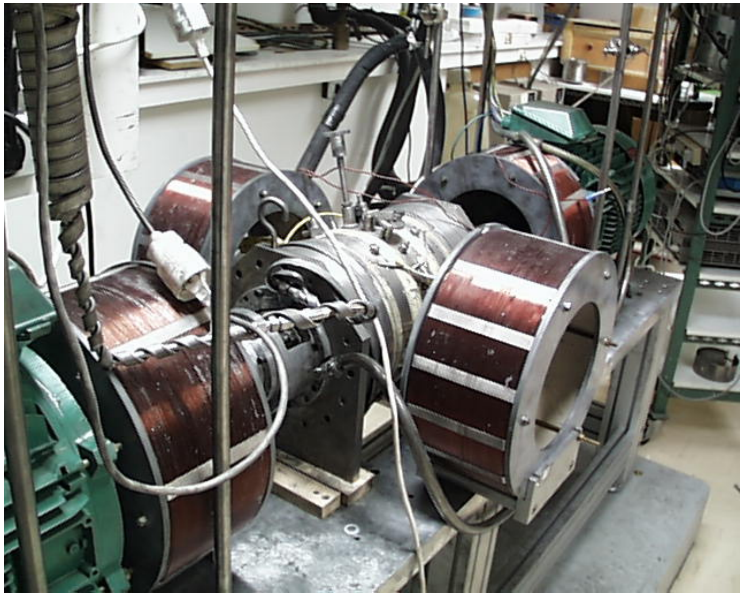
Van Karman experiments : VKG



5 litres gallium
R = 10cm
2*11 kW
Rm<16

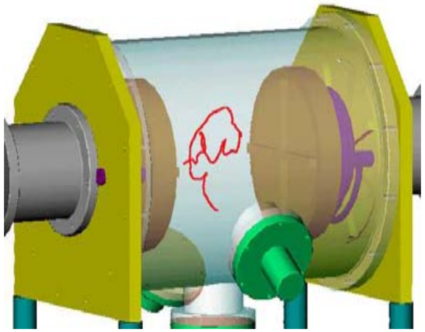
Magnetic expulsion





(Odier et al., 1998;2000)

Van Karman Sodoium



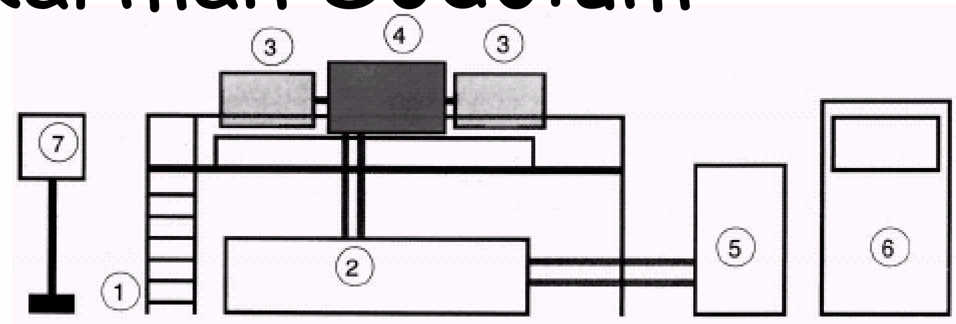
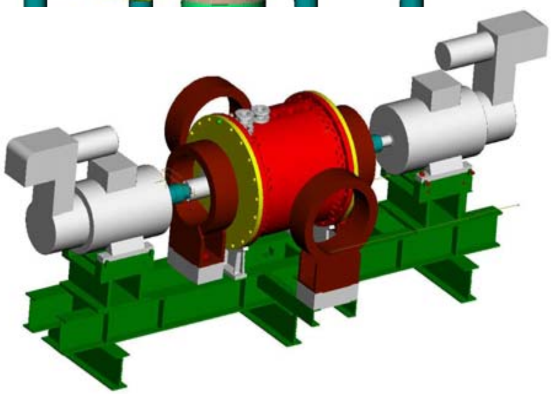
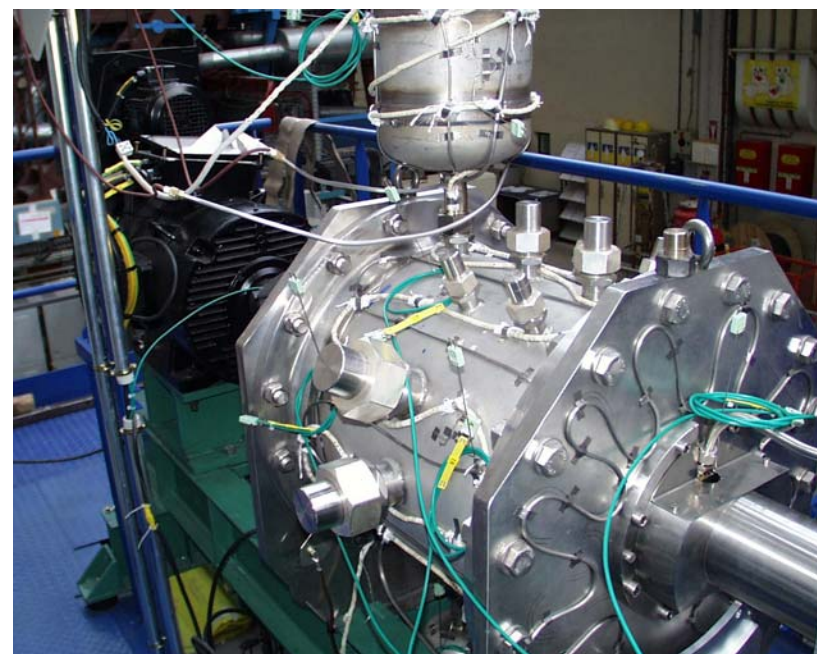


FIG. 1. Sodium experiment: (1) experimental platform, (2) sodium tank (270 l), (3) motors, (4) flow vessel (70 l, detailed in (2), (5) sodium purification unit, (6) control unit, (7) argon circuit command.

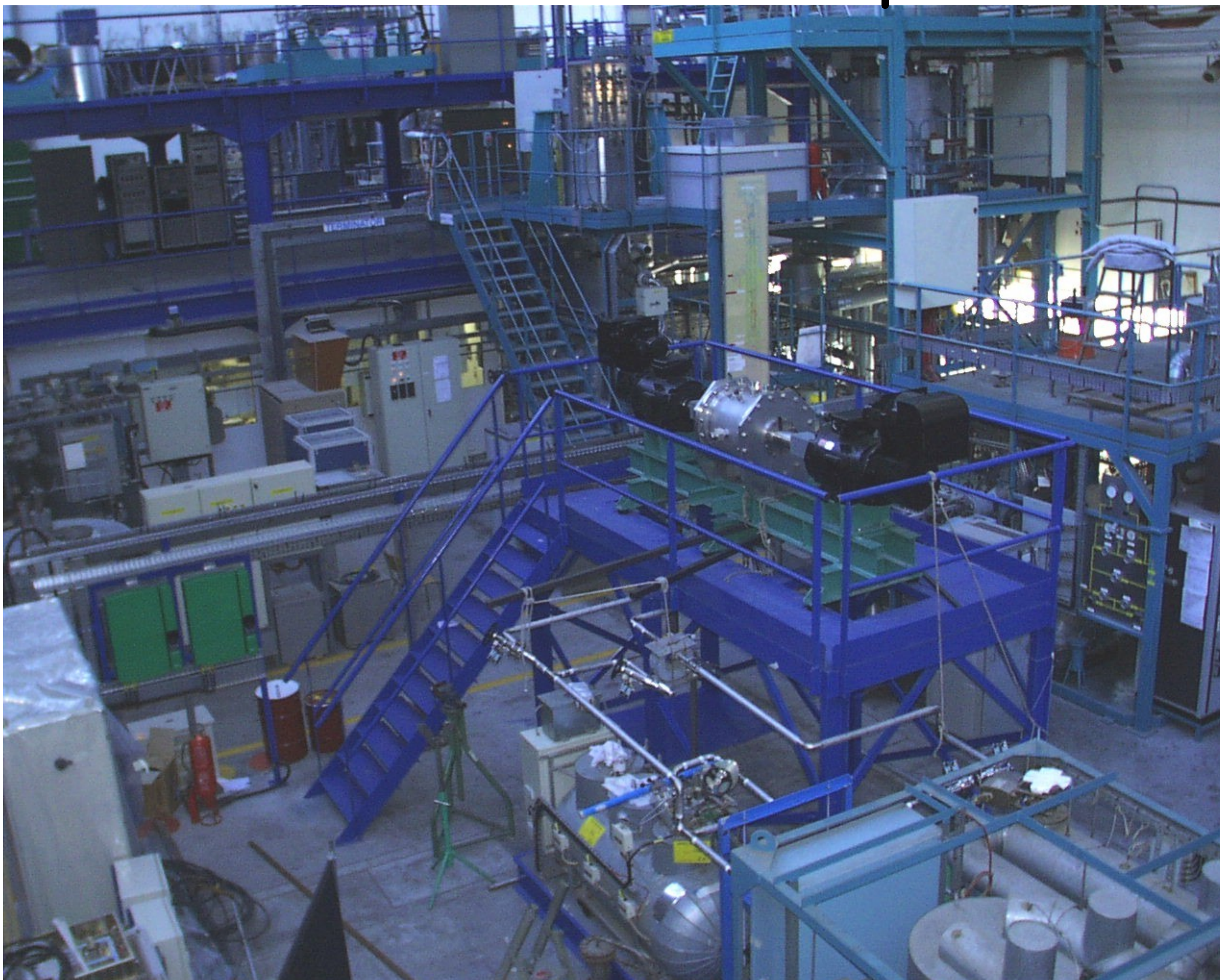


70 litres sodium, 2*75 kW, 1500 rpm, Rm<50

R=20 cm, H=2R

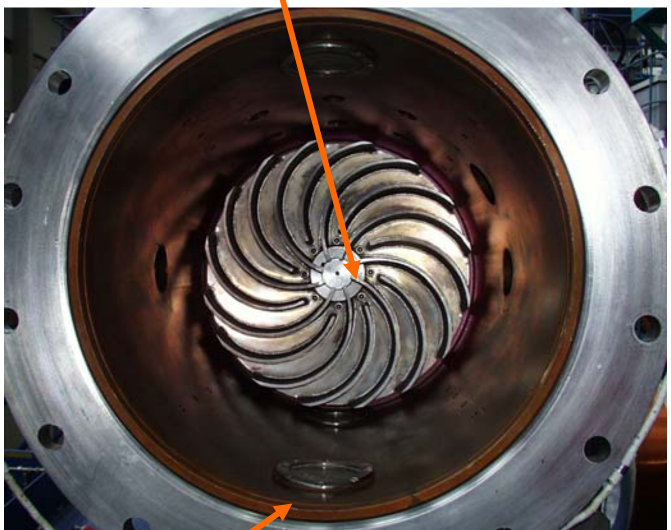


View of the Cadarache experiment



VKS: optimisation of the flow

Poloidal / Toroïdal ≈ 0.8



1 cm of cupper

$R_{mc} \sim 70$ or $R_{m\ max} \sim 55$

(Marié et al., 2001)
(Bourgoin et al., 2002)

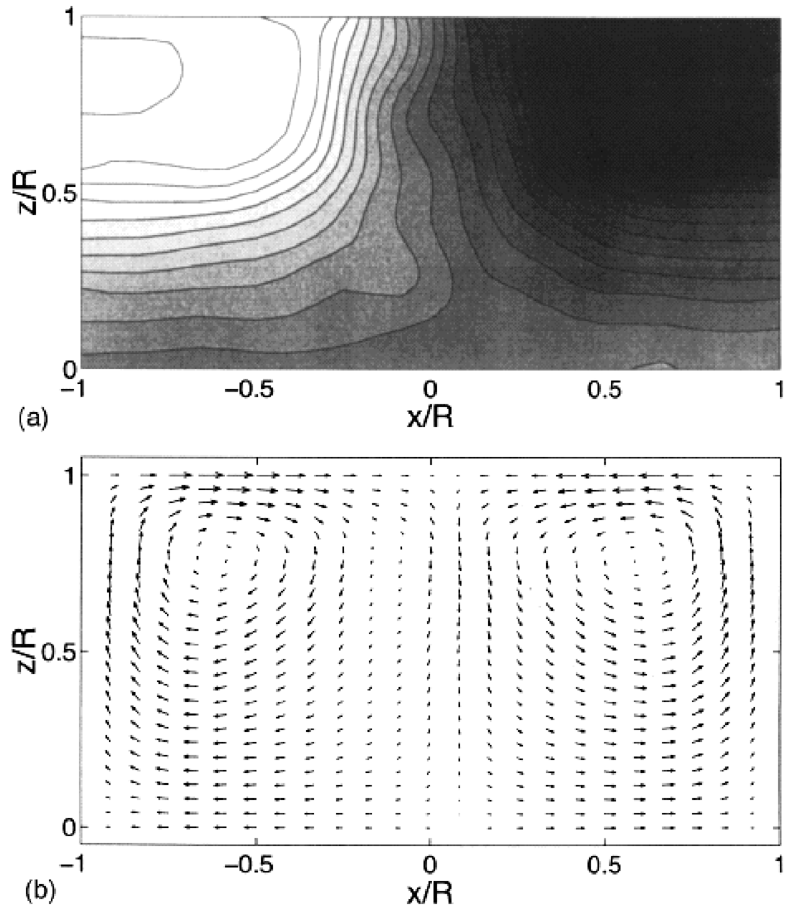
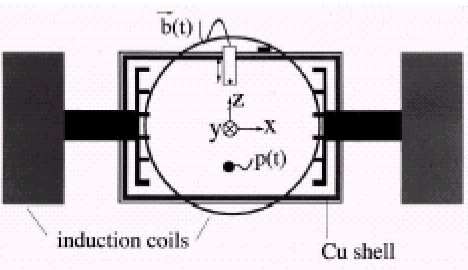
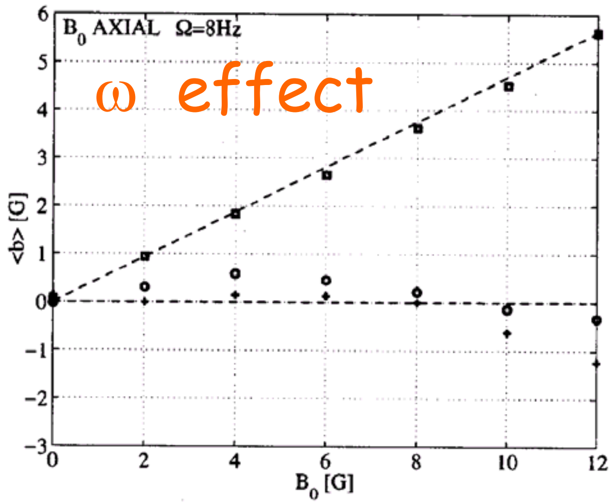


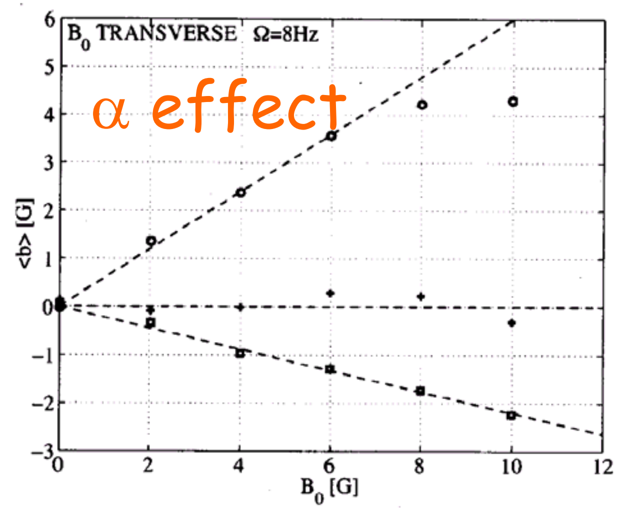
FIG. 3. Mean velocity field in the water experiment: (a) toroidal and (b) poloidal component of the velocity in the meridian plane. The abscissa corresponds to the normalized axial direction with the disks located at $x/R = \pm 1$, and the ordinate corresponds to the normalized radial direction (with $z/R=0$ at the center of the disks). In this measurement, the rotation rate of the disks is $\Omega=5$ Hz.

LDV et UDV

VKS: MHD effects

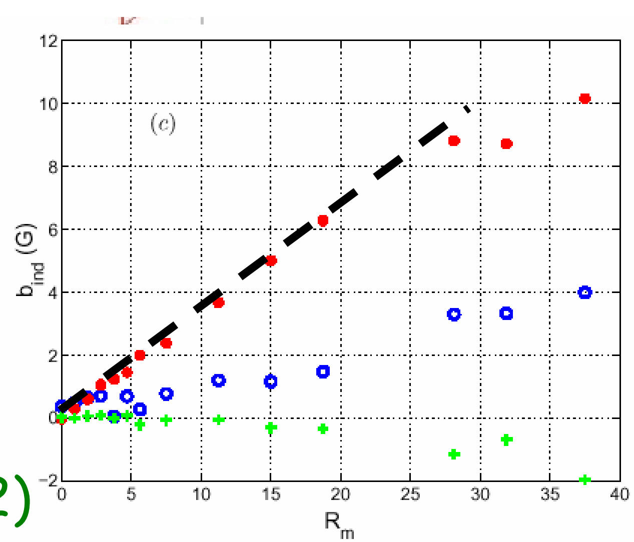




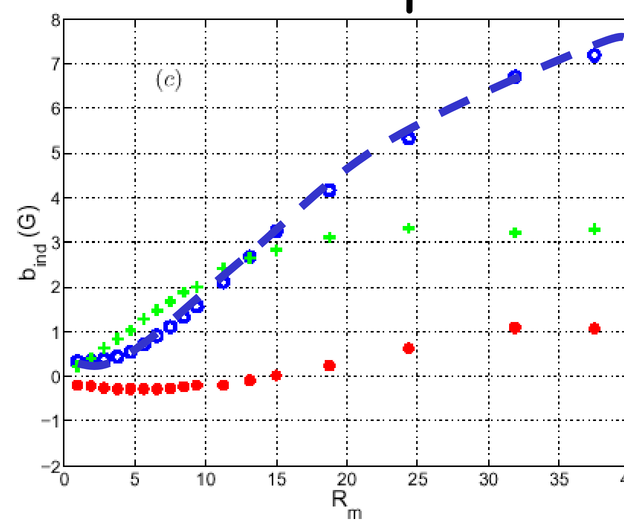


N << 1

B_o passive



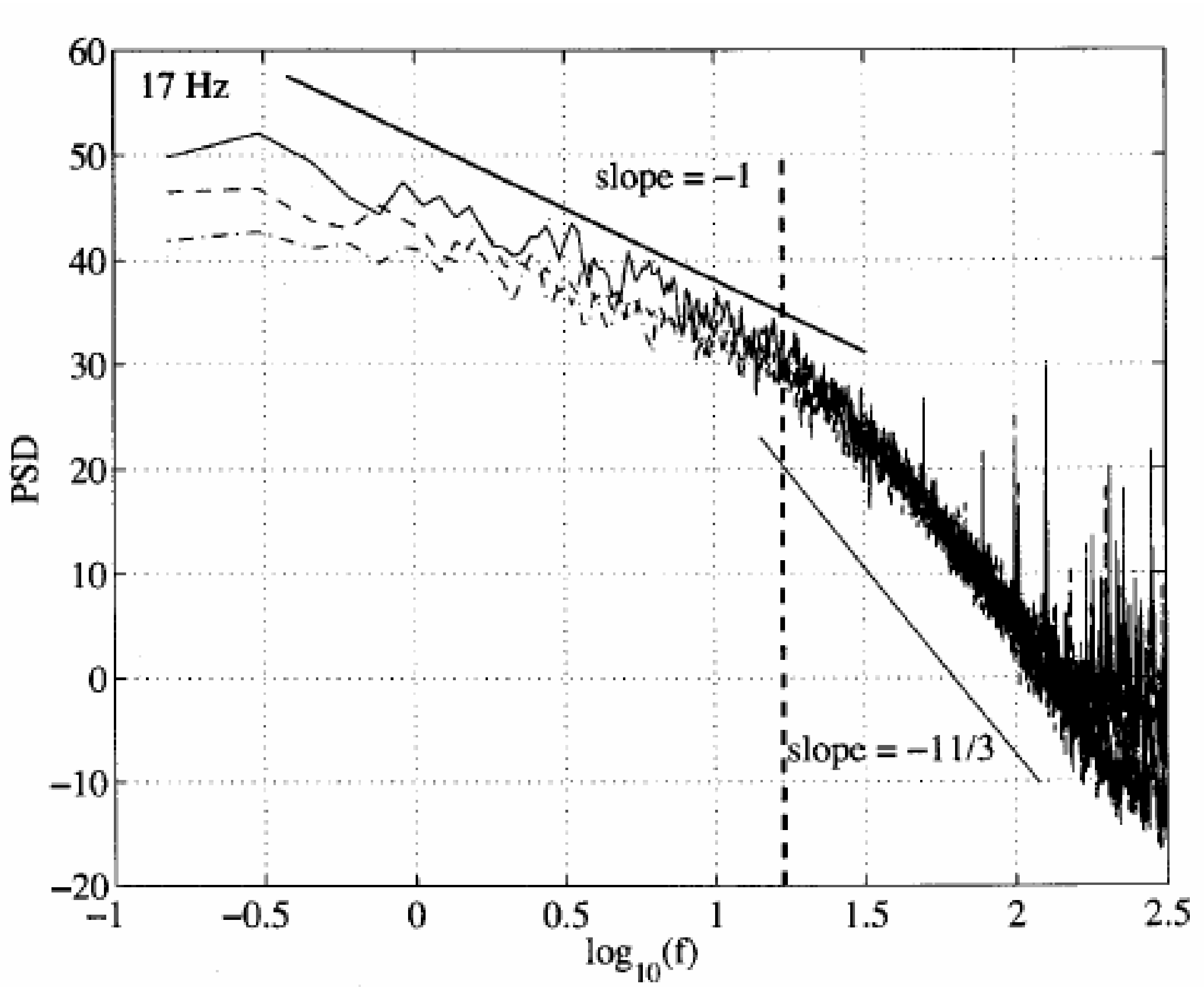
Expulsion



(Bourgoin et al., 2002)

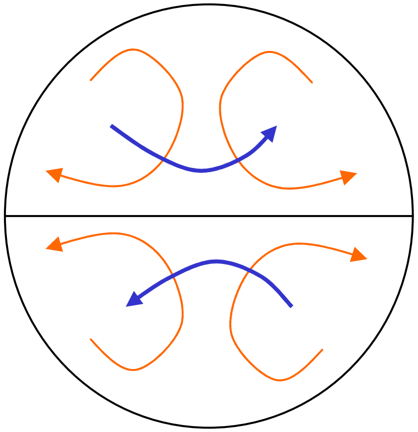
(Marié et al, 2002)

VKS : spectra



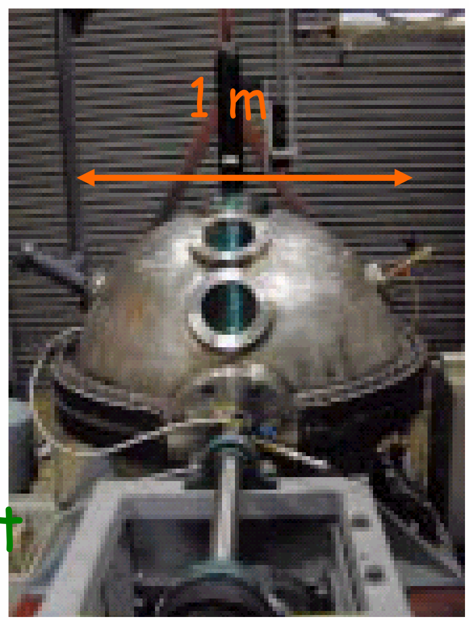
(Bourgoin et al., 2002)

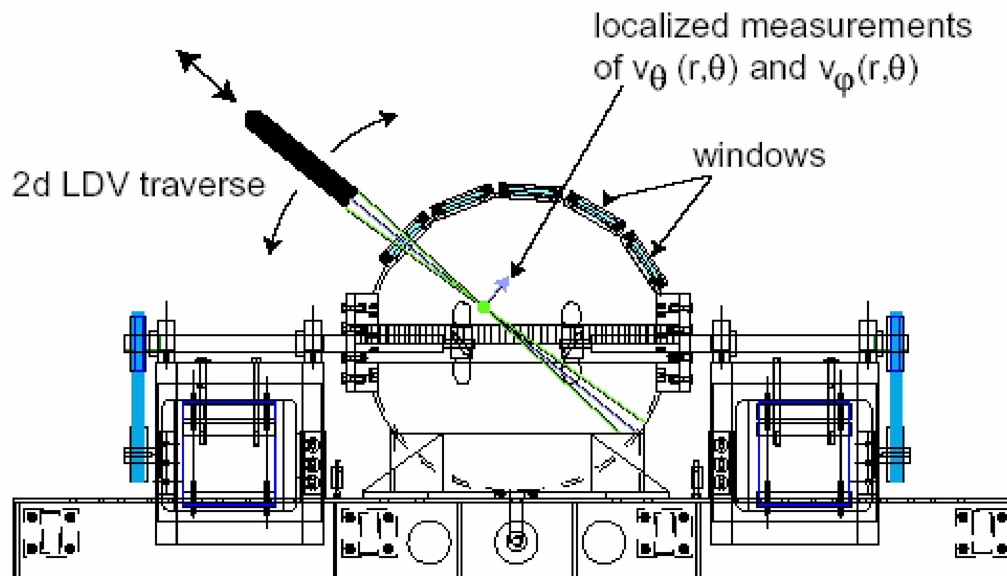
Madison Experiment



Optimisation of
S2T2 kinematic model
(Dudley and James, 1989)
$R_{mc} = 47$

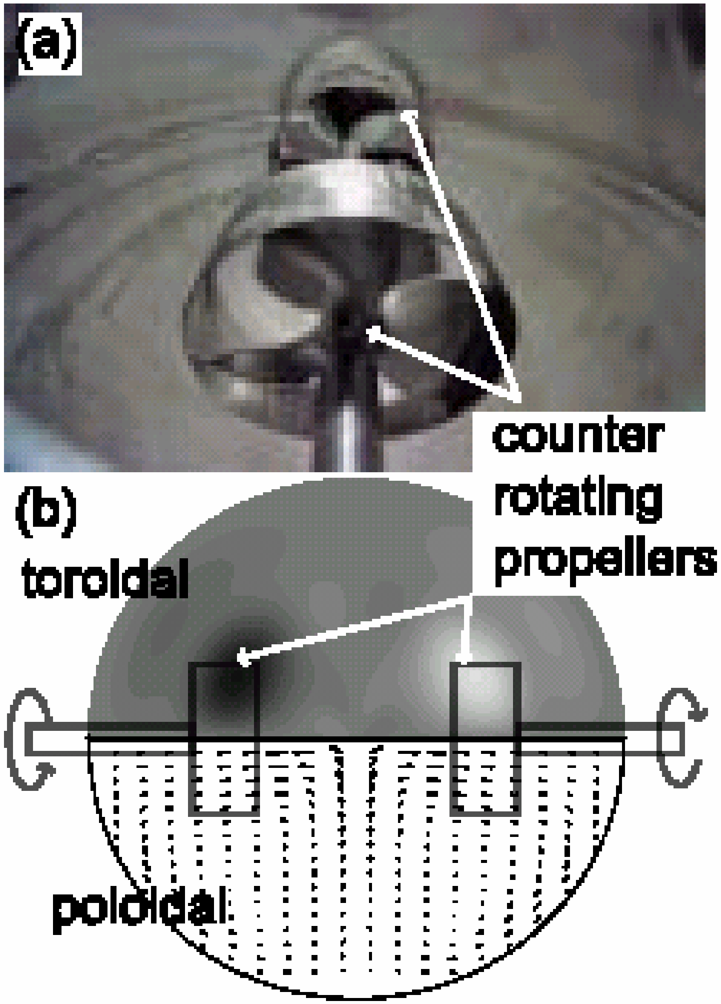
2* 50 kW
1750 rpm

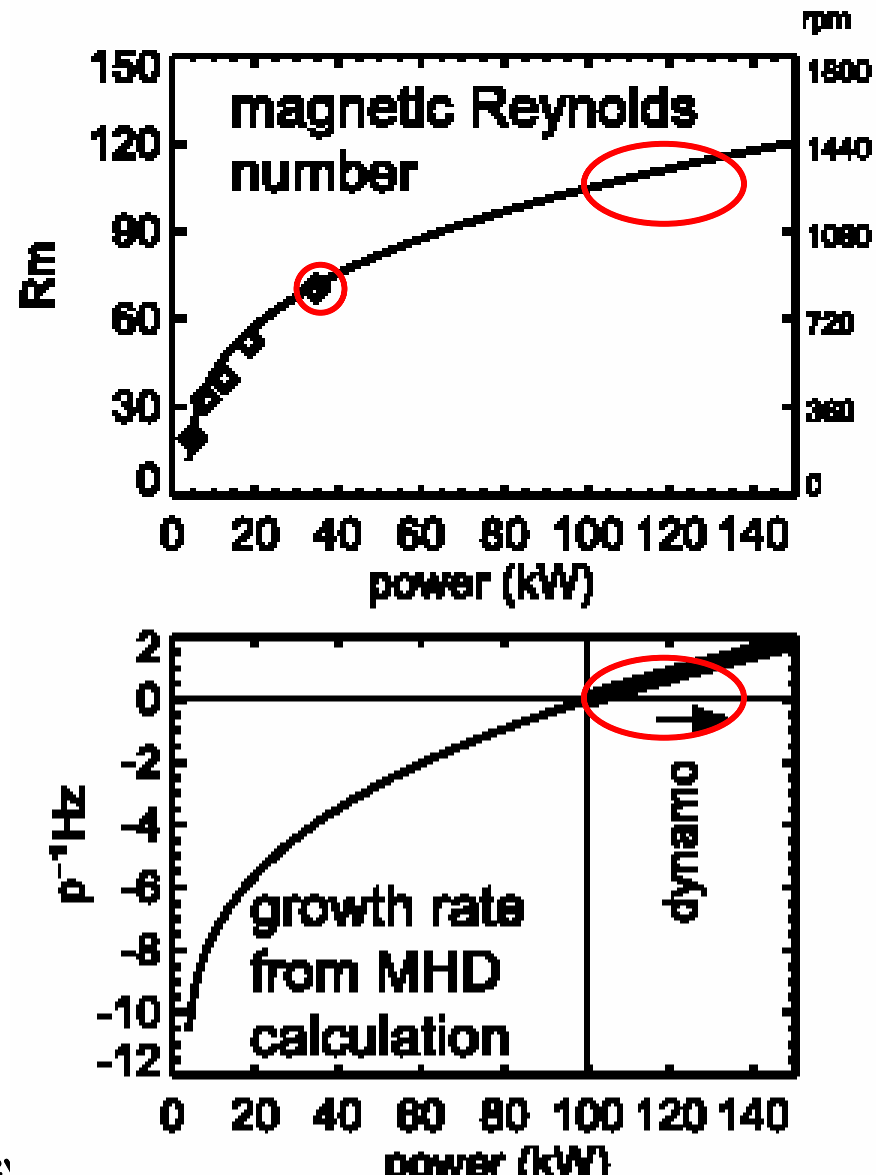




(Forest et al., 2002)

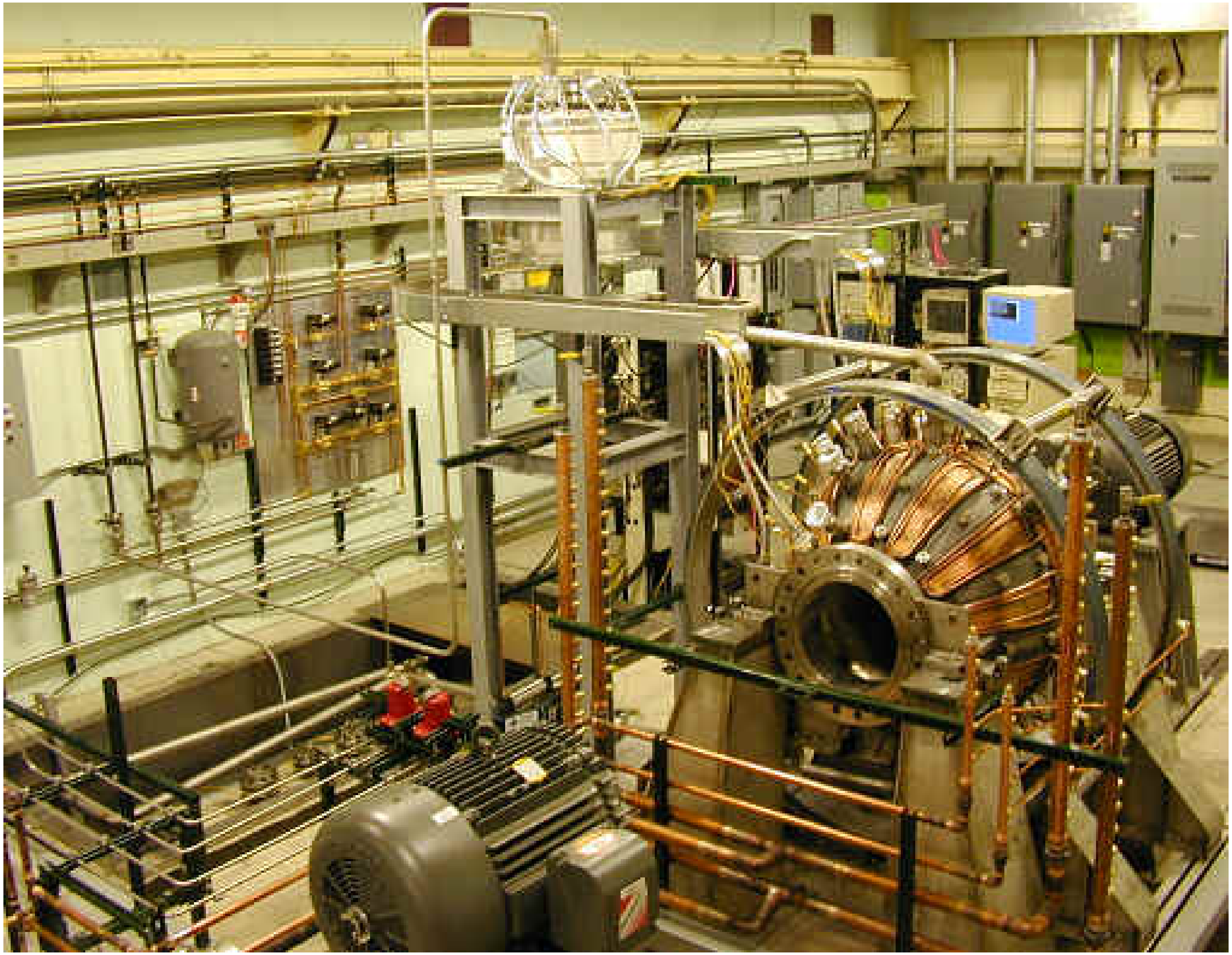
Madison: Onset of the average flow





(Forest et al., 2002)

View of the Madison experiment



Diameter=1m
150 kW
V~20m/s
125-150°C
35 kW cooling
120G axial
R_m~250 > 100

The Perm project

Ponomarenko type

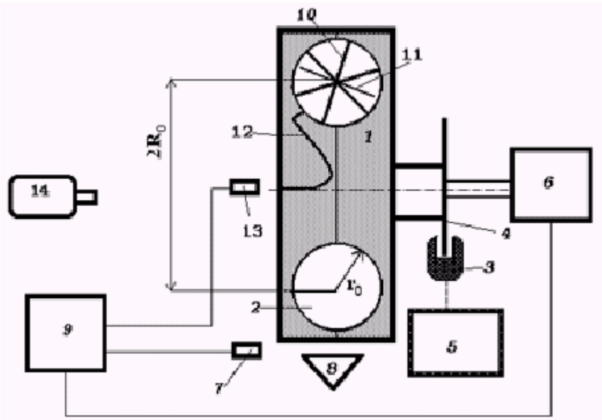


Fig. 4. Apparatus for water experiment: *1* – plexiglass cylinder, *2* – toroidal channel, *3* – brakes, *4* – braking disc, *5* – braking control, *6* – electromotor, *7* – tachometer, *8* – lighting, *9* – computer, *10* – diverter, *11* – free rotating flat blade, *12* – optical fiber, *13* – optical probe, *14* – video camera.

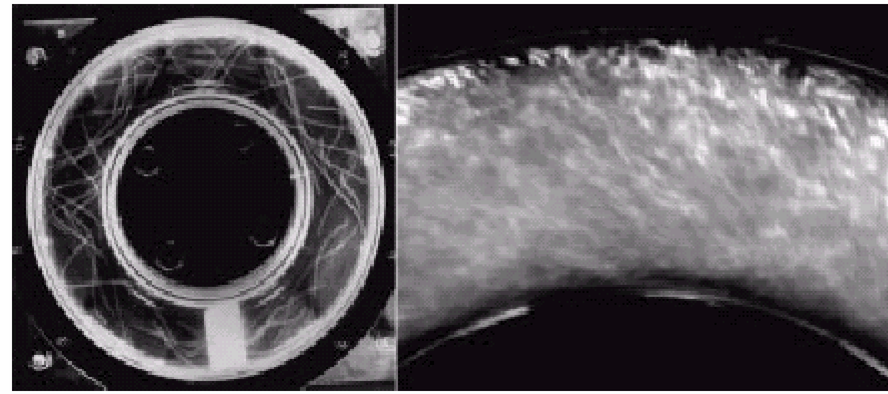
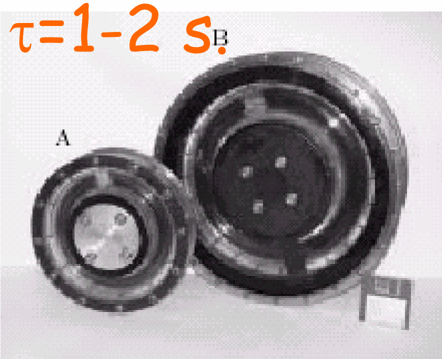


Fig. 7. Screw flow in channel A at the later stage of evolution (1.5 s after full stop). On the left panel, the polystyrene particles display a large-scale screw structure of the flow. On the right panel, small kalliroscopic particles show a small-scale structure of the turbulent flow. Both snapshots are taken for the same moment of evolution. One diverter is used, which can be seen in the lower part of the channel as a light body.

Water: 2 kW, 3000 rpm
0.2 à 0.5 s breaking
τ=1-2 s.



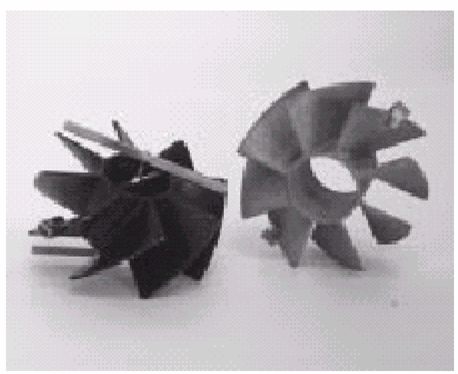


Fig. 5. Two channels: A (small) and B (large), used in water experiments.

Fig. 6. 8-blade flow diverters. The left diverter is fitted with two flat freely rotating blades, which enable one to measure azimuthal velocities upstream and downstream the diverter.

(Frick et al, 2002)

Sodium experiment:
R=0.4 m, r=0.12 m
115 litres Na
3000 rpm
Vmax=140 m/s
Rm=40
Breaking 0.1 s

Perm: Optimisation of the flow

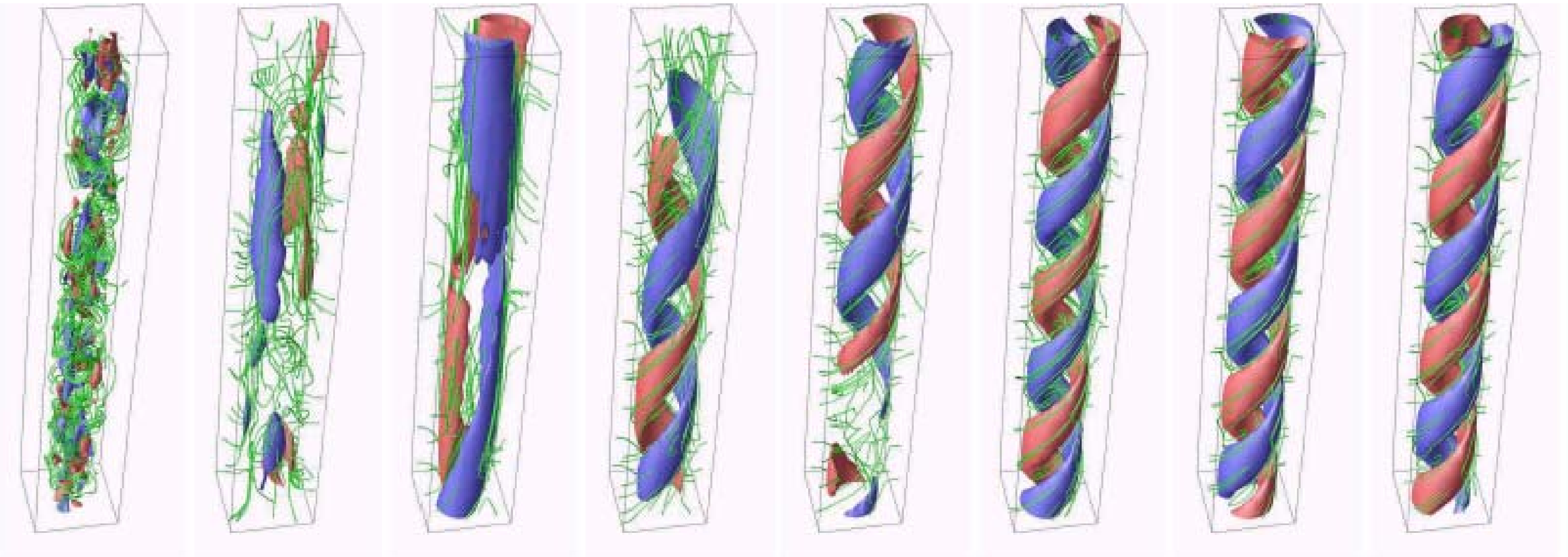
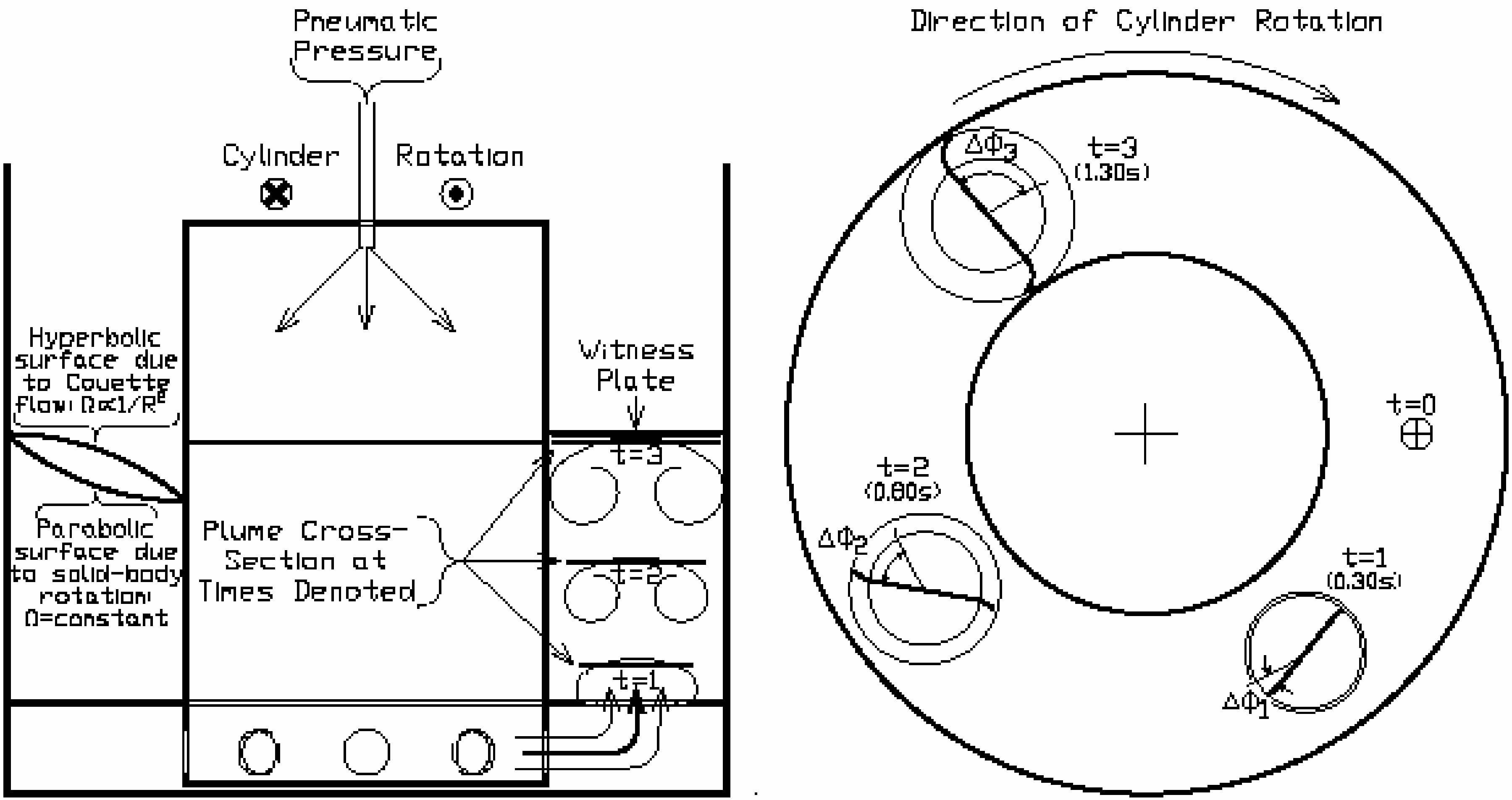


FIG. 9: Structure of the magnetic field for different times of Run 1. From left to right, the times are 0.0, 0.05, 0.1, 0.15, 0.2, 0.3, 0.4 and 0.5 s; the braking time is $T_b = 0.1$ s. The surfaces are isosurfaces of the magnetic field strength (red: $B_z > 0$, blue: $B_z < 0$). The lines are magnetic field lines. The diverter is located at the bottom; the direction of the flow is upwards.

Amplification factor of 3… 0.1s
Increase of μ → 0.2 s.
Dependent of the initial magnetic field

(Dobler et al., 2003)

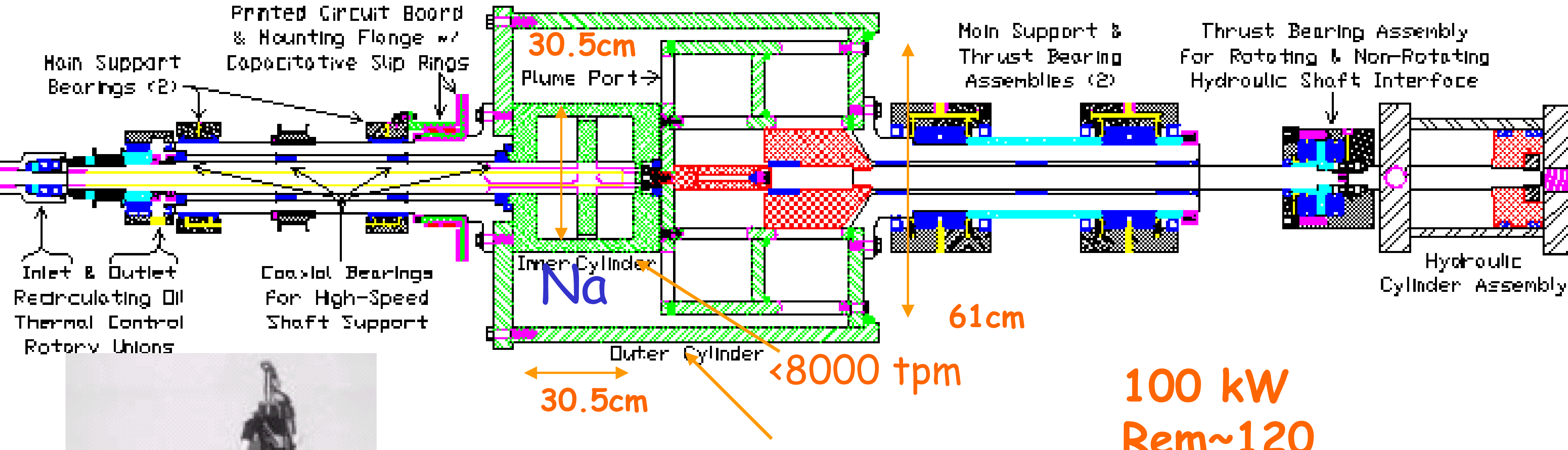
Socorro group: α - ω type dynamo



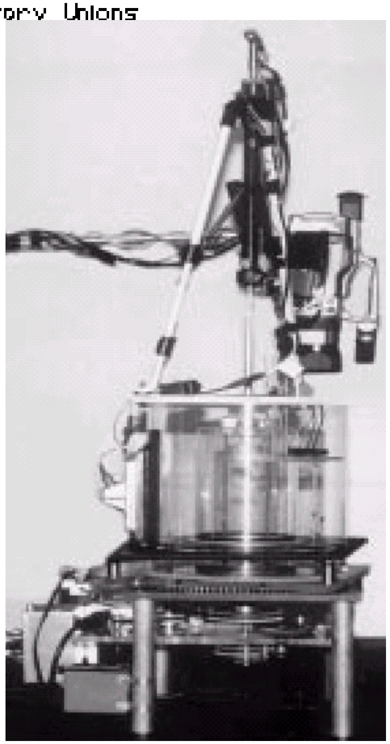
(Colgate et al., 2002)

Taylor-Couette flow (ω effect)
+ Sodium plumes (α effect)

Socorro: design of the experiment

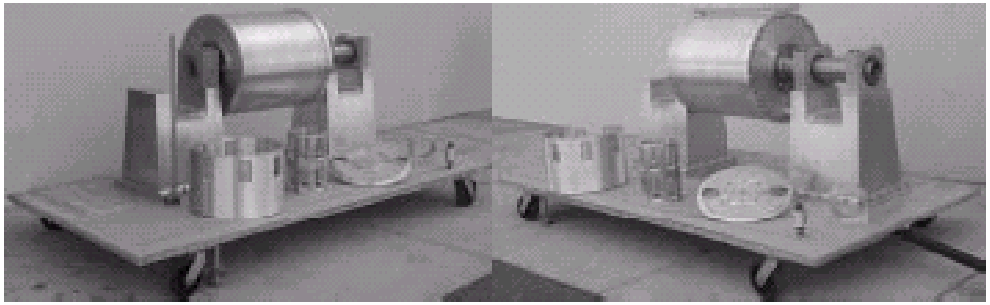


100 kW
Rem~120



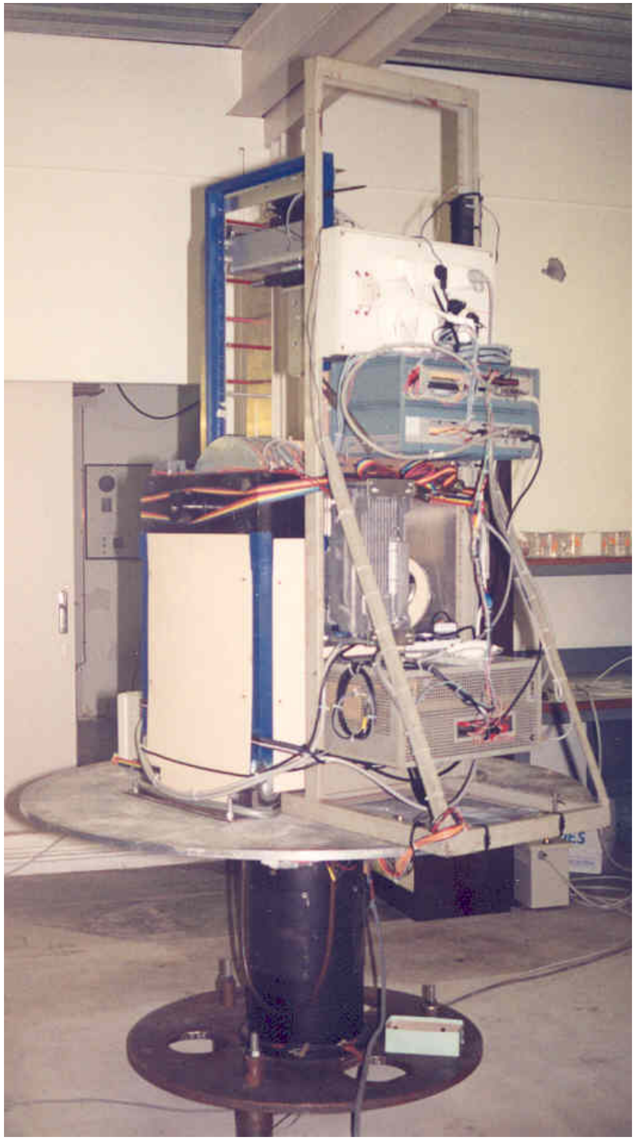
Water experiment

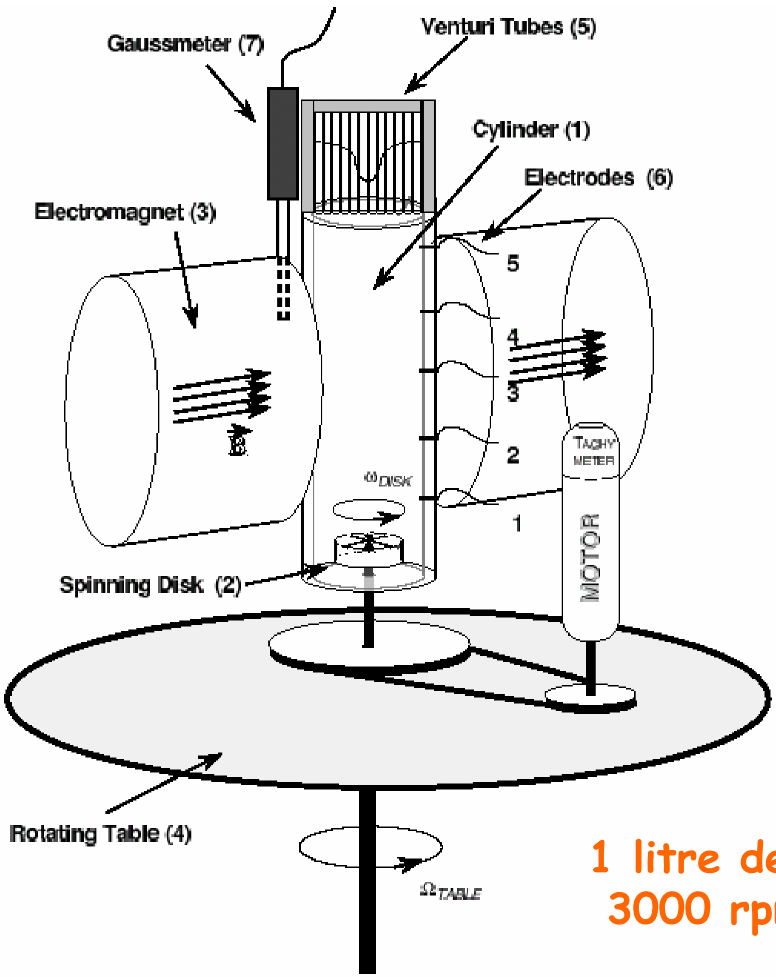
Sodium tank



(Colgate et al., 2002)

The Grenoble project.

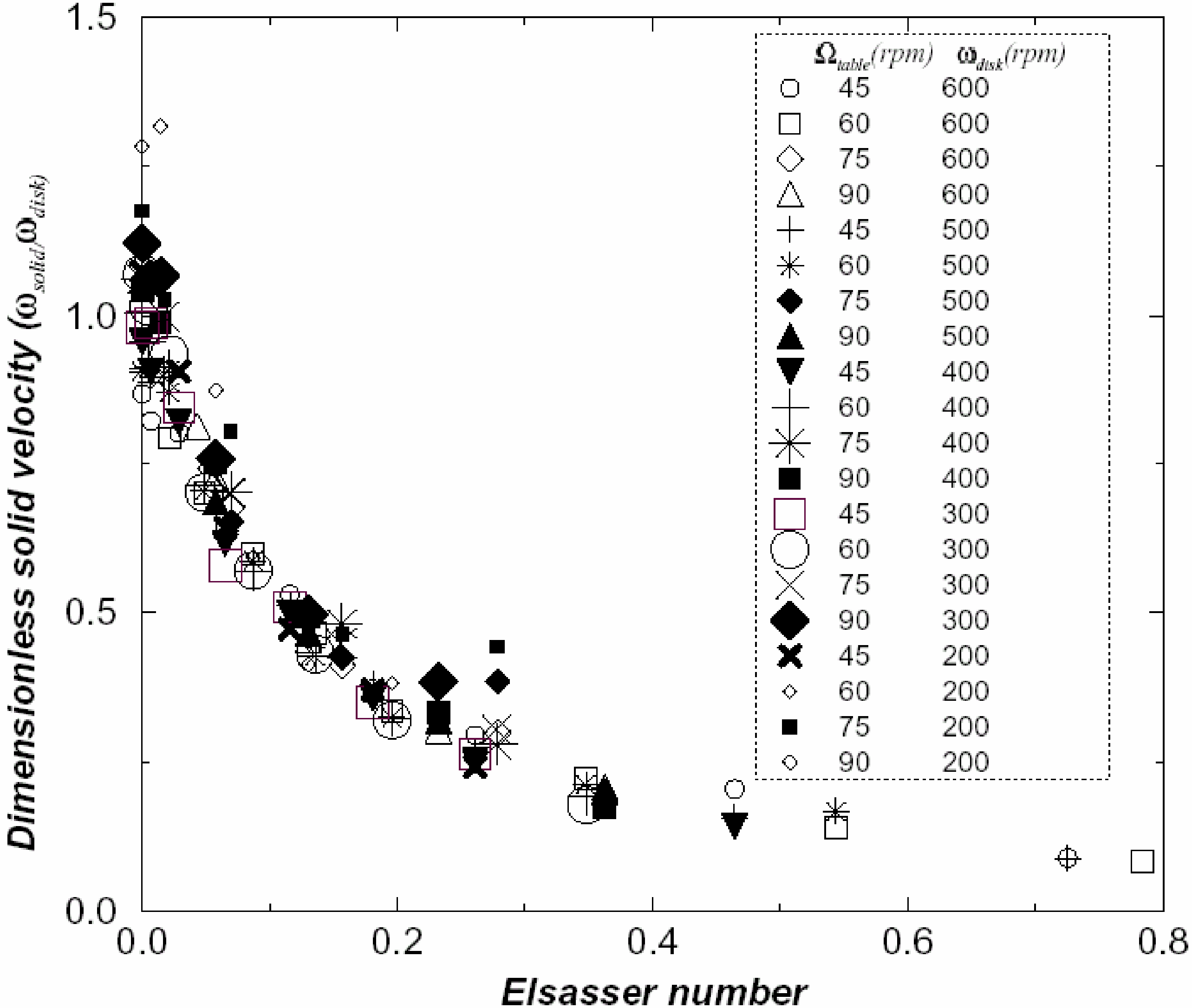




1 litre de gallium,
3000 rpm.

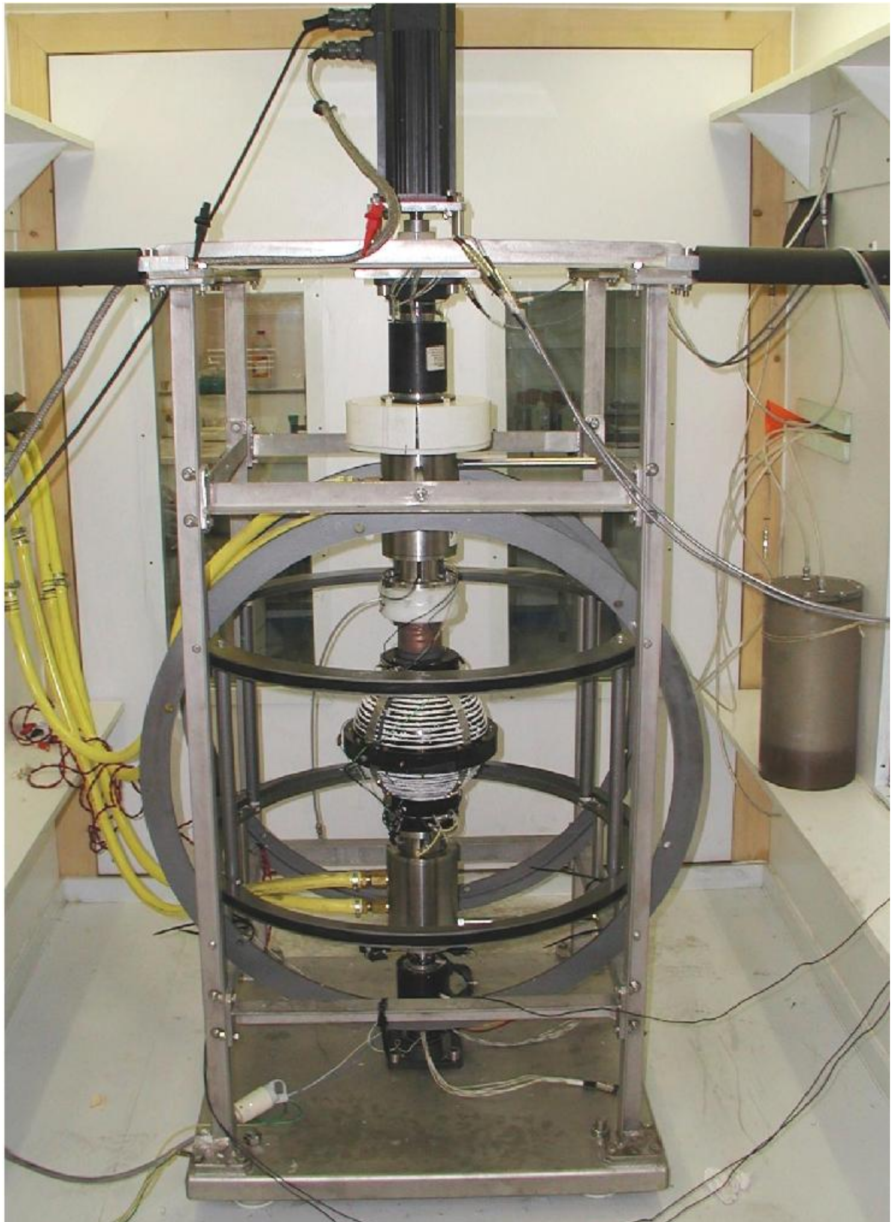
(Brito et al., 1995; 1996)

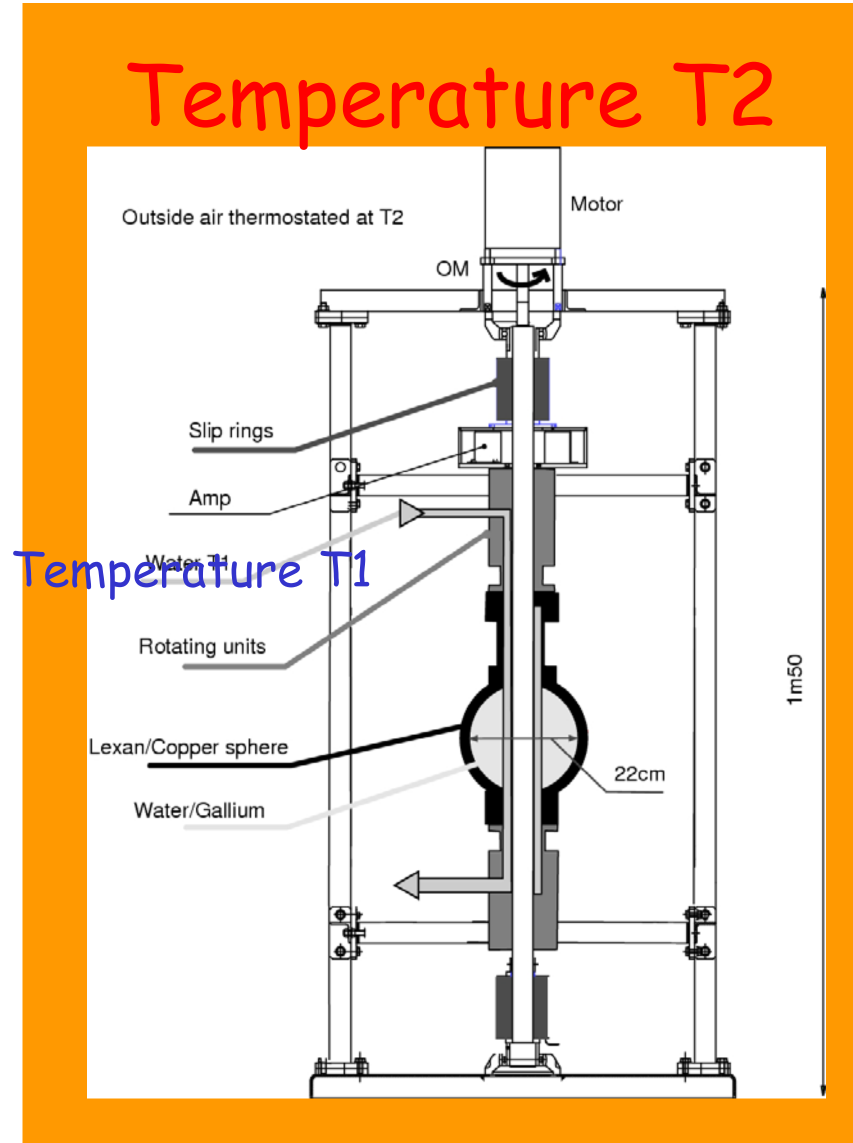
An Ω quenching effect?



(Brito et al., 1995)

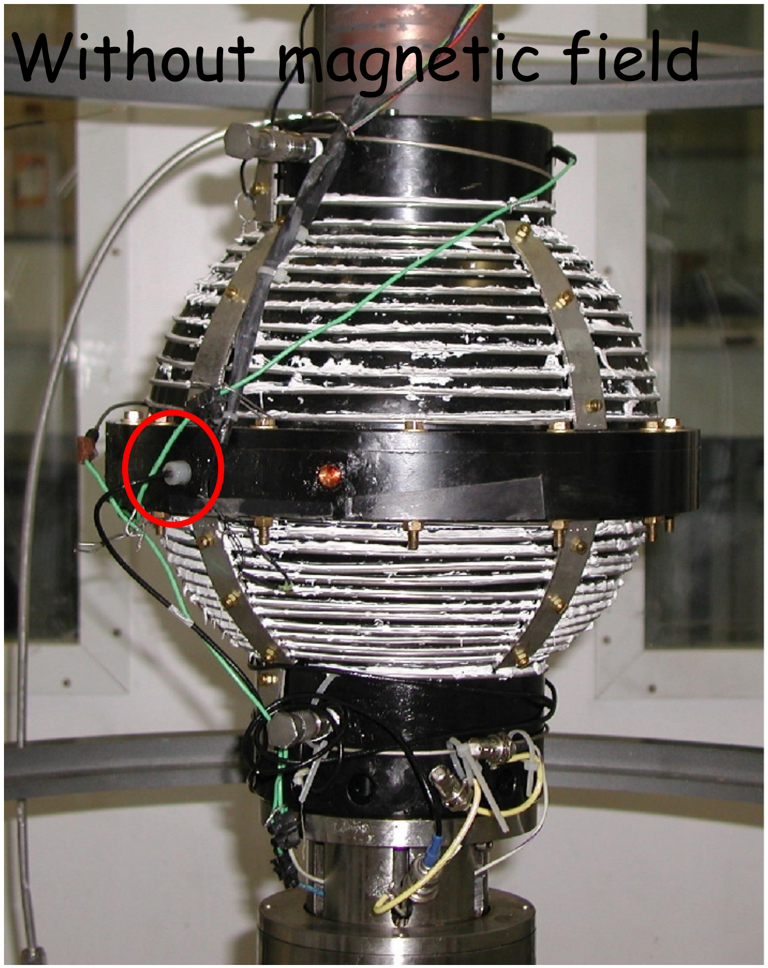
Convective study

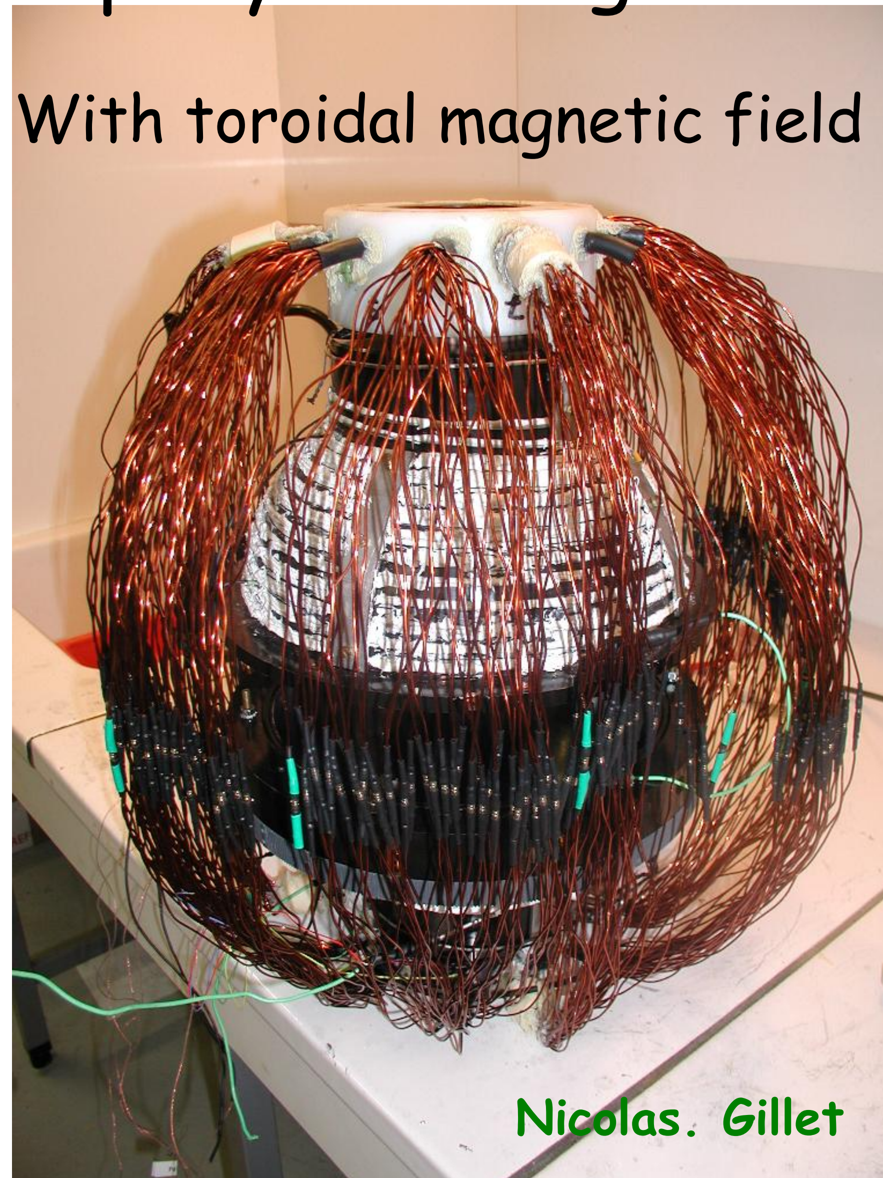




Thermal convection in rapidly rotating shell

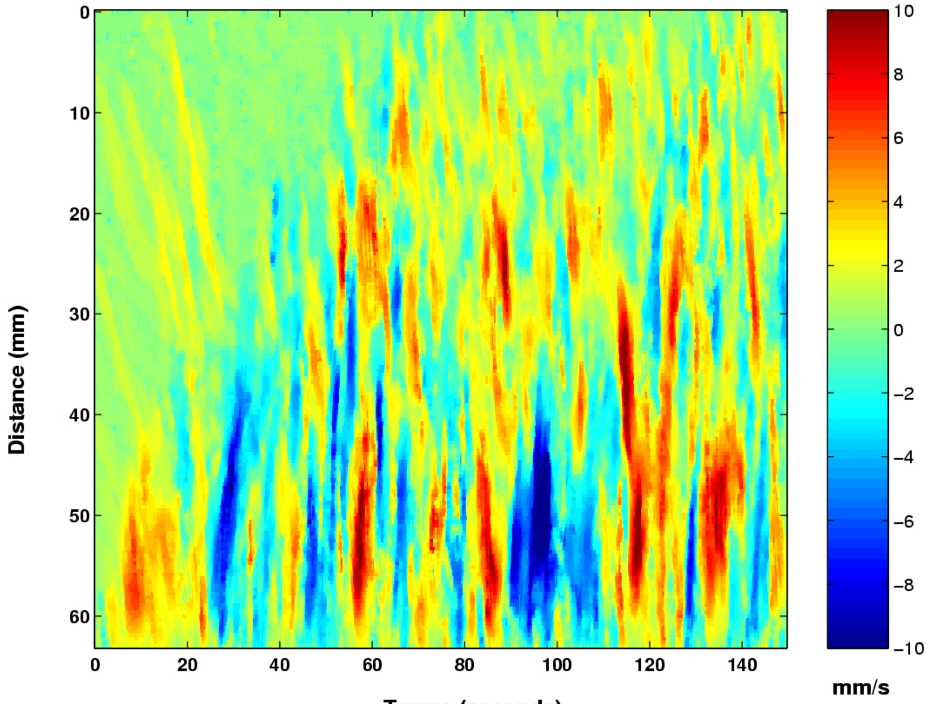
5 litres of gallium, up to 1000 tpm.

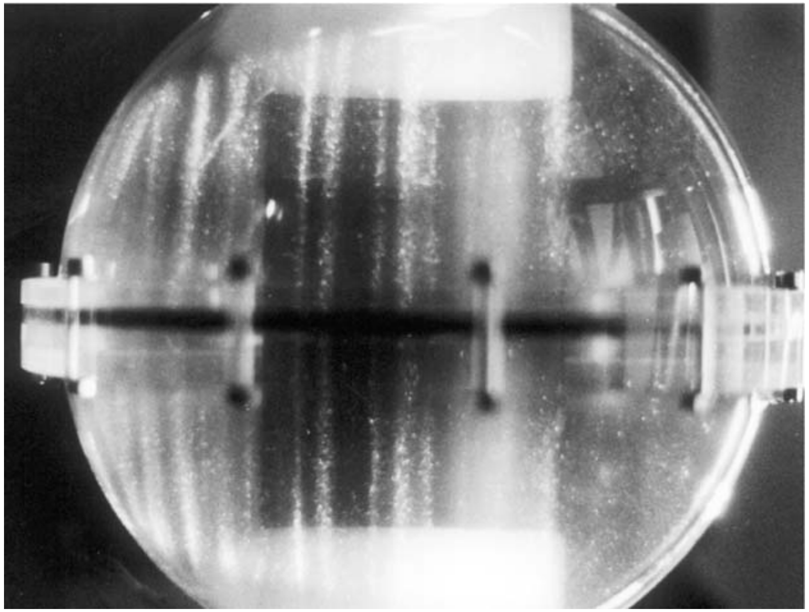


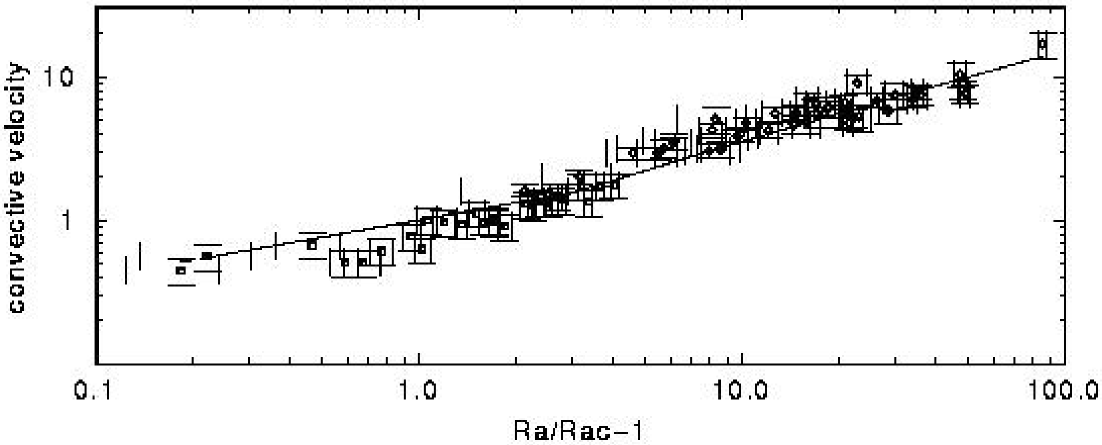


(Aubert et al., 2001)

Ultrasonic velocity measurements



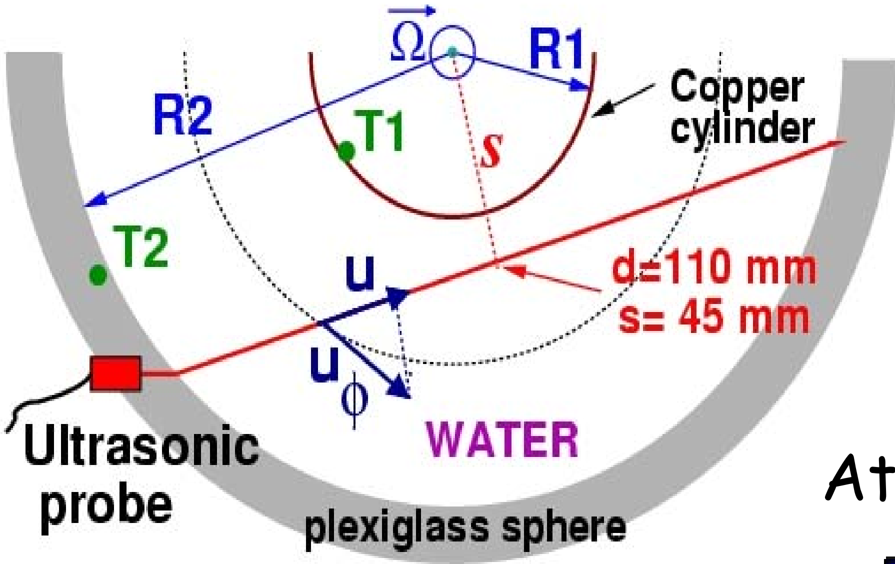




(Aubert et al, 2001; Aubert et al., 2003)

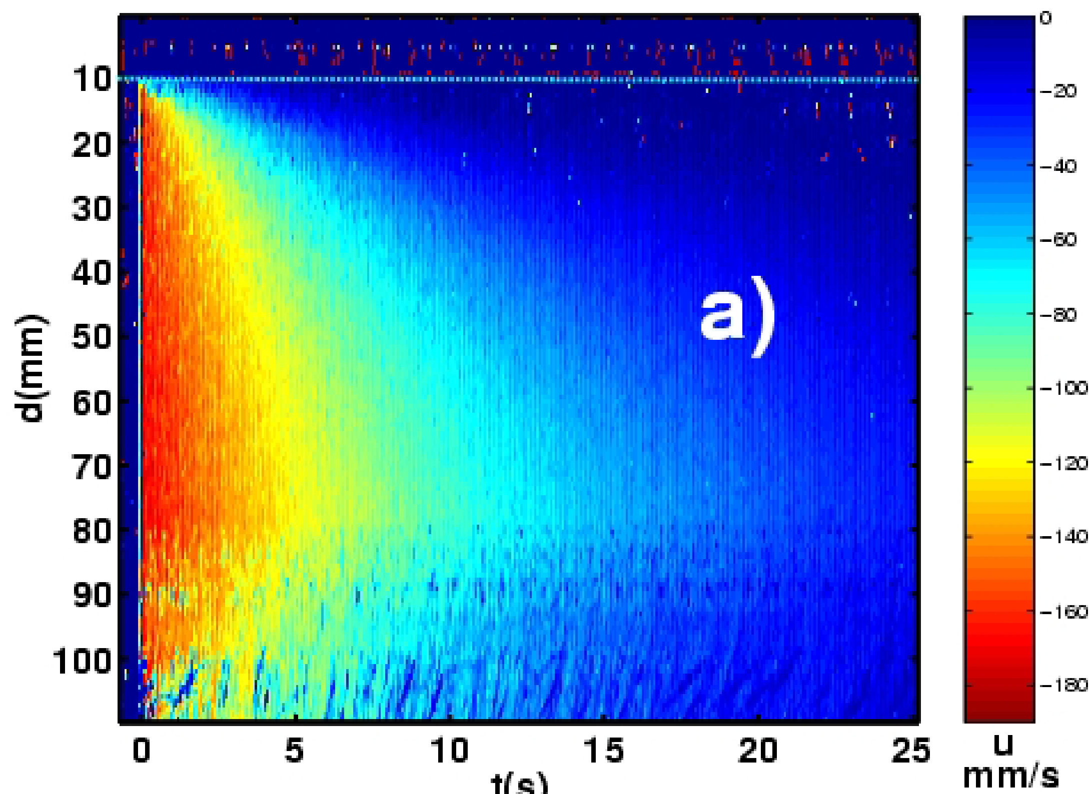
$$\frac{U_{conv}}{\Omega D} = \left(\frac{\alpha g F}{\rho C_p \Omega^3 D^4}\right)^{2/5}$$

Viscosity measurement



Spin-up experiment

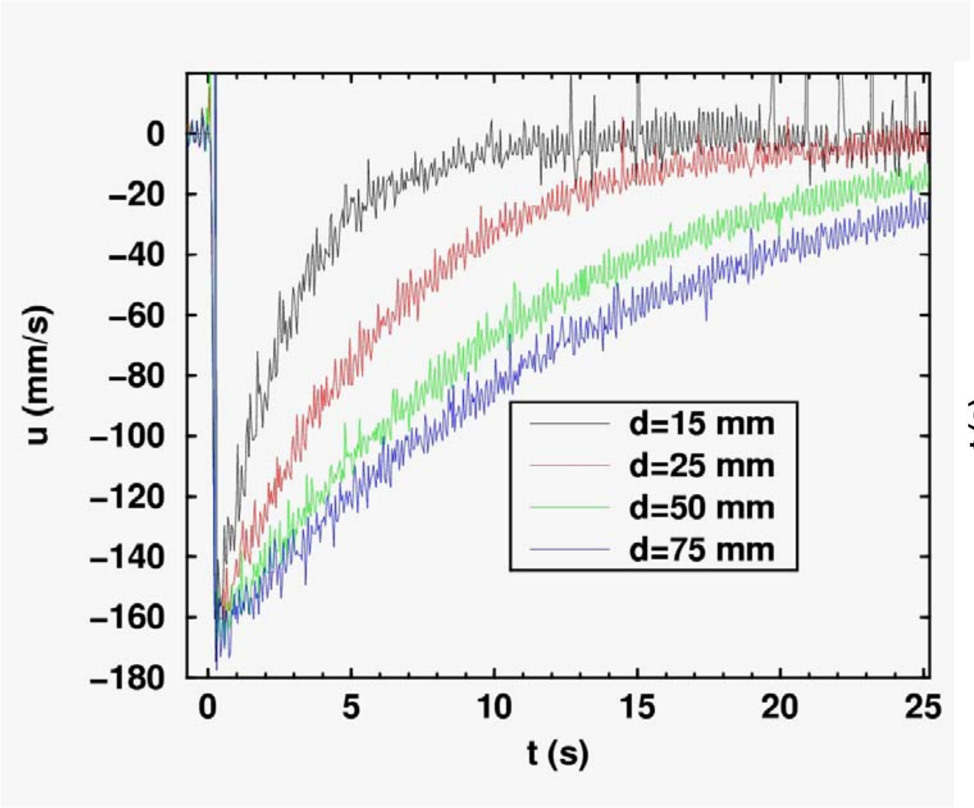
At t=0, Ω =300 rpm --> Ω=340 tpm

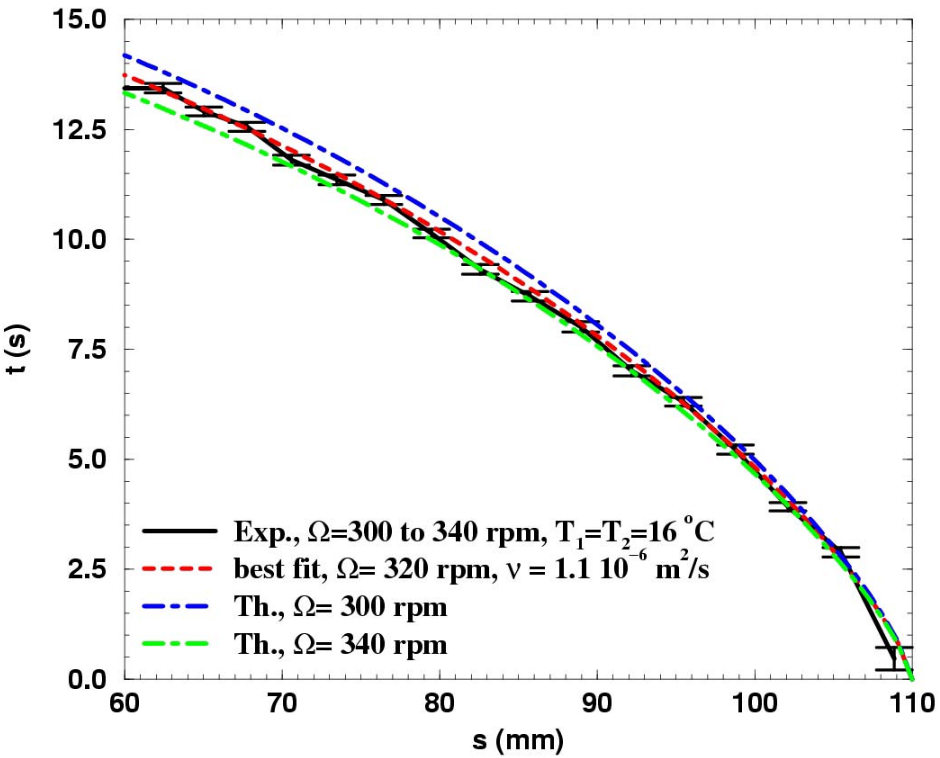


Brito et al, 2003

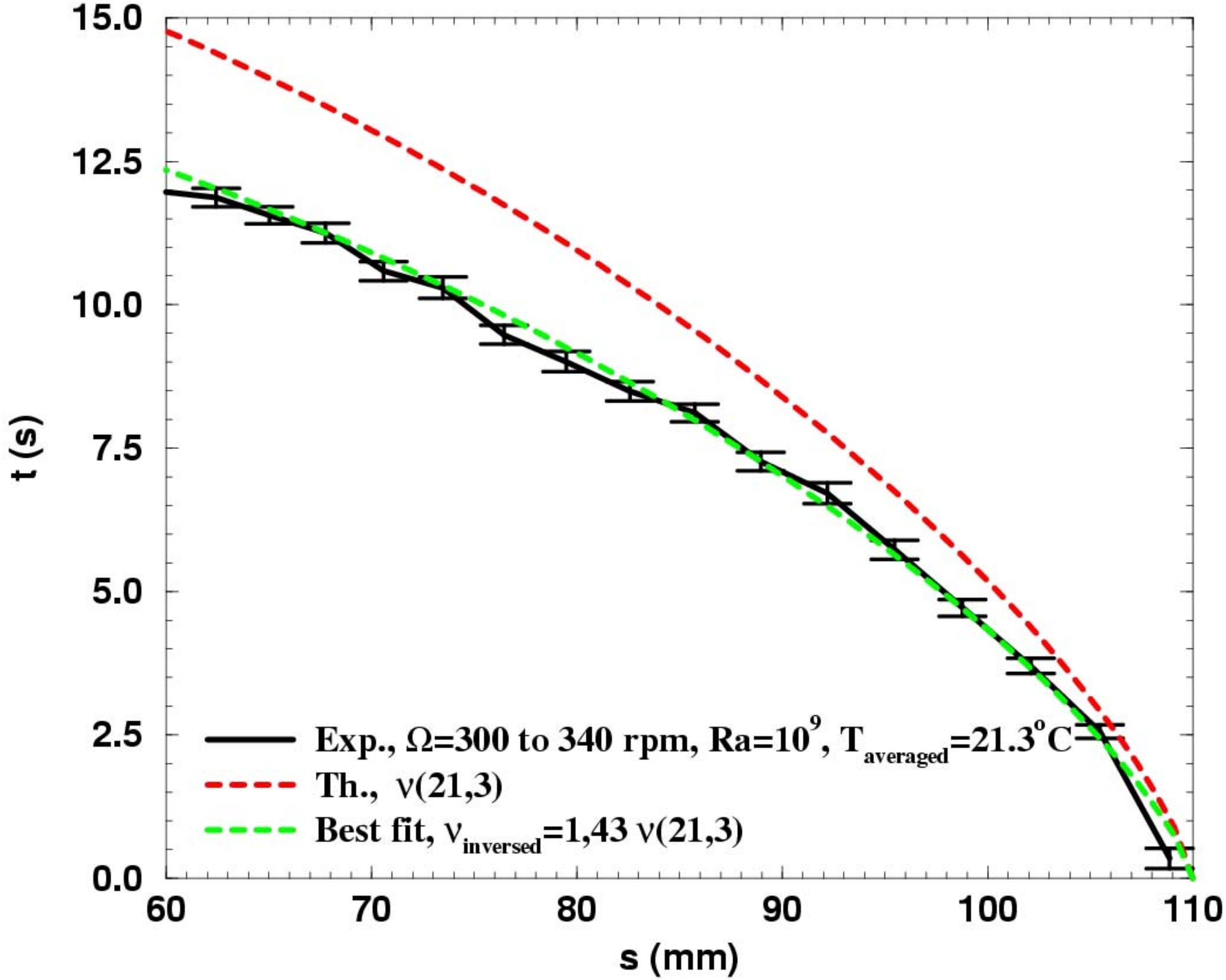
(Greenspan, 1968) theory

$$u_\phi(s,t) = s\Delta\Omega \, \exp\left[- \frac{t}{E^{-1/2}\Omega^{-1}(1-s^2/R^2)^{3/4}} \right]$$

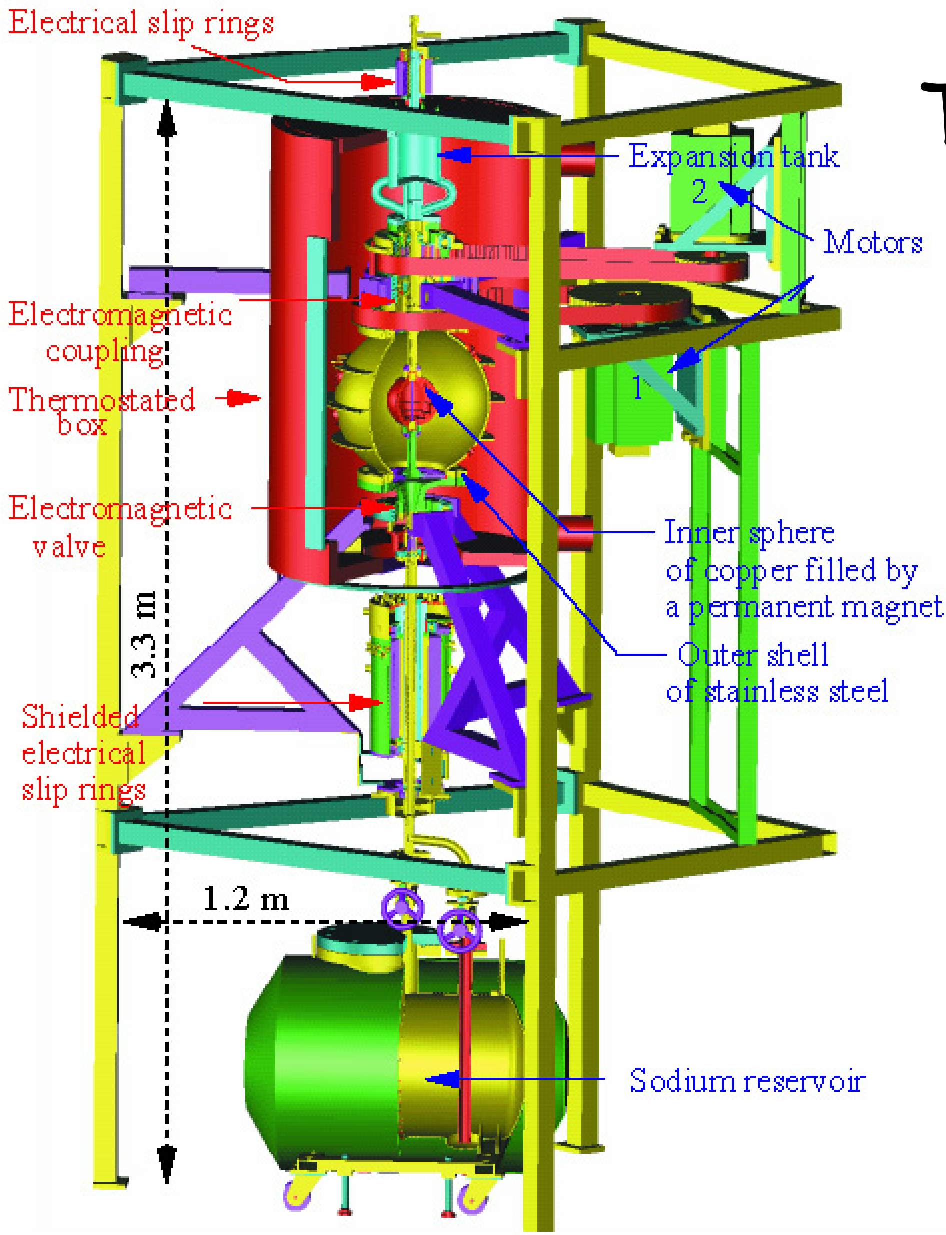




Turbulent viscosity measurement



The DTS experiment



Spherical Couette experiment

45 litres of Na, 2*10 kW
Rm < 30

(Cardin et al., 2002)

A magnetostrophic experimental dynamo: A planetary dynamo model

$R_m = 100$

$a = 1$ m

Power = 600 kW

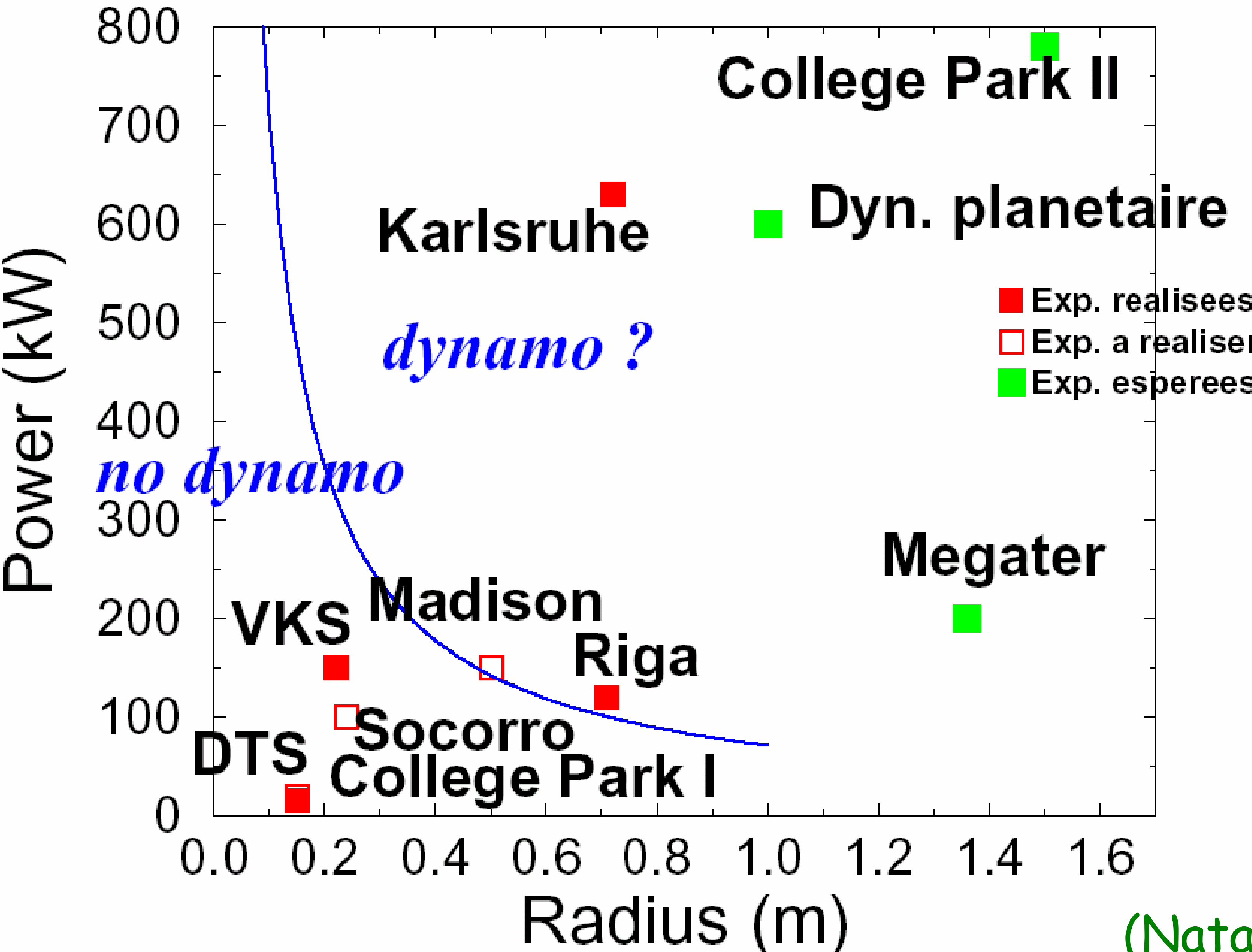
$\Omega = 450$ rpm

$\Delta\Omega = 150$ rpm

$B = 0.3$ T

(Cardin et al., 2002)

Conclusion ?



(Nataf,2003)