New Mexico Dynamo Experiment: an Experiment to Demonstrate αω-dynamos in Accretion Disks

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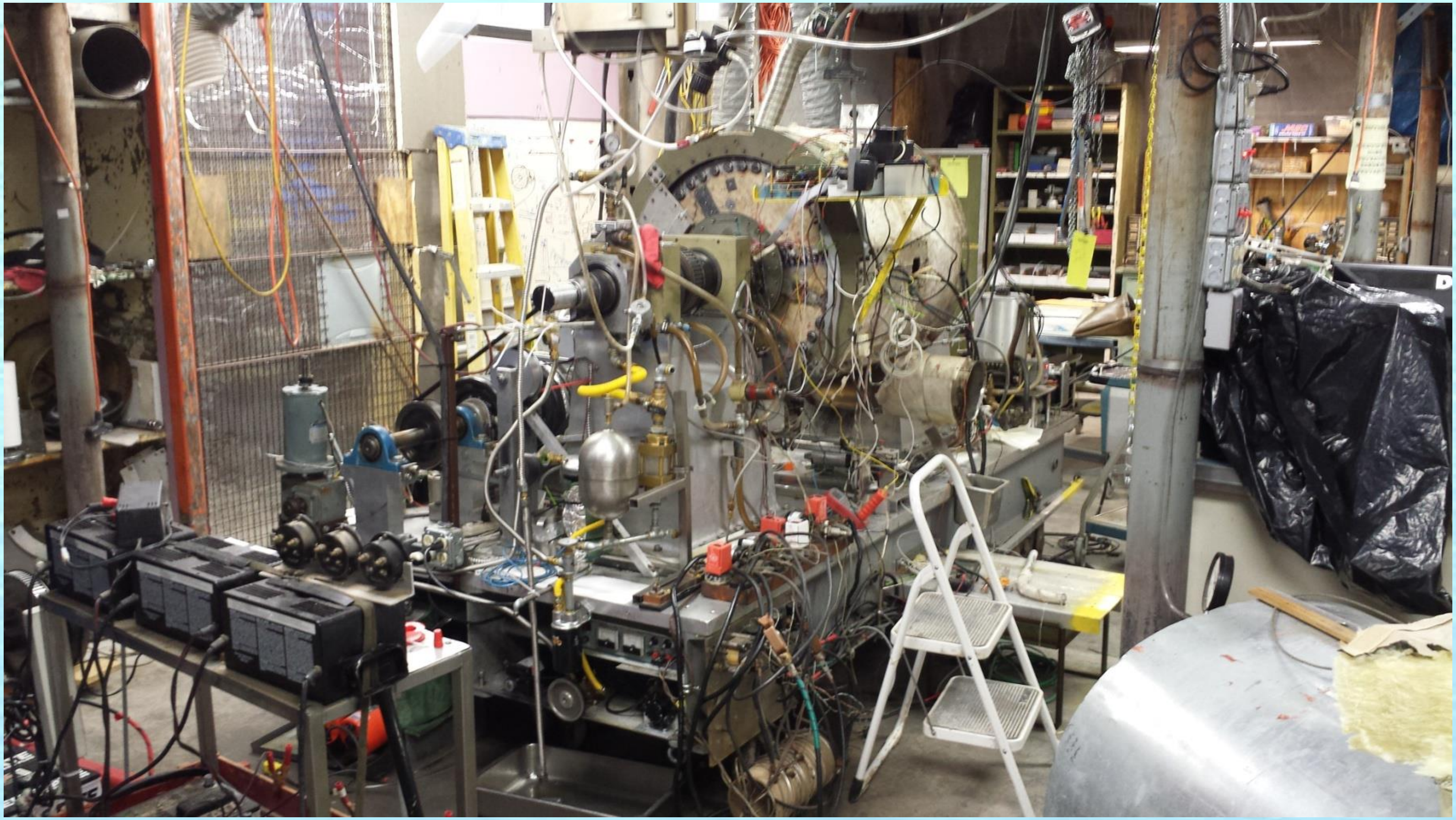
New Mexico Liquid Sodium Dynamo Today !



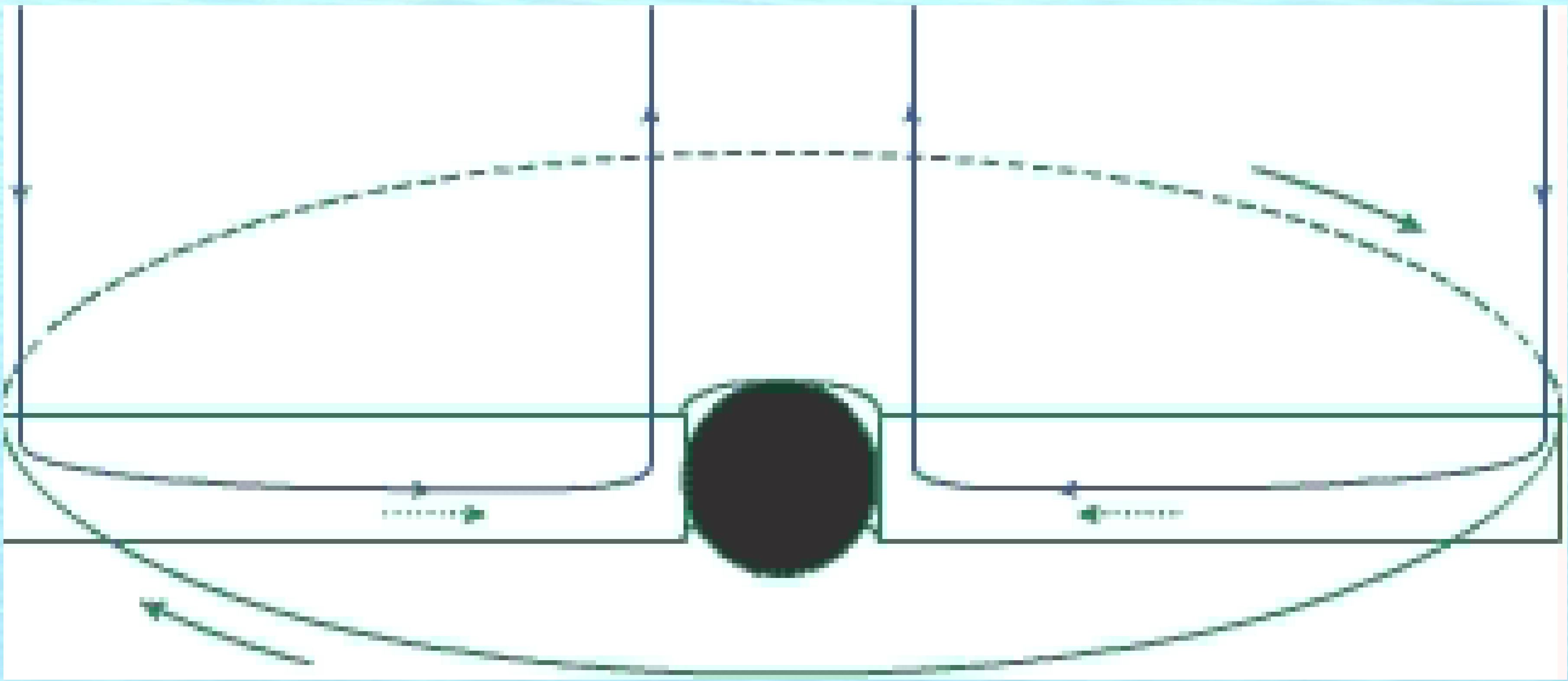
Outline

- New Mexico liquid sodium αω-dynamo experiment is based on a star-disk collision model.
- Apparatus for ω-phase has been set up with Re up to 1.0×10^7 and Rm up to 94.
- X8 ω–gain has been obtained in near-stable Taylor-Couette (TC) flows.
- Recently, ω–gain and β-effect have been investigated in turbulent TC flows.
- The α-phase is being planned, as well as DAQ system upgrade.

New Mexico Liquid Sodium Experiment is for demonstrating how magnetic fields are generated by flowing conducting fluids based on a Star-disk collision model

Seed poloidal field $\xrightarrow{\omega\text{-effect: differential rotation}}$ Toroidal field

α-effect: plumes created by star-disk collisions

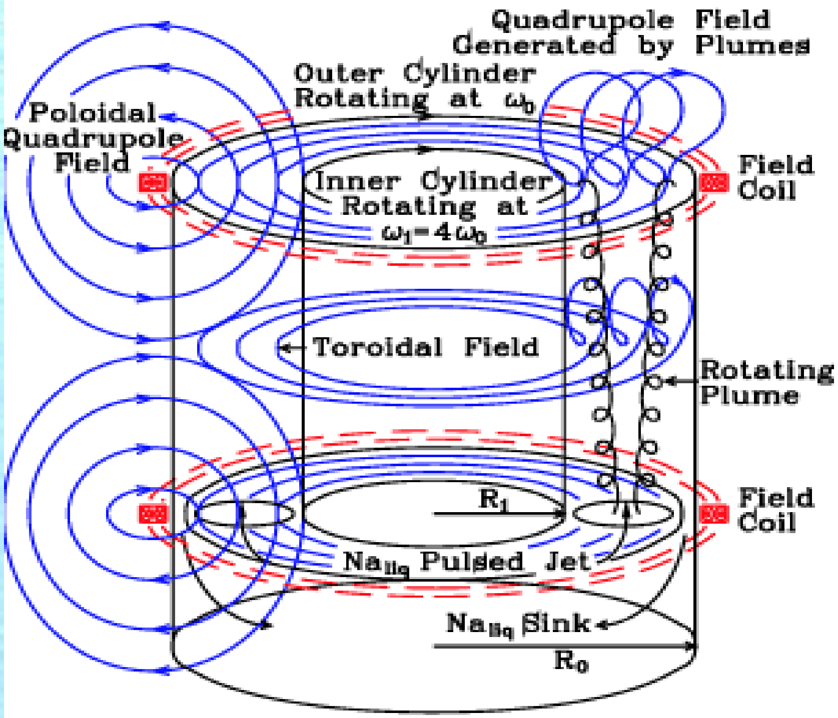


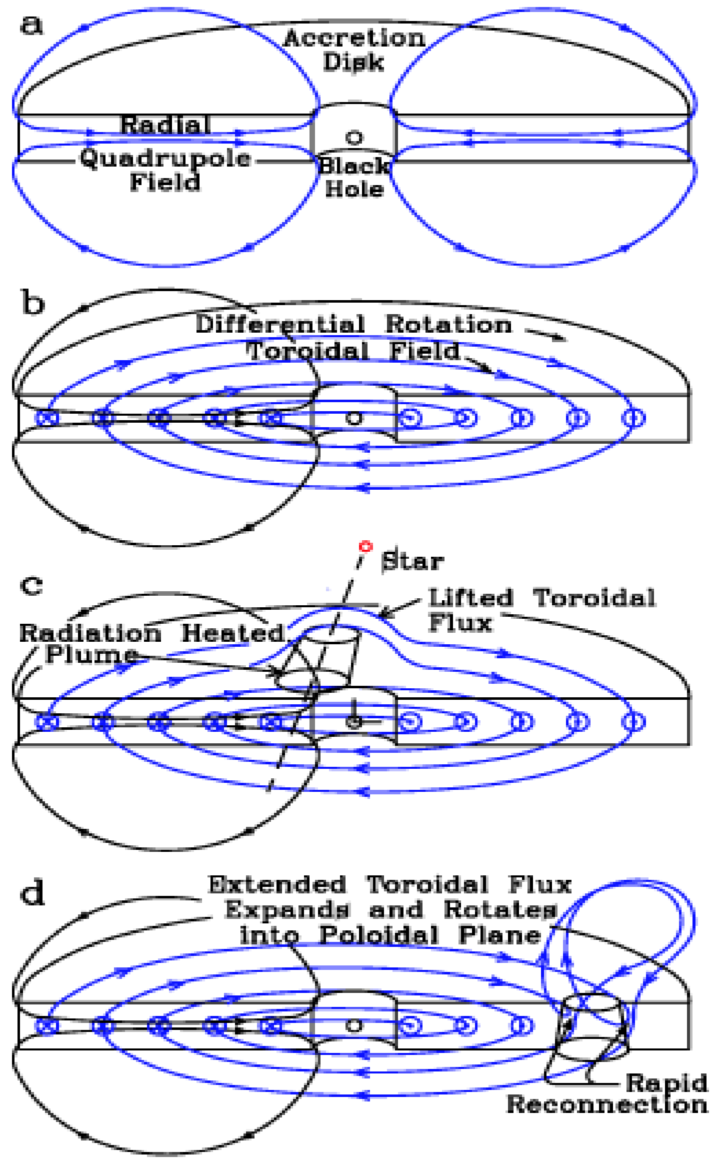
Our experiment

Liquid Sodium $\longrightarrow$ plasma

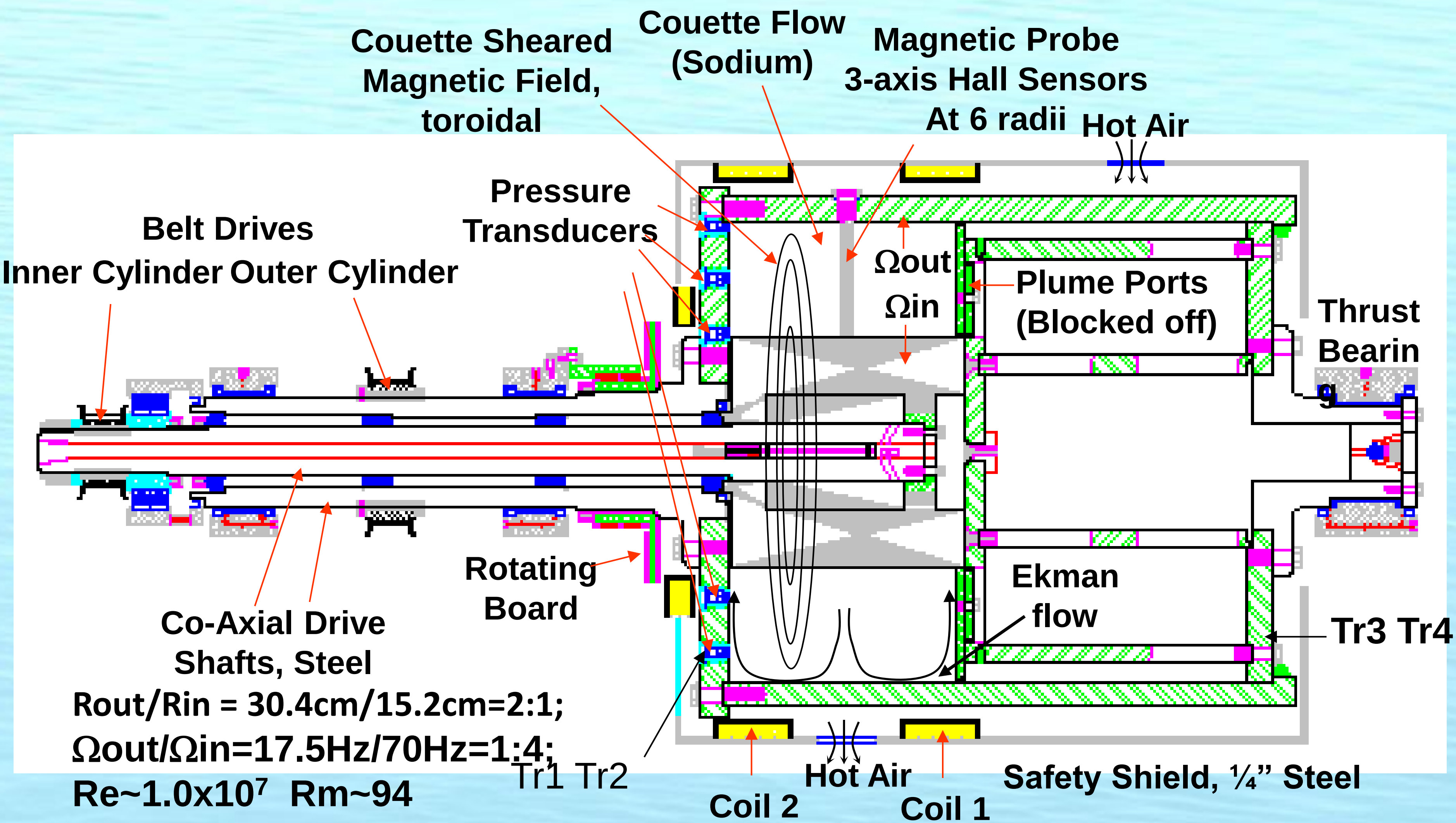
Taylor-Couette flow $\longrightarrow$ ω-effect

Plumes created by Jets $\rightarrow$ α-effect





Schematic of the apparatus



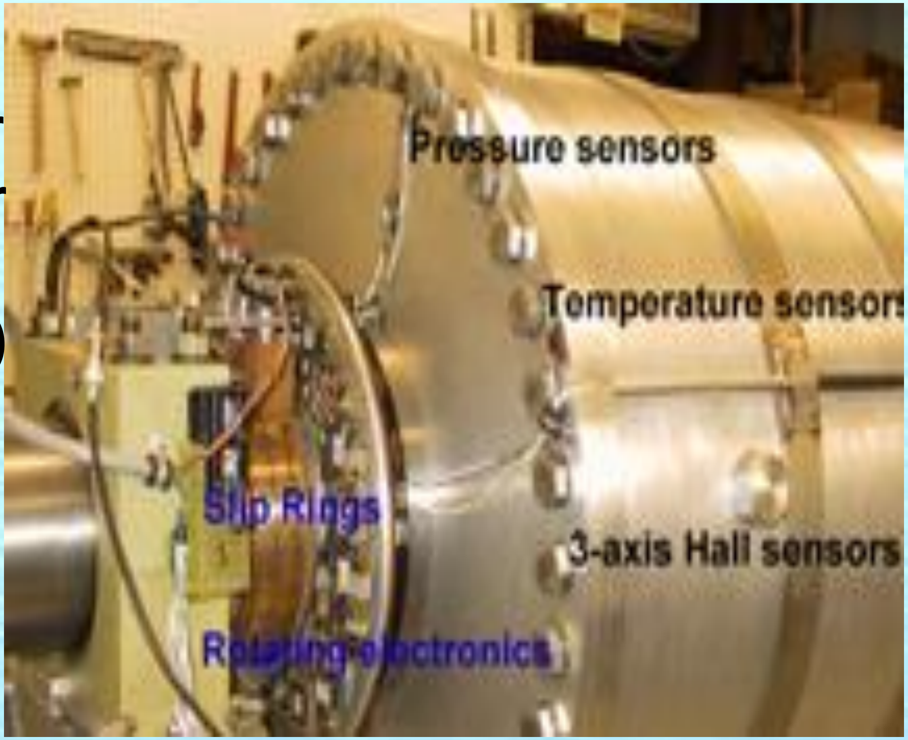
Rout/Rin = 30.4cm/15.2cm=2:1;

Ωout/Ωin=17.5Hz/70Hz=1:4;

Re~1.0x10^7 Rm~94

Key parameters of the NM dynamo experiment

Outer cylinder: 0.6 meter diameter
Inner cylinder: 0.3 meter diameter
Working fluid: liquid sodium.
Speed: 70 (inner) & 17.5 Hz (outer)
Stable Couette flow, Re = 1.0x10^{7},
Rm = 94 at T = 110^{o}C.



$$\mathrm{Re} = (\omega_{in} - \omega_{out})(R_{in} - R_{out})^2 / \nu$$

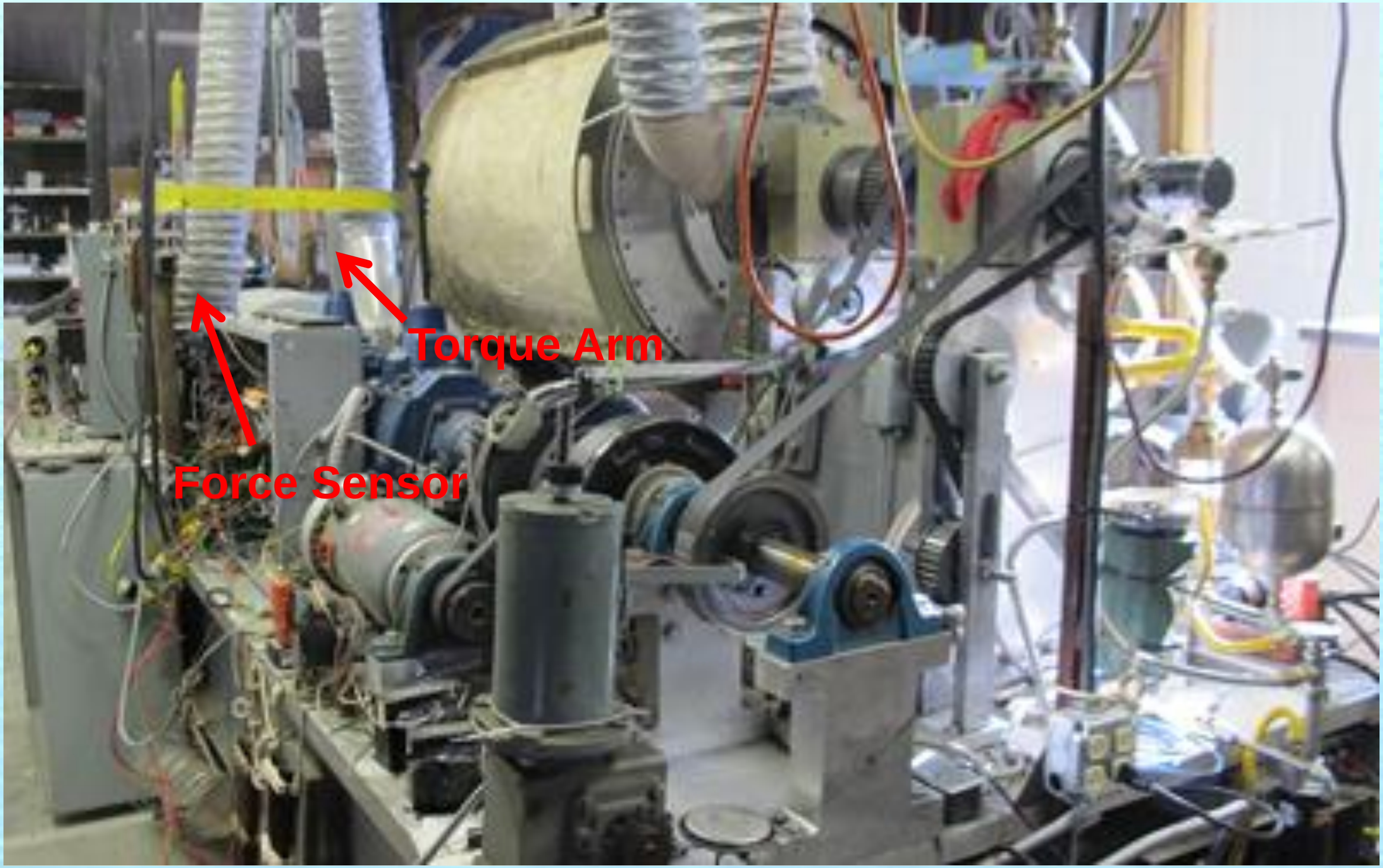
$$Rm = (\omega_{in} - \omega_{out})(R_{in} - R_{out})^2 / \eta_m$$

The ω-gain (B_{Φ}/B_{r0}) is up to x8 in near-stable TC flows when both cylinders spin at 68 (inner) and 17.5 Hz (outer) (Rm = 94)

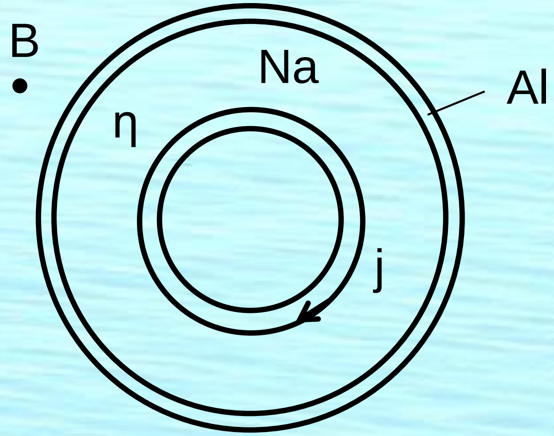
S. A. Colgate, H. Beckley, J. Si, etc, Phys. Rev. Lett. 106, 175003 (2011)

Measurement at 68 and 17.5Hz has been repeated later, similar result has been obtained.

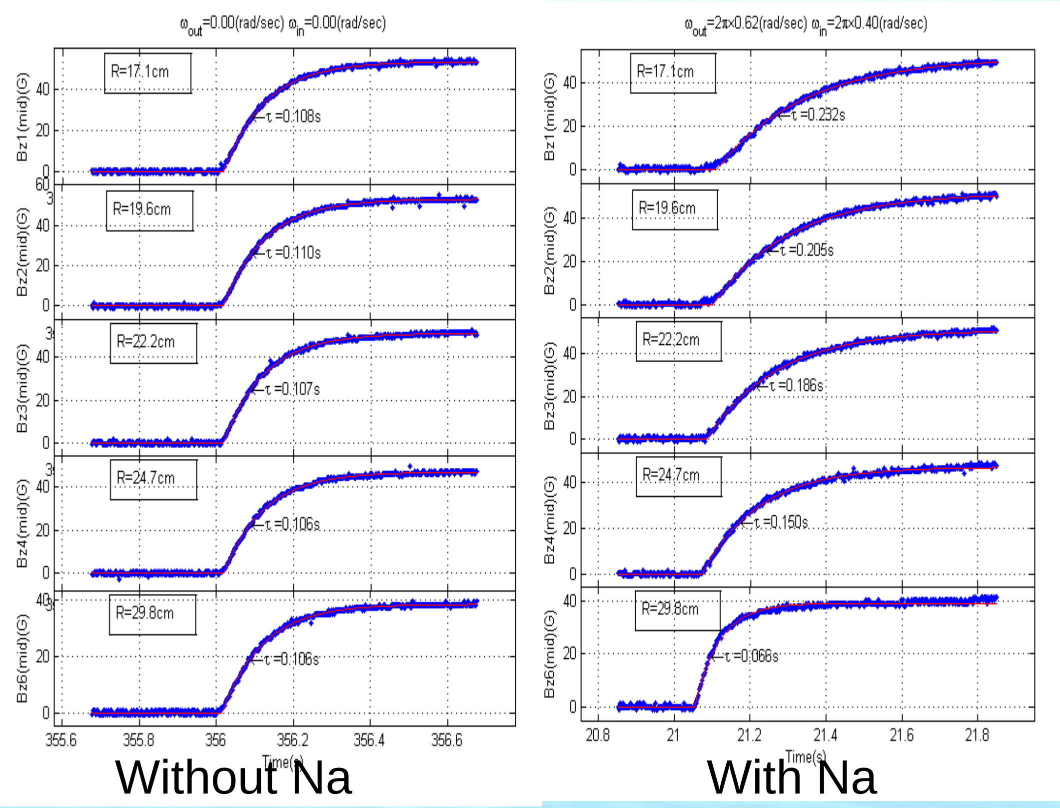
Turbulent resistivity has been studied in highly turbulent flows by letting the outer cylinder stationary



Two methods are used: #1. Turbulent resistivity in perpendicular direction can be inferred by measuring the rise time τ of magnetic field inside the flow when an external axial field is applied.



Higher η, shorter τ
Smaller R, longer τ



Note the induced j is in the azimuthal direction. Which means decay/rise time is determined by

$$\eta_{\perp}^{turb}$$

For infinitely long cylinder

$$B_z(t,r) = B_0 - \sum_{n=1}^{\infty} \frac{2B_0}{k_n J_1(k_n)} J_0(k_n r/R)\, e^{-\frac{\eta}{\mu_0}\frac{k_n^2}{R^2} t}$$

Two methods are used: #2. ω-gain measurement infers the effect of turbulent resistivity in the direction parallel to the rotation axis.

ω-gain vs Rm can be measured as

$$\omega - \text{gain} = f(\Omega_{in})$$

With a quadrupole B configuration, Bθ is mostly determined by

$$j_z = U_\theta B_r / \eta_{//}^{turb}$$

If turbulent resistivity is strong and related to Ω_{in}.

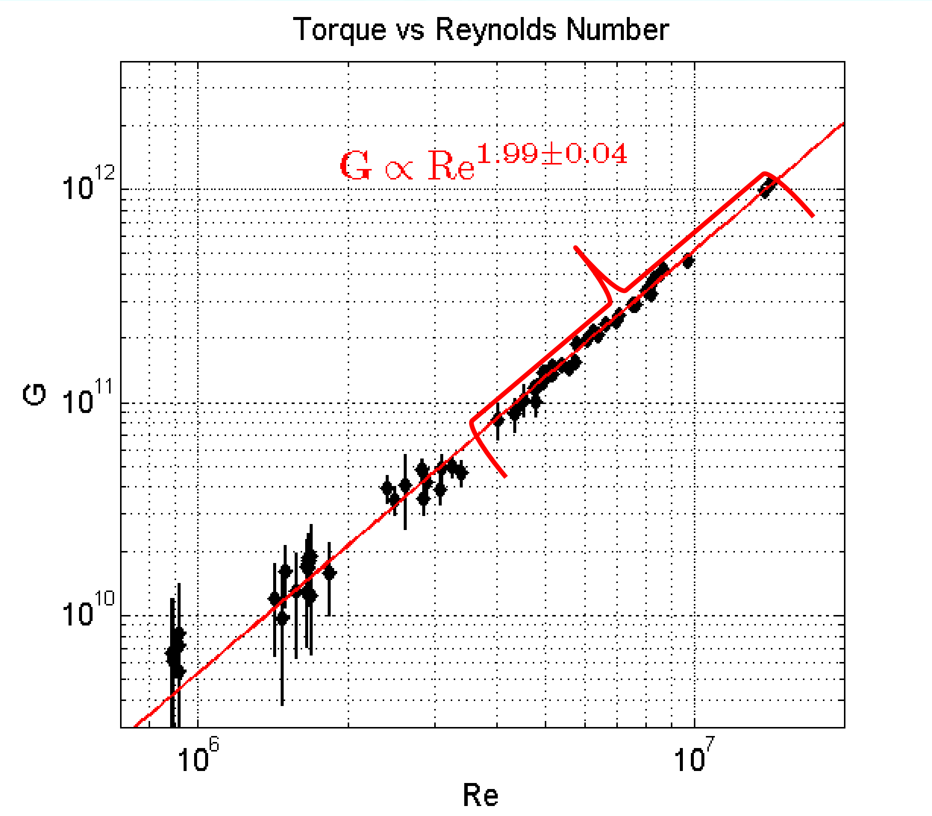
$$\omega - \text{gain} \propto Rm, eff \propto \frac{\Omega_{in} R_{in} \Delta R}{\eta_{Na} + \eta_{turb}}$$

ω-gain vs Ω_{in} relation is nonlinear.

On the other hand, if $\eta_{//}^{turb}$ is weak, then

$$\omega - \text{gain} \propto \Omega_{in}$$

Turbulent resistivity for the isotropic homogeneous approximation case can be examined by Torque vs Re



$$\eta^{\mathrm{turb}} \approx 2.02\times10^{-14}\,\mathrm{Re}\quad \mathbf{\Omega.m}$$

At 48Hz (inner), for sodium at 110°C,

$\mu_0\beta$=2x10^{-7}~2η_{Na}

When the outer cylinder is stationary, non-dimensional torque

$$\boxed{G=\frac{T}{\rho\nu^2 L}\propto \mathrm{Re}^2}$$

Measured Power dissipation rate per unit mass

$$\boxed{\varepsilon=\frac{T\Omega_{in}}{M}\propto \mathrm{Re}^{\alpha+1},\quad \alpha\cong 2}$$

Homogeneous isotropic turbulence

$$\boxed{\varepsilon\propto\frac{u^3}{\Delta R}}$$

Mean-field dynamo theory

$$\boxed{\beta=\frac{1}{3}u^2\tau_{corr}\approx\frac{1}{3}uL\propto \mathrm{Re}}$$

$$\boxed{\omega-\mathrm{gain}\ \propto \mathrm{Rm},eff\ \propto\frac{\Omega_{in}}{1+C_0\Omega_{in}}}$$

The estimated perpendicular turbulent resistivity is only a few percent of the resistivity of sodium

Without rotation

$$F(t) = f(\eta_{Na} t)$$

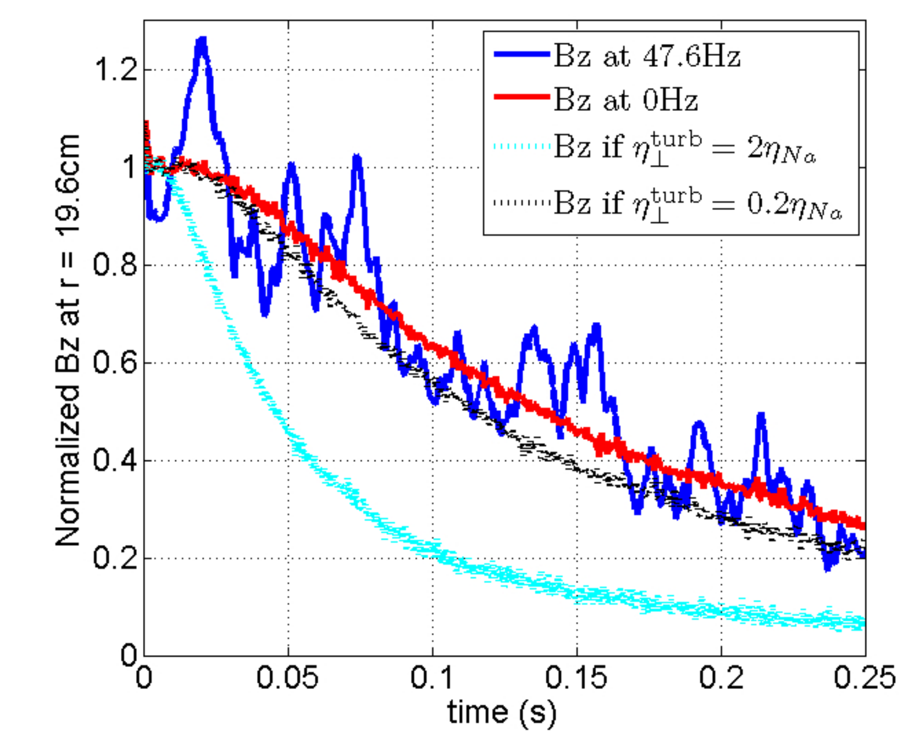
With rotation

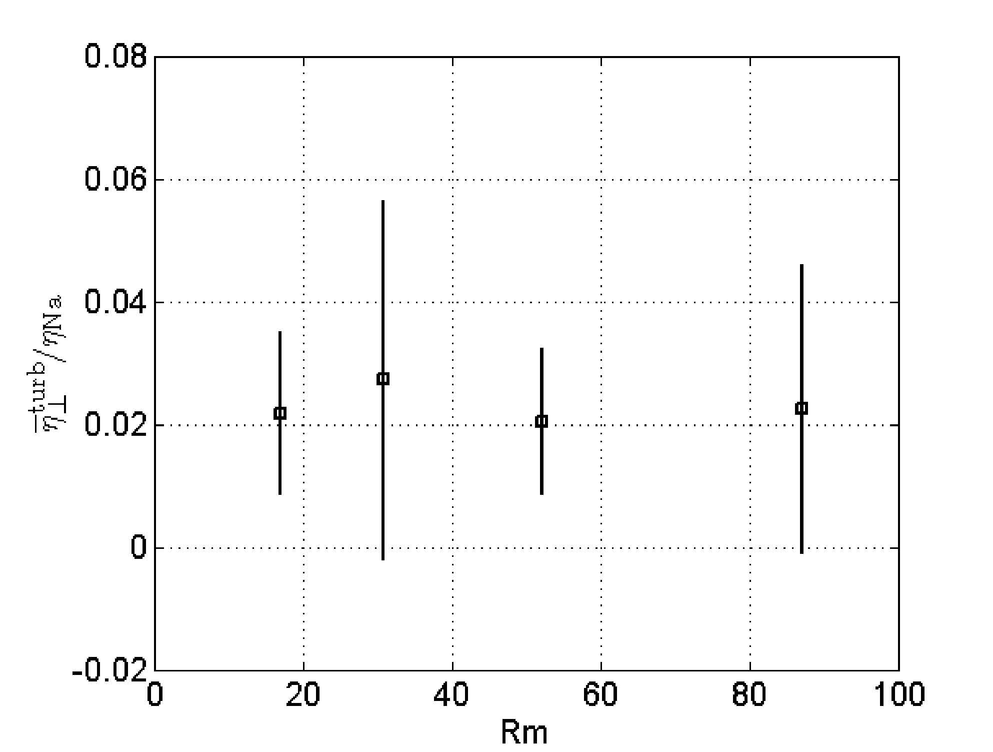
$$G(t) = f(\eta_{\text{eff}} t)$$

Ideally

$$F[(1 + R_\eta)t] = G(t)$$

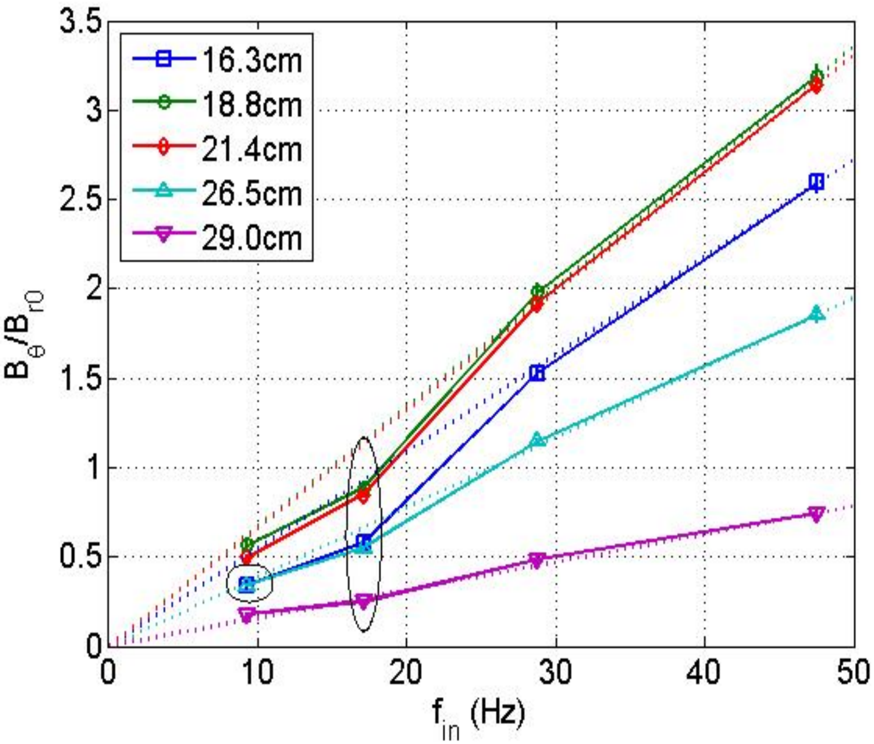
$$R_\eta = \overline{\eta}_\perp^{\text{turb}} / \eta_{\text{Na}}$$

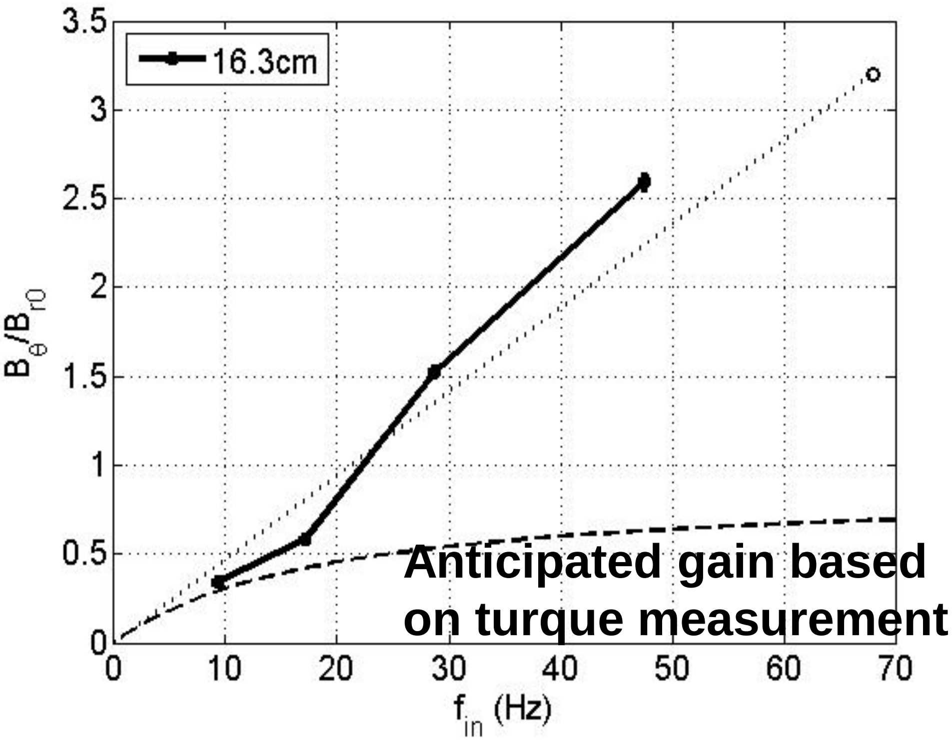




In practical, $\eta_\perp^{turb}$ can be estimated by the least square curve fitting.

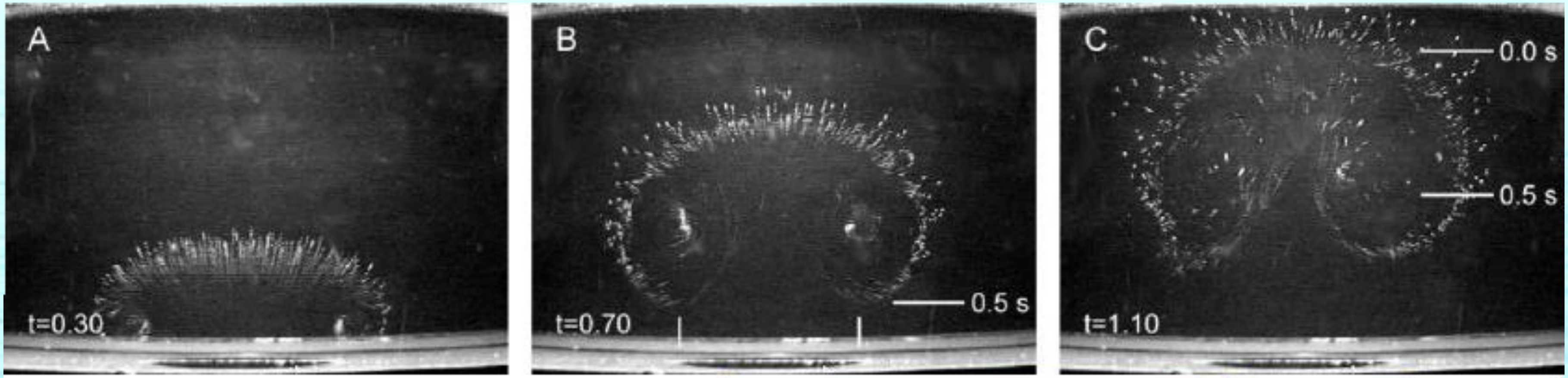
Also ω-gain vs Rm shows linear behavior at high speeds, gain reduction at low speeds. It hints possible anisotropic turbulent resistivity at low speeds. However, $\eta_{//}^{turb}$ is suppressed as speed increases.

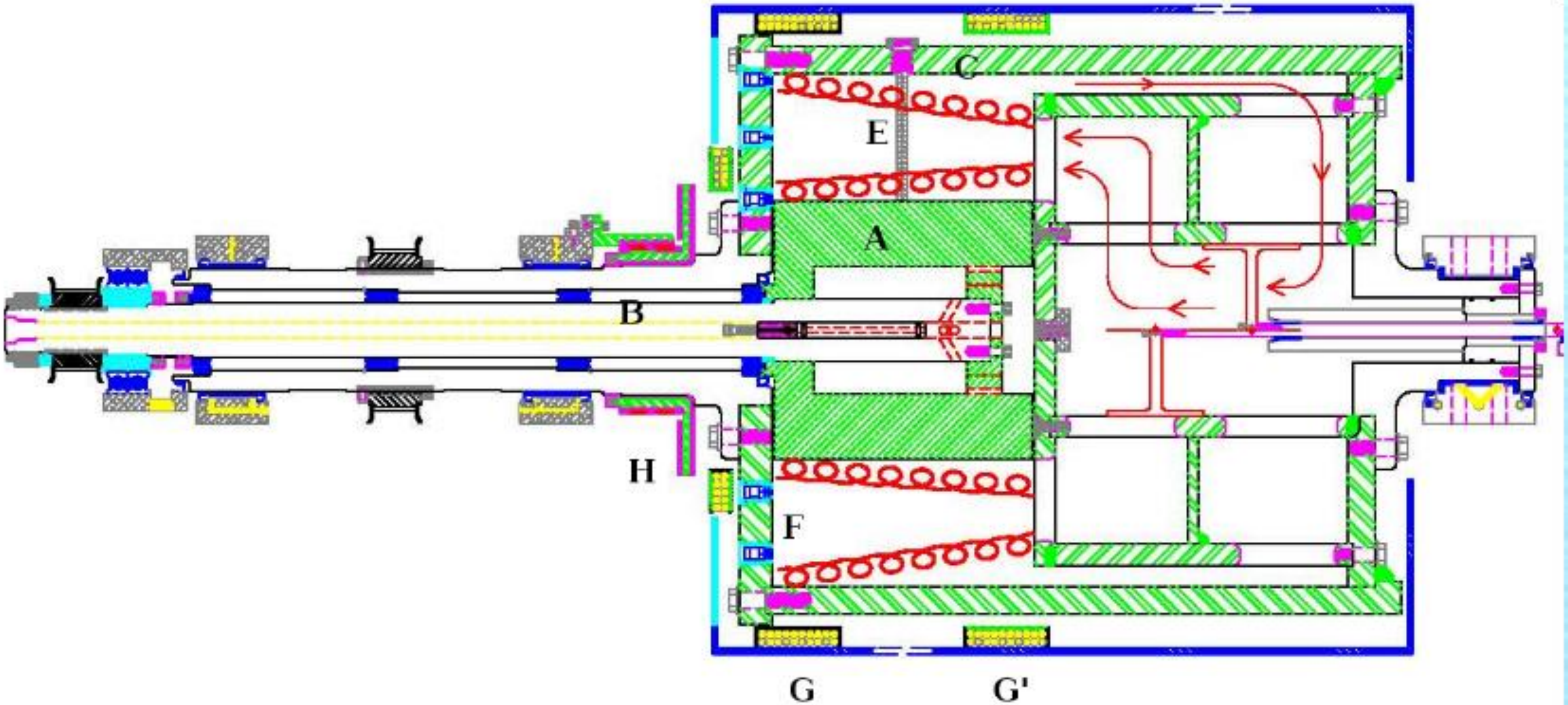




Jiahe Si, Stirling A Colgate, Richard G Sonnenfeld, et al, Physics of Plasmas (1994-present) 22 (7), 072304

The plan for α-phase





New DAQ will use National Instruments modules, data will be transmitted via WiFi from rotating frame

NI single-board computer

+

ADC module

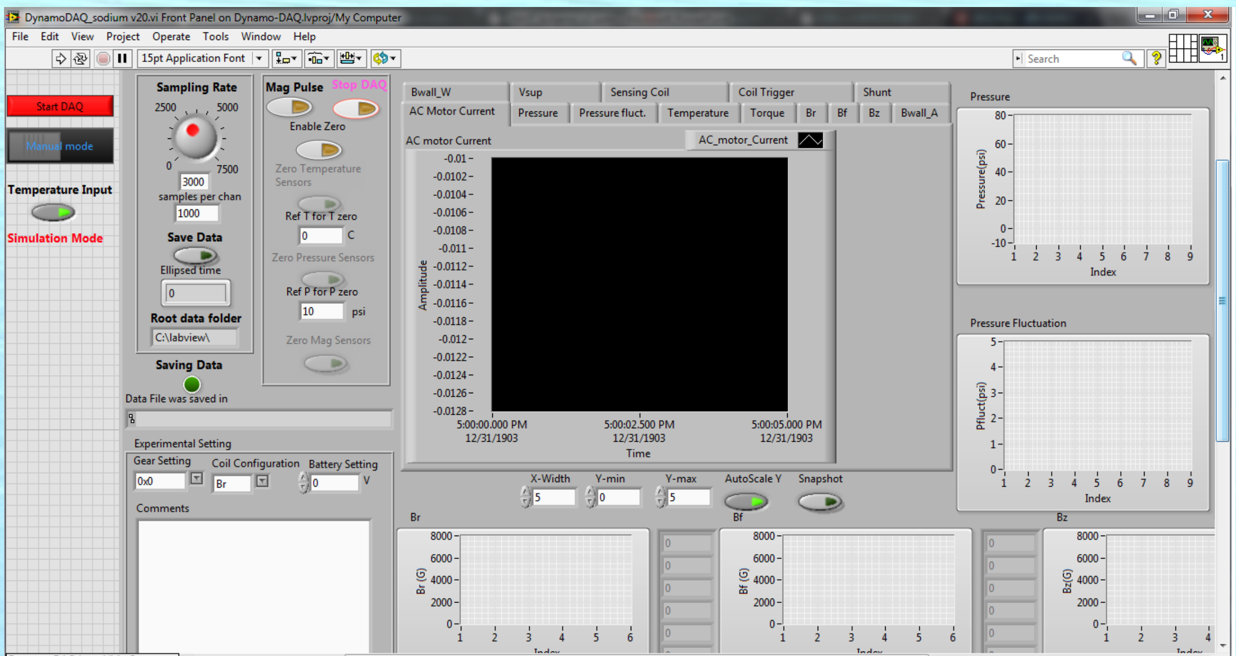
+

WiFi adapter

+

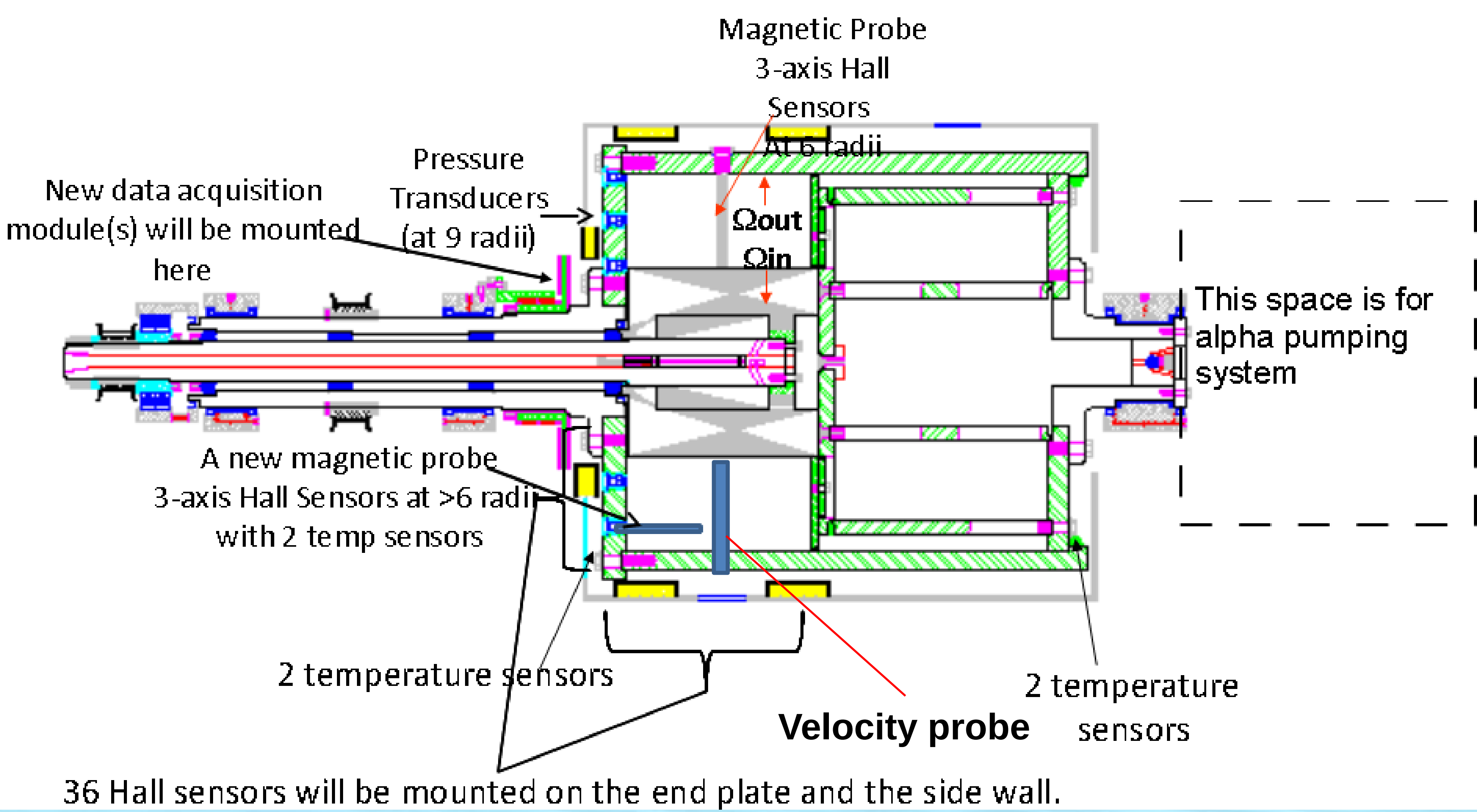
Power supplies, amps, etc

+



Labview DAQ software

The plan for Data Acquisition (DAQ) upgrade



Summary

- X8 ω-gain has been observed. This means a complete $\alpha\omega$-loop can be achieved by converting >1/8 portion of toroidal flux to poloidal direction.
    - Design of α-phrase is underway, NM dynamo provides best chance to demonstrate full alpha-omega loop.
- NM dynamo allows varying the level of turbulence in the fluid to further explore the role of turbulence in dynamos.
- The fluid Re up to 10^7 provides access to a new regime in pure hydrodynamics.

Acknowledge

We gratefully acknowledge

• The funding over the years by NSF, LANL via a cooperative arrangement with NM-Tech, the IGPP program at LANL, and NMT.

• The facilities of NM-Tech, machine shop, administration, EMRTC, CMSO, and many others have made this development possible.

•U-Wisc dynamo group for sharing their knowledge, experience, and donating their equipment.

•National Instruments graciously lent us DAQ hardware and provided consultation for free.

• Many undergraduate students have participated in this project.

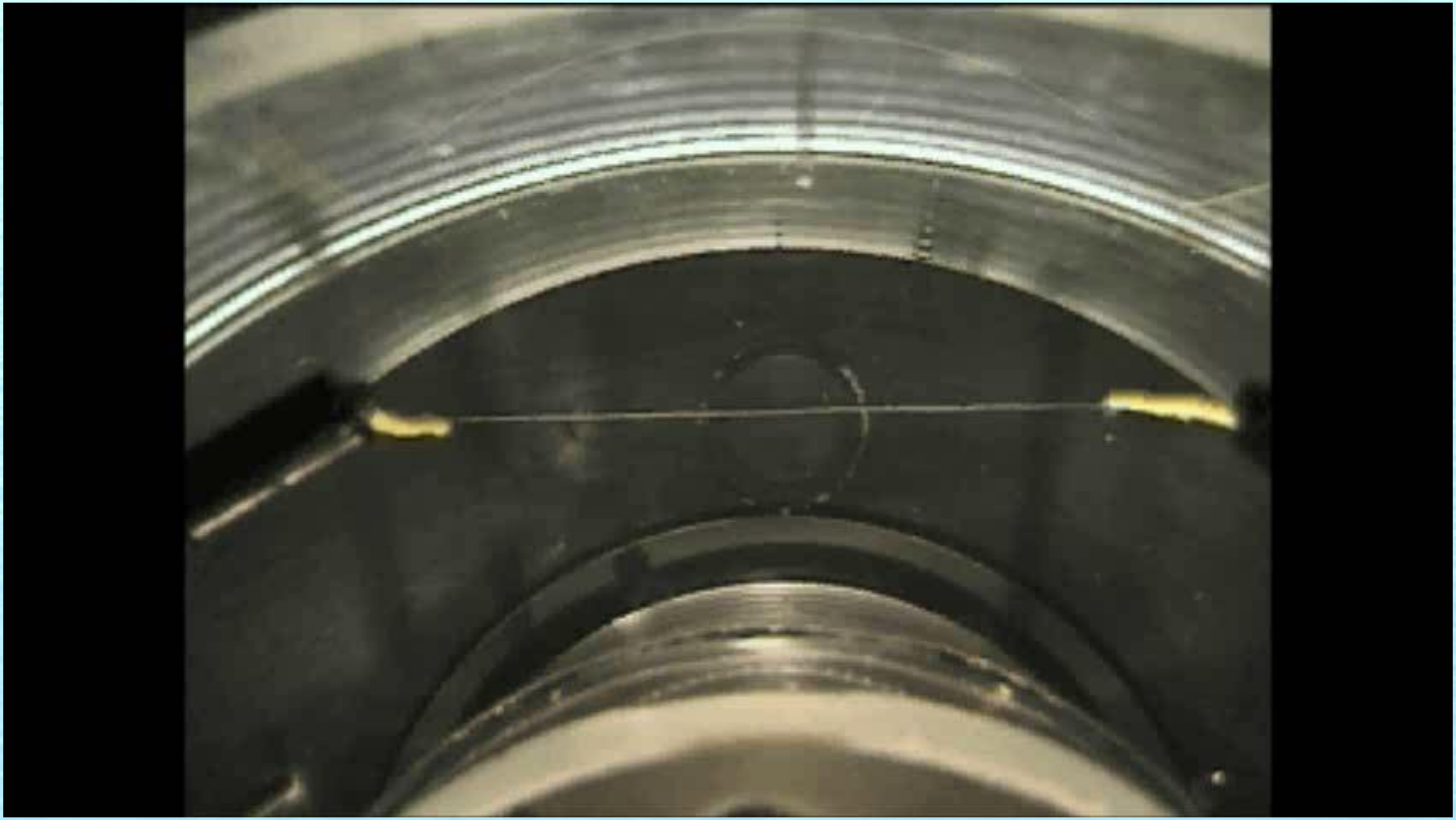
• The LANL/LDRD program and the DoE/OFES via Center for Magnetic Self-Organization.

• The support from 4 private donors.

http://kestrel.nmt.edu/~dynamo/

Or search 'New Mexico Dynamo'

α-helicity has been demonstrated in water experiments



In highly turbulent state, angular momentum profile tends to be flat in the bulk

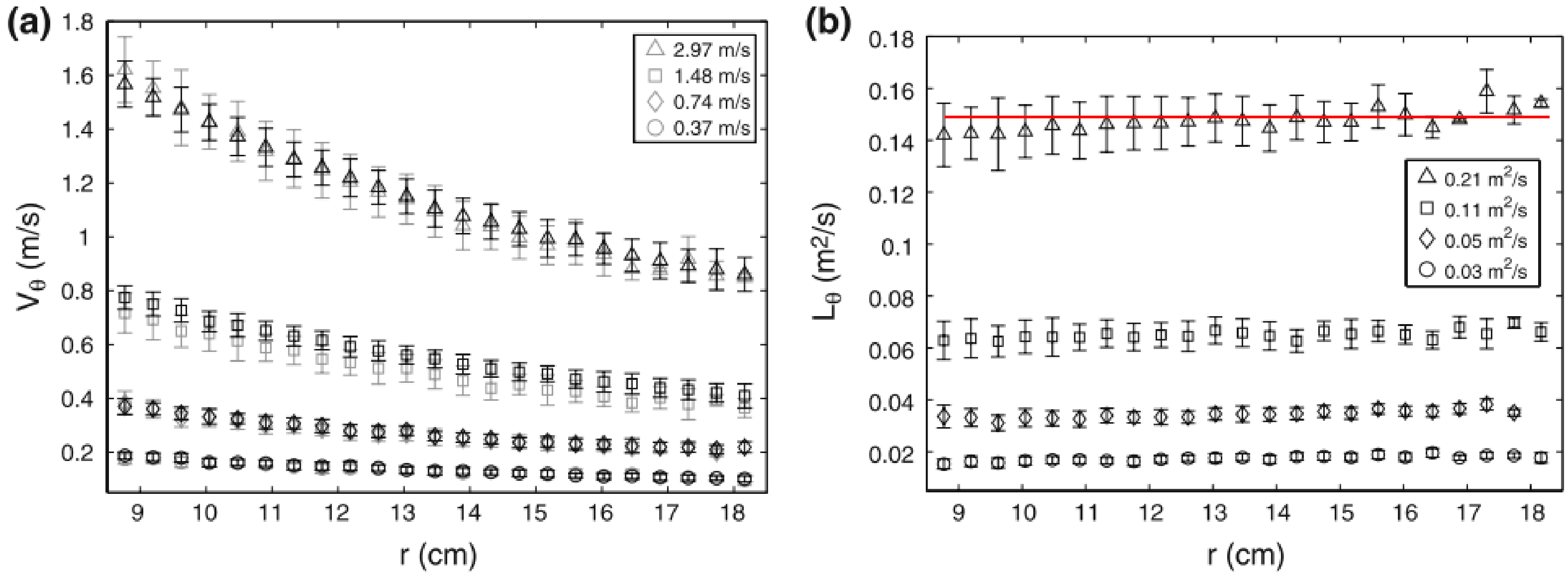
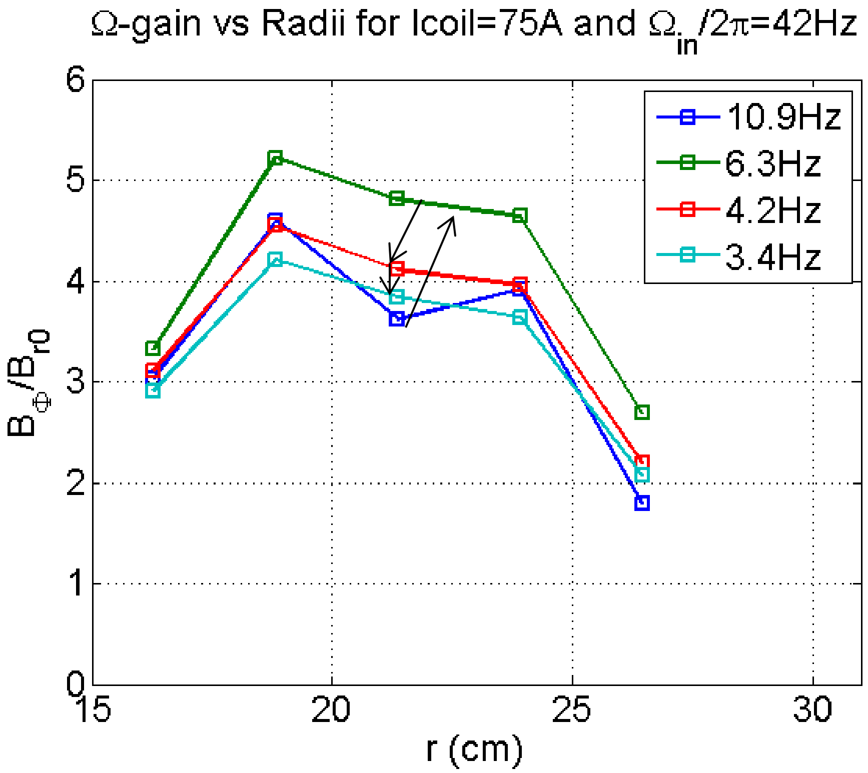
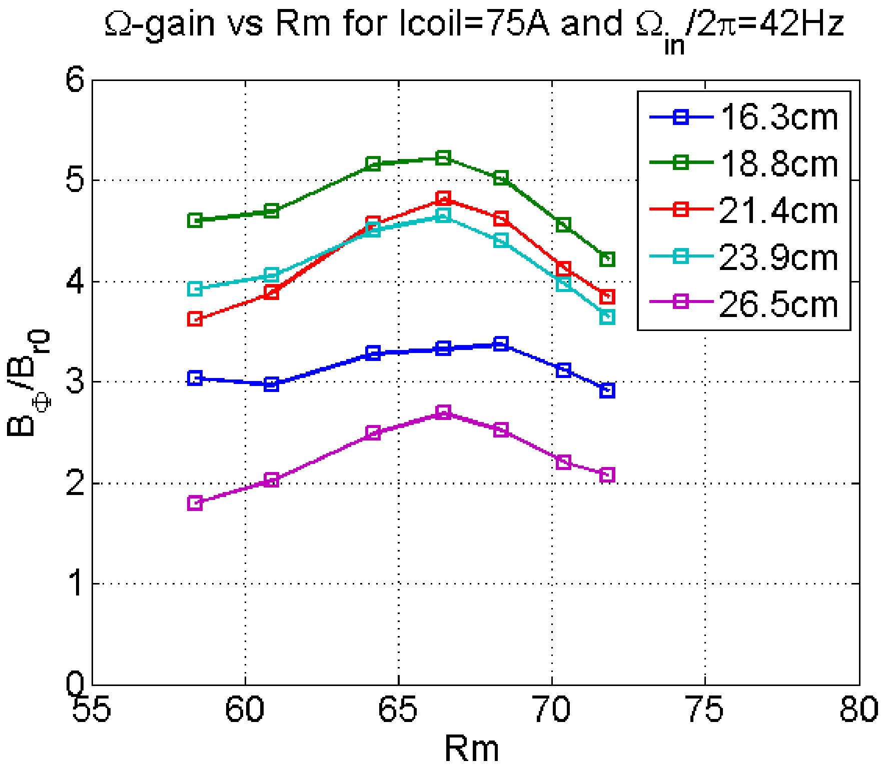


Fig. 3 Mean azimuthal velocity (**a**) and specific angular momentum (**b**) for four characteristic inner cylinder (and *inner ring*) speeds, corresponding to Reynolds numbers of approximately 5×10^4, 1×10^5, 2×10^5, and 4×10^5. Values in the legends represent the rotational surface speed (**a**) and specific angular momentum of the inner cylinder surface (**b**). The velocities from both water and the glycerol mix are overlaid in (**a**); water in *black* and the glycerol mixture in *gray*. All data are from $z = 7$ cm

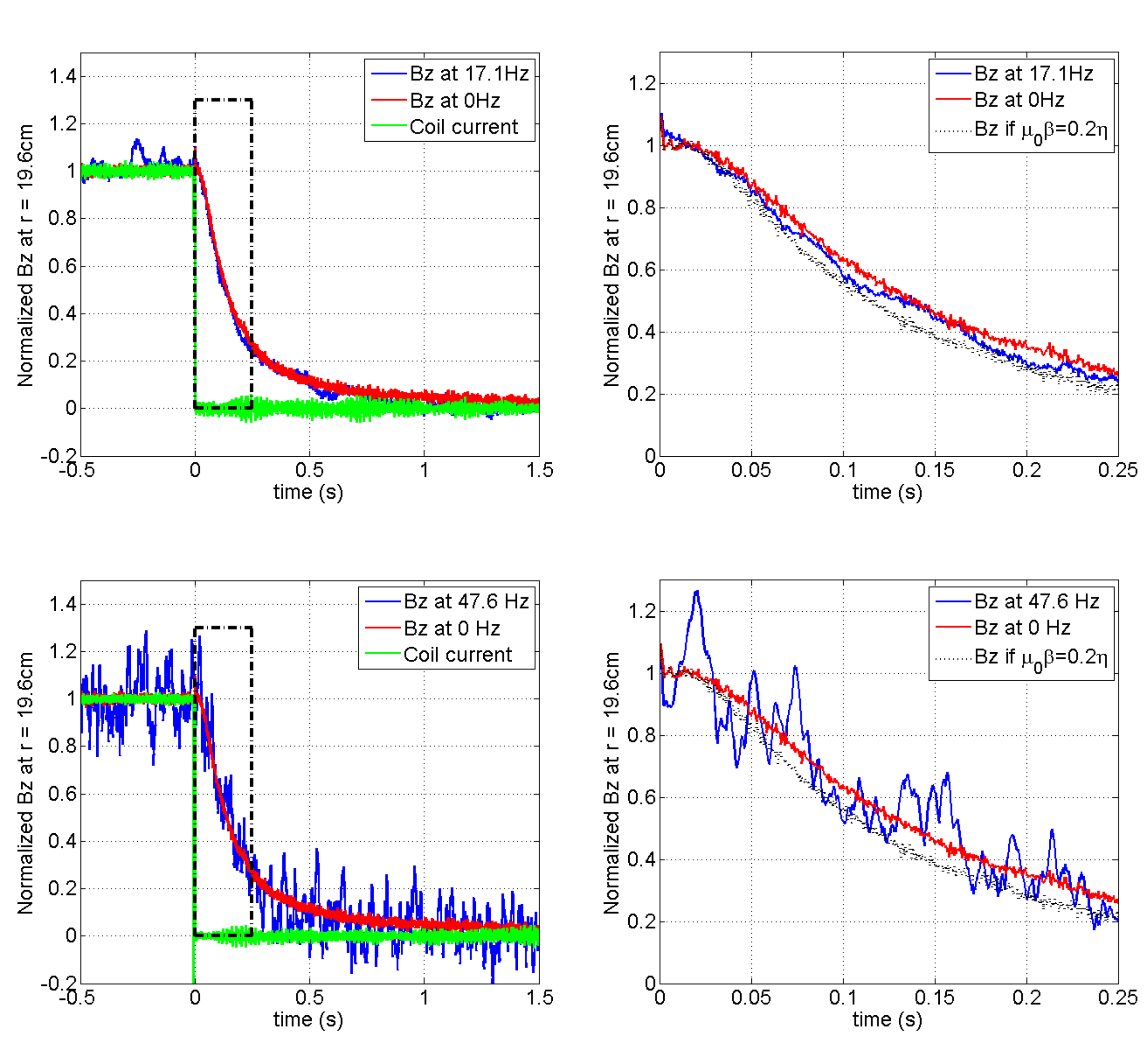
From M.J.Burin, E.Schartman, H.Ji, Exp Fluids 2010
There are also simulations, e.g. H.J.Brauckmann and B.Echhardt, J. Fluid Mech. (2013)

The ω-gains were also measured by spinning down the outer cylinder to make the flow unstable

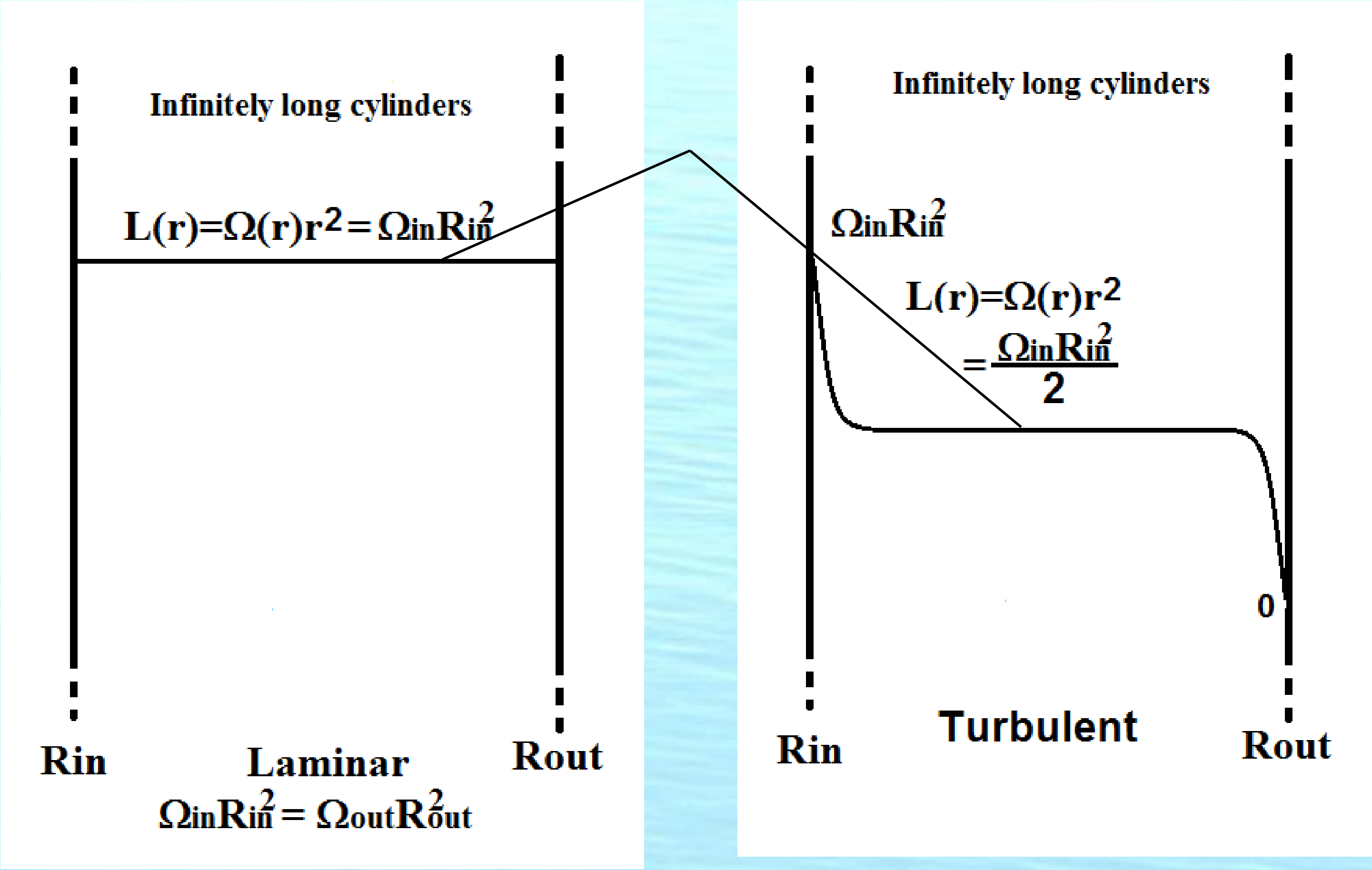




Fall time measurement doesn't shows strong turbulent resistivity in the azimuthal direction.



For current experimental setting, at high speeds, the dynamo gain is mainly determined by the mean velocity (angular momentum) profile.



Near-stable case Rm=92, Gmax=8(measured).

If Ωout$\rightarrow$0, Rm$\rightarrow$124, Gmax $\rightarrow$4

Turblent case, Rm=86, Gmax=3.1 (measured).

4 /124*86$\rightarrow$2.8, quantitatively consistent!

Suppression of $\eta_{\perp}^{turb}$ may be caused by reduction of correlation length by strong shear $\partial U_\theta / \partial r$.

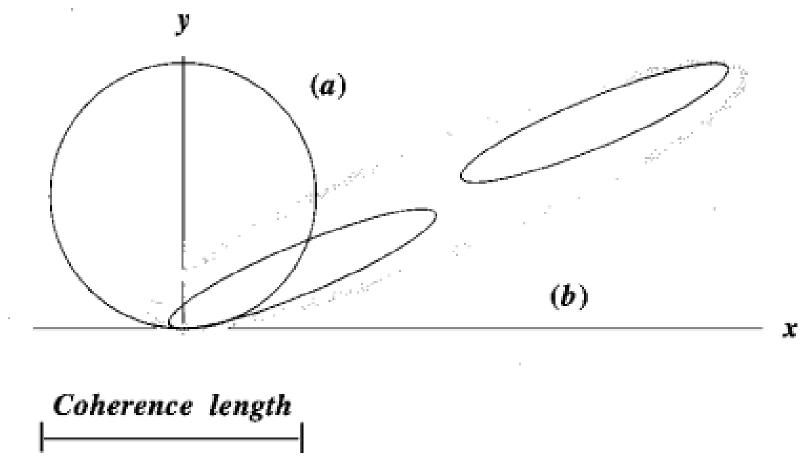


FIG. 1. A reference eddy [(a), no shear flow] sheared by unidirectional plane shearing (b) with $u_x(y) = \alpha y$. If the eddy is isolated it stretches into the shape indicated by the gray shaded curve. In turbulence, the eddy loses coherence in a coherence length, represented as a breakup into two eddies. The loss of coherence reduces the y scale relative to that of the reference eddy.

At 48Hz (inner), 0Hz(outer), Re=10^7, ΔR=15cm, the velocity gradient of mean flow is

$$\mathrm{Grad}_{\mathrm{mean}} \approx \frac{\Omega_{in} R_{in}{}^{2}}{2} \left(\frac{1}{R_{in}} - \frac{1}{R_{out}} \right) \Big/ \Delta R$$

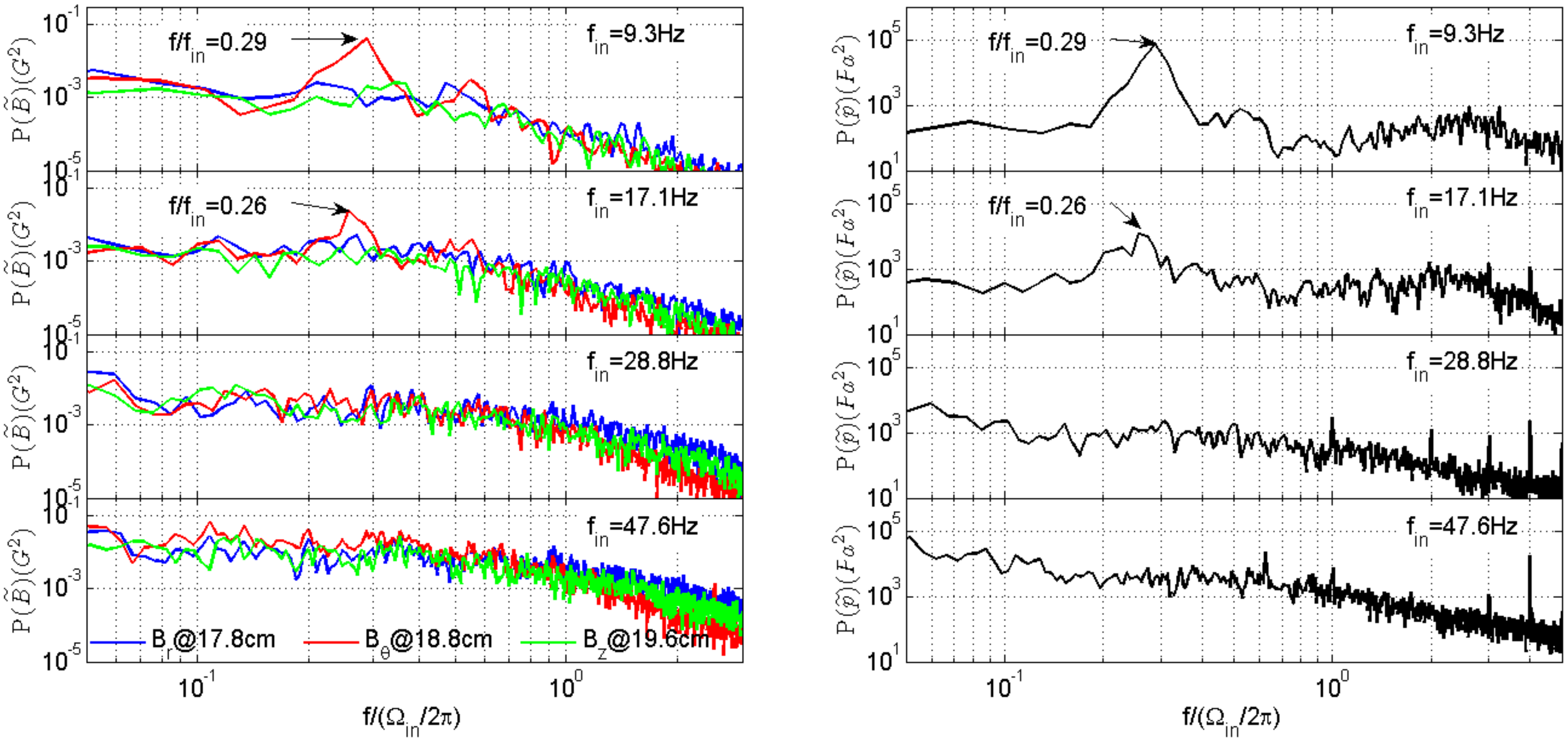
$$= 75 \sec^{-1}$$

velocity gradient based on homogeneous isotropic approximation

$$\mathrm{Grad}_{\mathrm{fluct}} \approx \tilde{u} / \Delta R \approx 21 \sec^{-1}$$

A necessary condition for the correlation length to be ~ΔR is that the velocity gradient of the larges eddies is greater than the gradient of the mean velocity, or the strong shear will speed up the de-correlation (Terry, Rev. Mod. Phys. 2000)

While suppression of $\eta_{//}^{turb}$ may be related to the transition of the Ekman circulation from coherent to turbulent.



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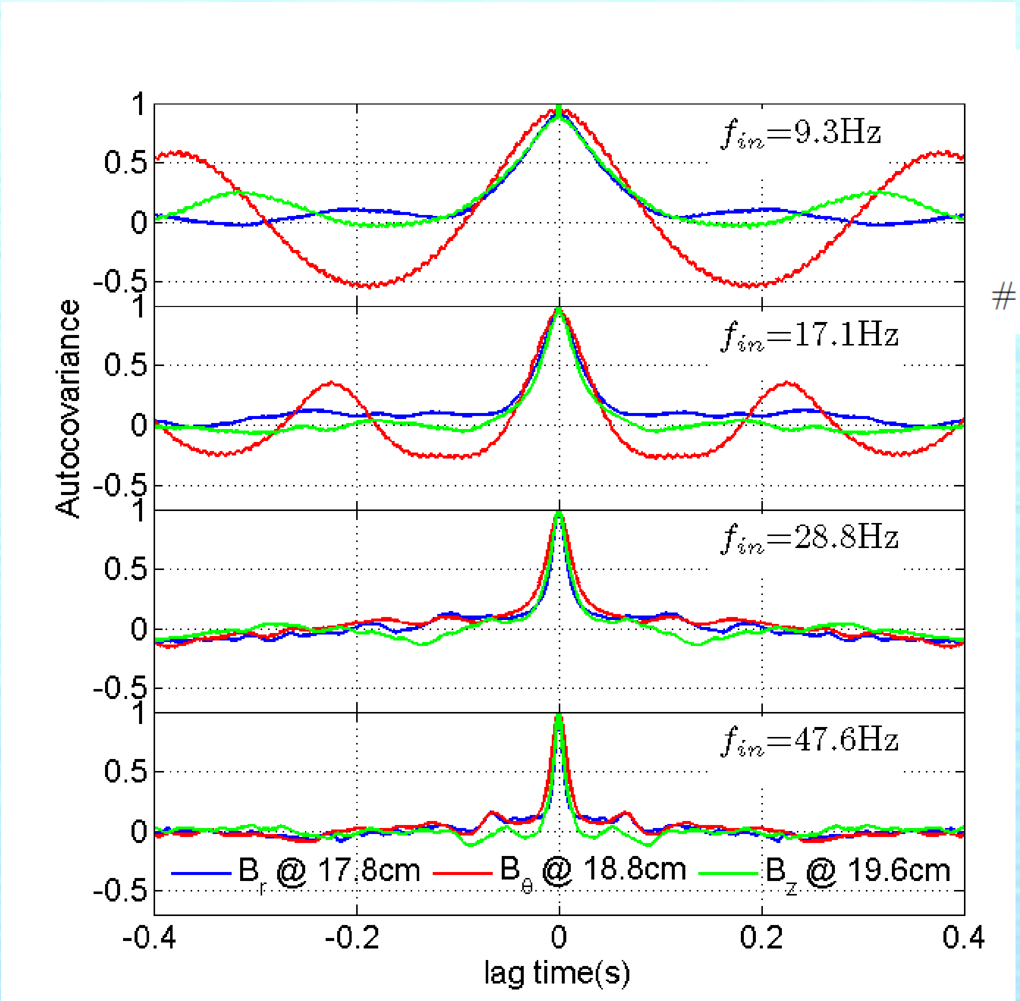


Velocity correlation length reduces as Ekman flow becomes more and more turbulent.

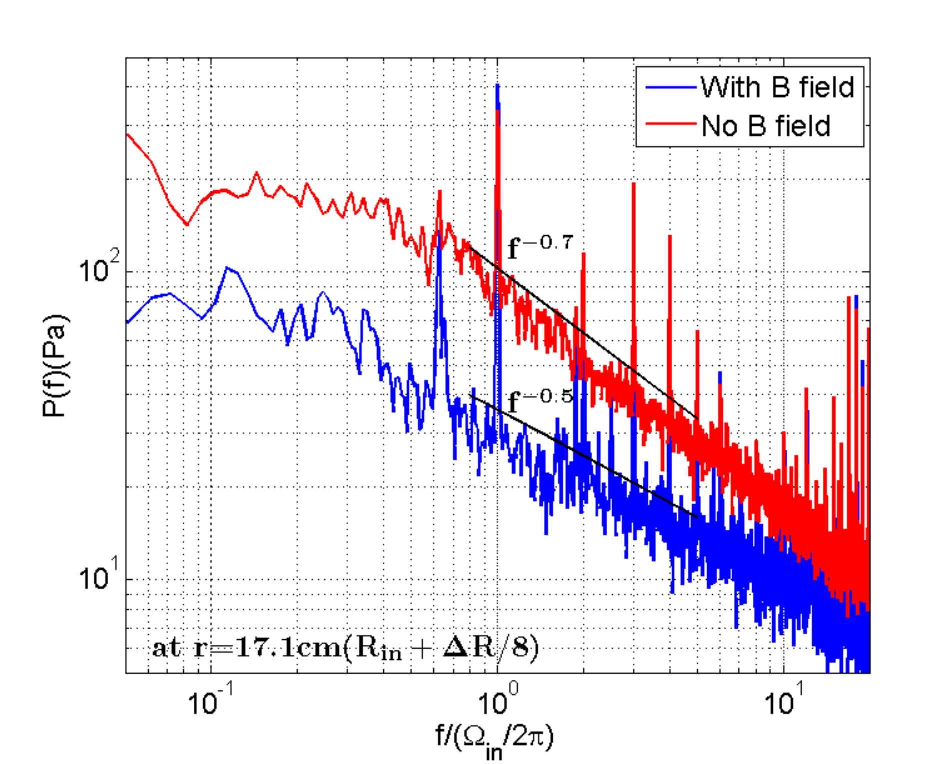
At 9.3 Hz

	u_r	u_θ	u_z	
B_r	$\times$	$\surd$	$\surd$	most
B_θ	$\surd$	$\times$	$\surd$	least
B_z	$\surd$	$\surd$	$\times$	medium
	least	most	medium#	

\# − u_z may also be coherent but have lower value than u_r.

A B fluctuation component is determined by the velocity fluctuations perpendicular to it. e.g. Br fluctuation is determined by u_θ and u_z So the behavior of Br reflects the combined effort caused by u_θ and u_z.
At 9.3 Hz, According to the behavior 3 magnetic components, we can see u_r is the least turbulent, while u_θ exhibits the most turbulent behavior. This is consistent with the image that at such rotation rate there is likely a relatively coherent Ekman flow.

Wall pressure spectra without B is consistent with Goody's model. The power increases to -0.5 with B~430G



Y.F. Hwang et al. / Journal of Sound and Vibration 319 (2009) 199–217

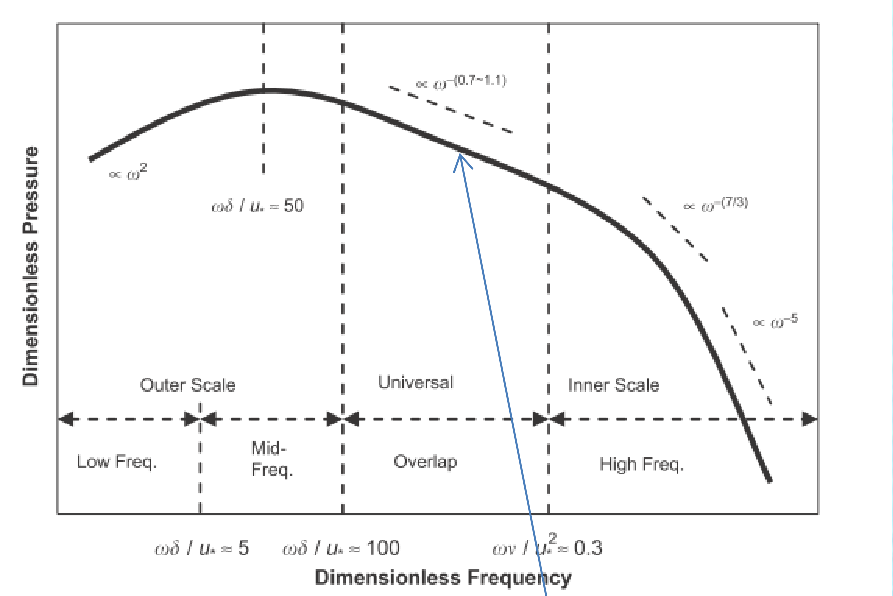
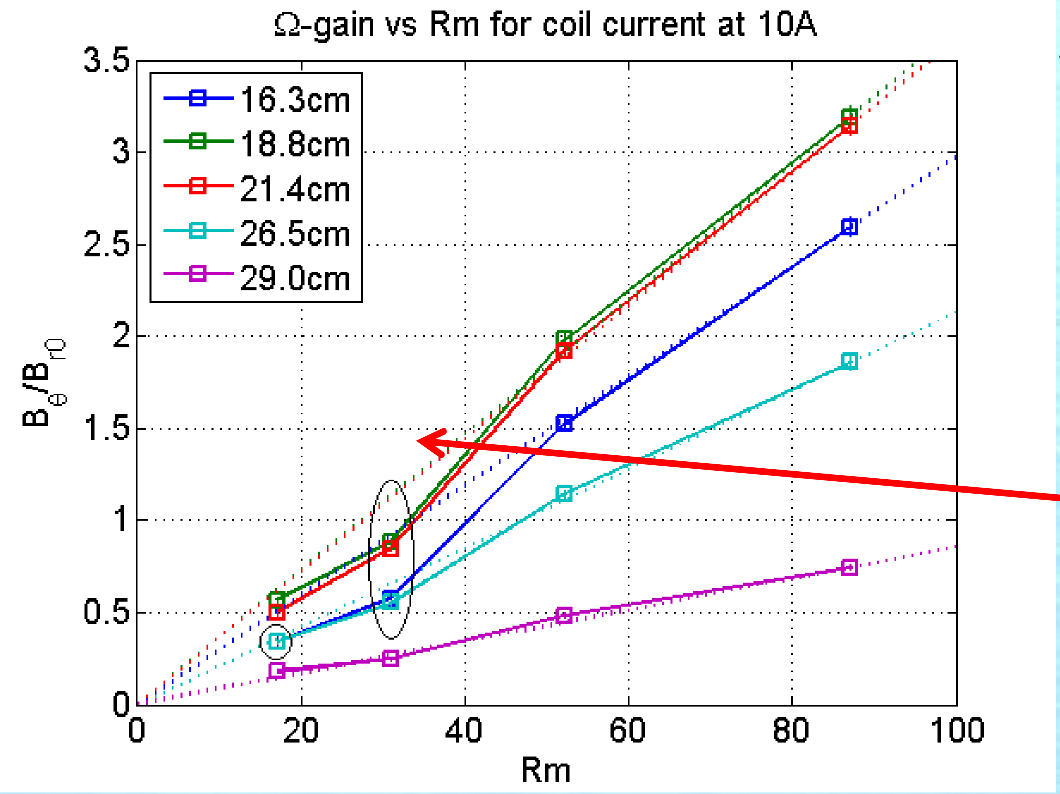


Fig. 1. General spectral characteristics of a TBL wall pressure spectrum at various frequency regions.

From Hwang, Journal of Sound and Vibration, 2009

The are different models on wall pressure spectra, in overlap region, Bradshaw1967 prodict the power is -1, Smol'yakov2000 -1.11, Goody2004, -0.7.

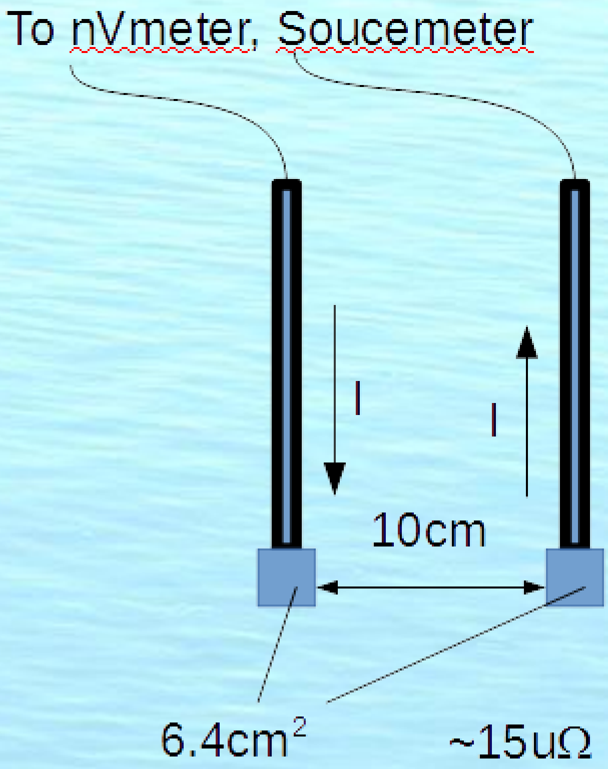
Measuring anisotropic turbulent resistivity locally.
To our knowledge, there is no similar experiment done by others. (We may publish a PRL paper if we get positive results).



Turbulent flows can be generated in our apparatus with the inner cylinder rotating while the outer one at rest. Our recent w-gain and penetration measurements indirectly show that turbulent resistivity is anisotropic at Rm ~31. We can focus on this region.
To measure turbulent resistivity, we propose two techniques

Technique #1: We can modify technique used by Reighard, A. B. and Brown, M. R, PRL, 2001.

Turbulent Resistivity is estimated by the resistance between 2 electrodes.



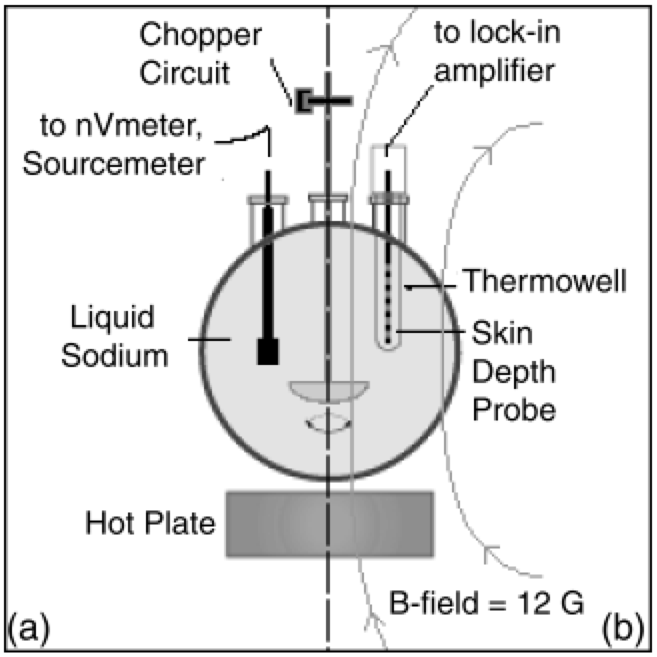
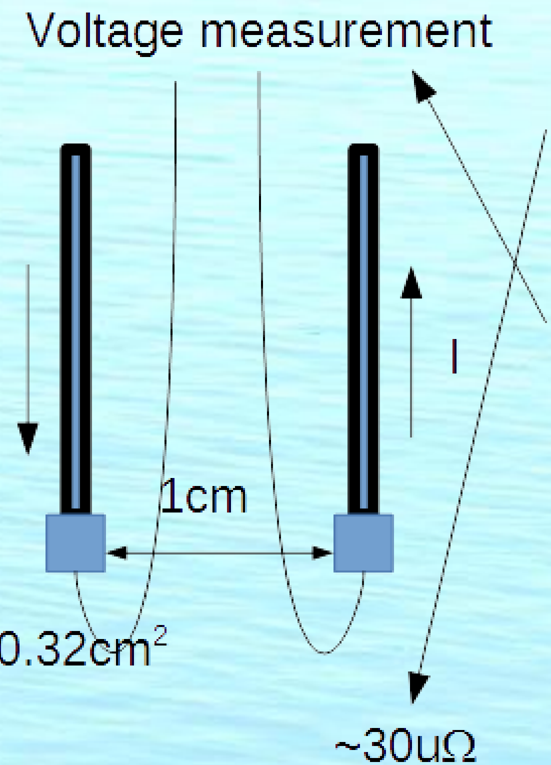


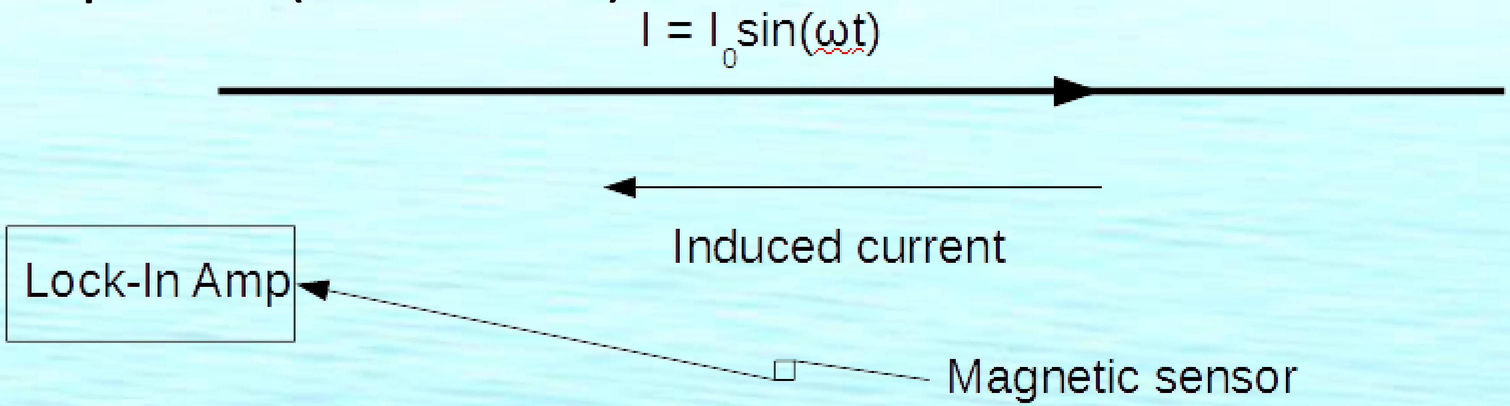
FIG. 1. Spherical sodium flow apparatus. Sodium was contained in heavy Pyrex flask ($r = 0.075$ m) and flow was driven by a Teflon propeller ($r = 0.035$ m). (a) Depicts one of the copper electrodes used for the dc measurement; (b) depicts the magnetic probe array used for the skin depth measurement.

Our modification for technique #1



- We can reduce the separation between the two electrodes and reduce the surface areas of the electrodes.
- In Reighard and Brown's setup, the voltage is measured at end of the electrodes, so the effect of temperature change on the electrodes has to be excluded. We can used two leads to measure the voltage. Since the current in leads is very small, we don't need to worry about the effect of temperature change.
- The challenge now is on the DAQ electronics, while in Reighard and Brown's setup the meters are off-the-shelf products.

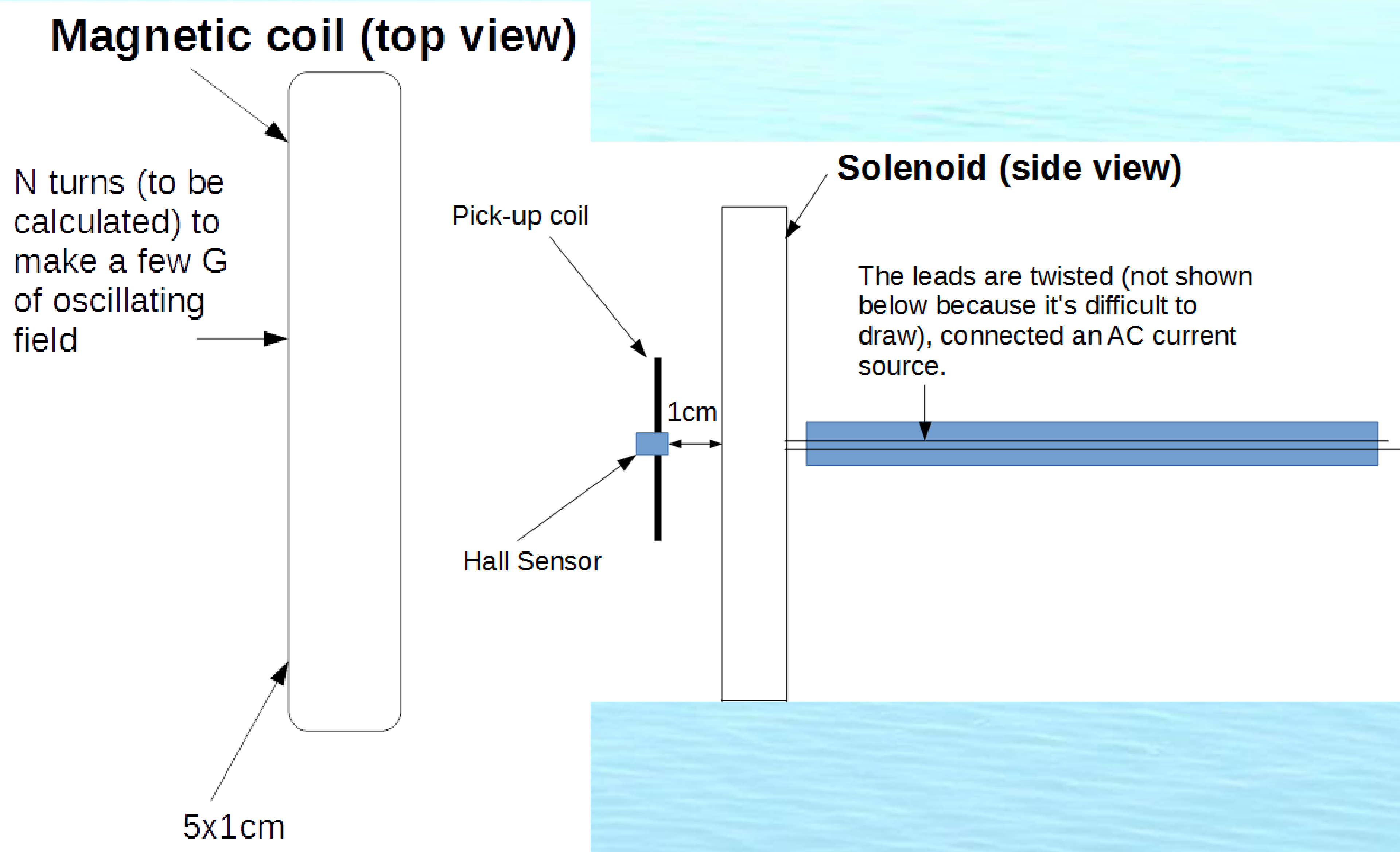
Technique #2 (basic idea)



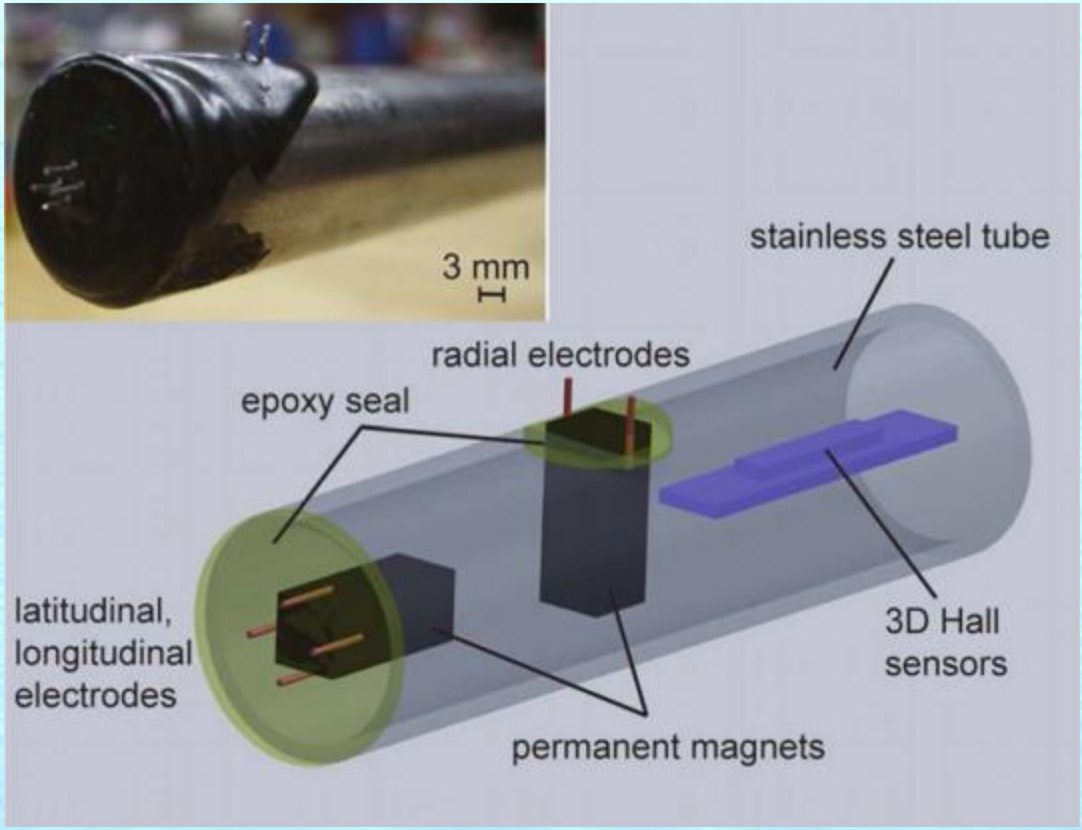
The signal received by the magnetic sensor will have a phase delay determined by the distance from the wire, the effective resistivity in the direction of the wire between the sensor and the wire. (Remember in our penetration measurement that it takes time for the field to penetrate through sodium flows.) Any change of the effective resistivity will change the phase delay.

We can choose a frequency to make the phase-delay to be around 180 degree without turbulence.

Technique #2 (my proposed setup #2)



Direct velocity field measurement will improve our understanding of processes inside the apparatus



Rahbarnia et al, ApJ 2012
U-Wisconsin Dynamo group

Rm>>1

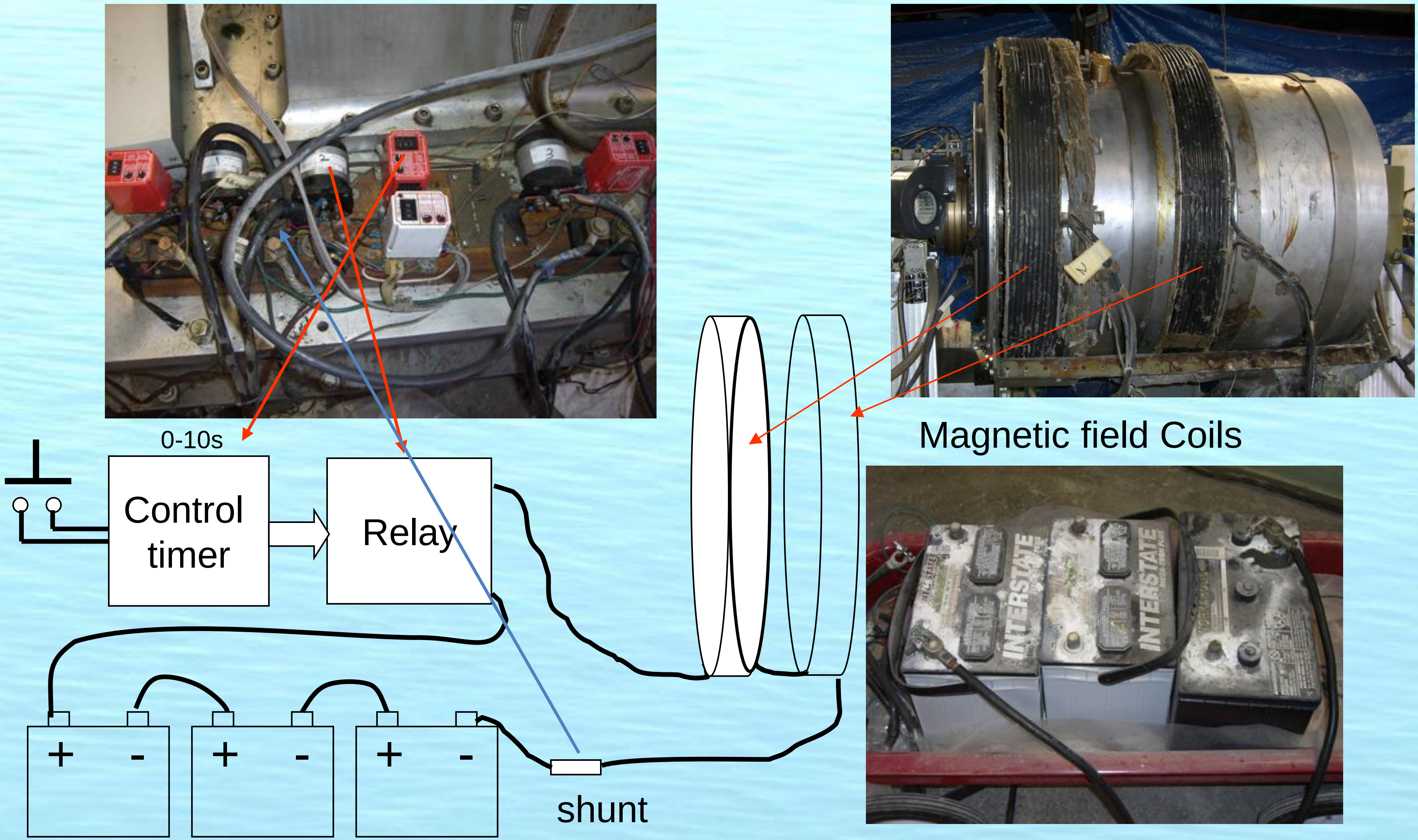
$$\vec{E} \approx \vec{U} \times \vec{B}$$

$\vec{U}$ **can be inferred from**

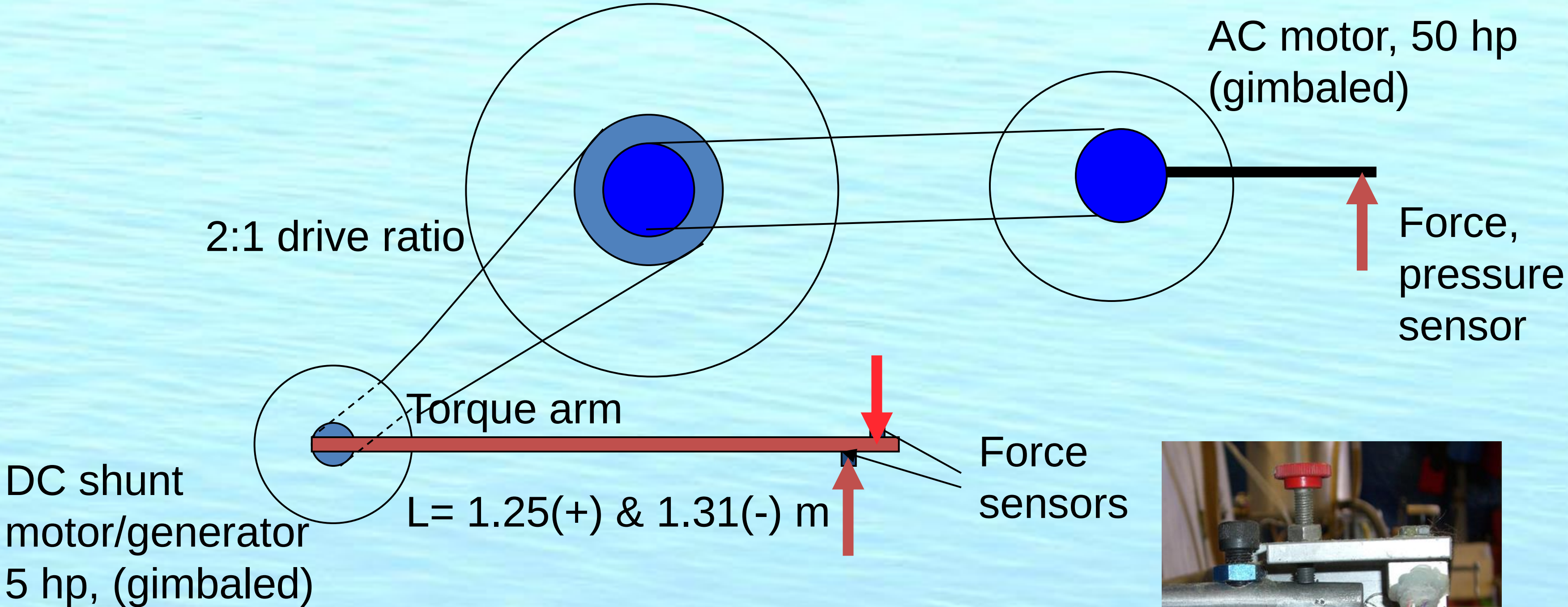
$\vec{B}$ **and** $\vec{E}$

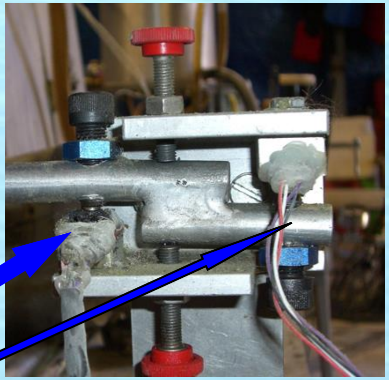
The same method is also used by dynamo group in Leon, France (Miralles, et al, PHYSICAL REVIEW E, 2014).

Car batteries (6 to 48V) are used to drive magnetic coil currents



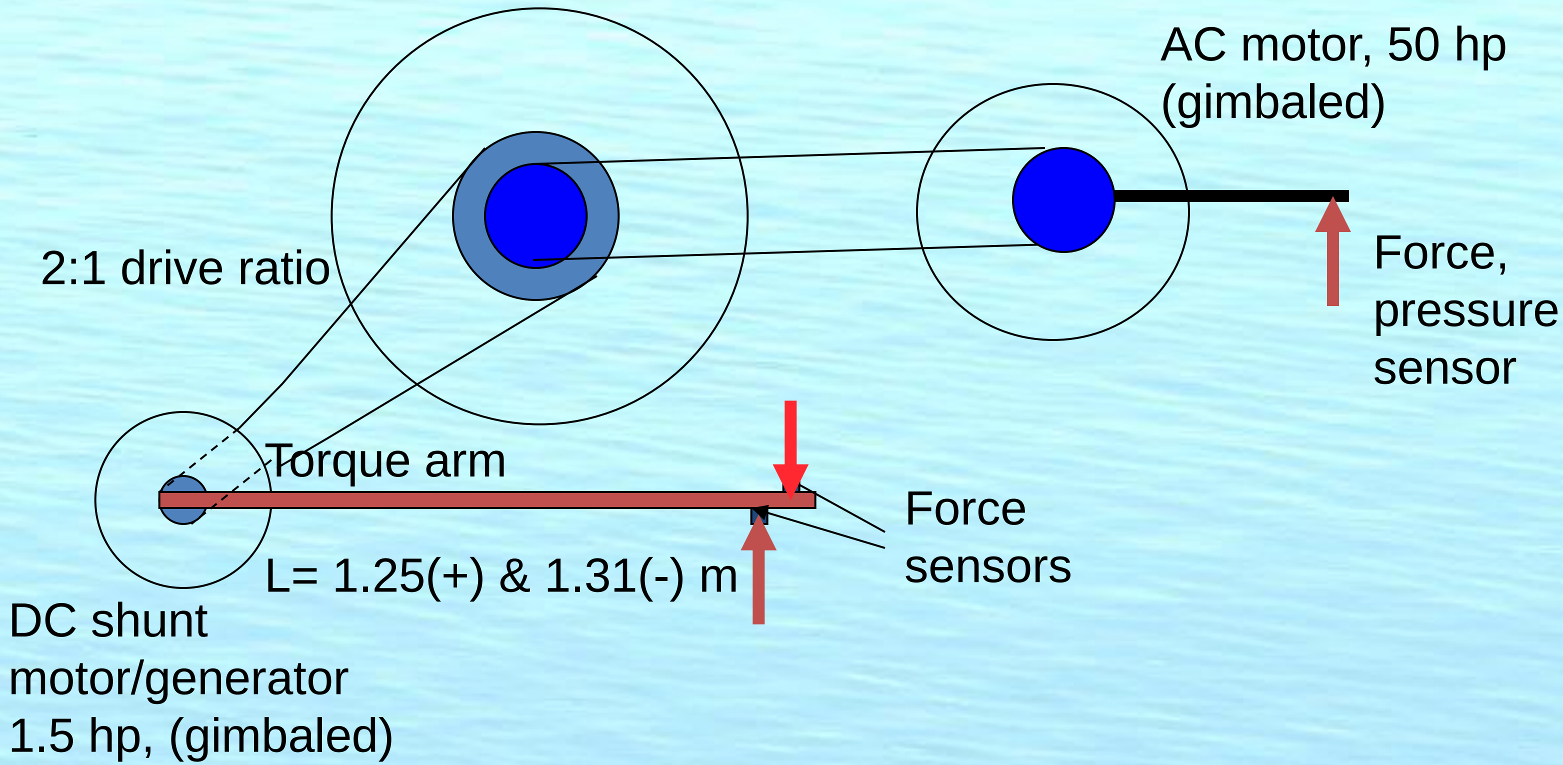
The torque on the spinning outer cylinder can be measured through a gimbaled dc motor



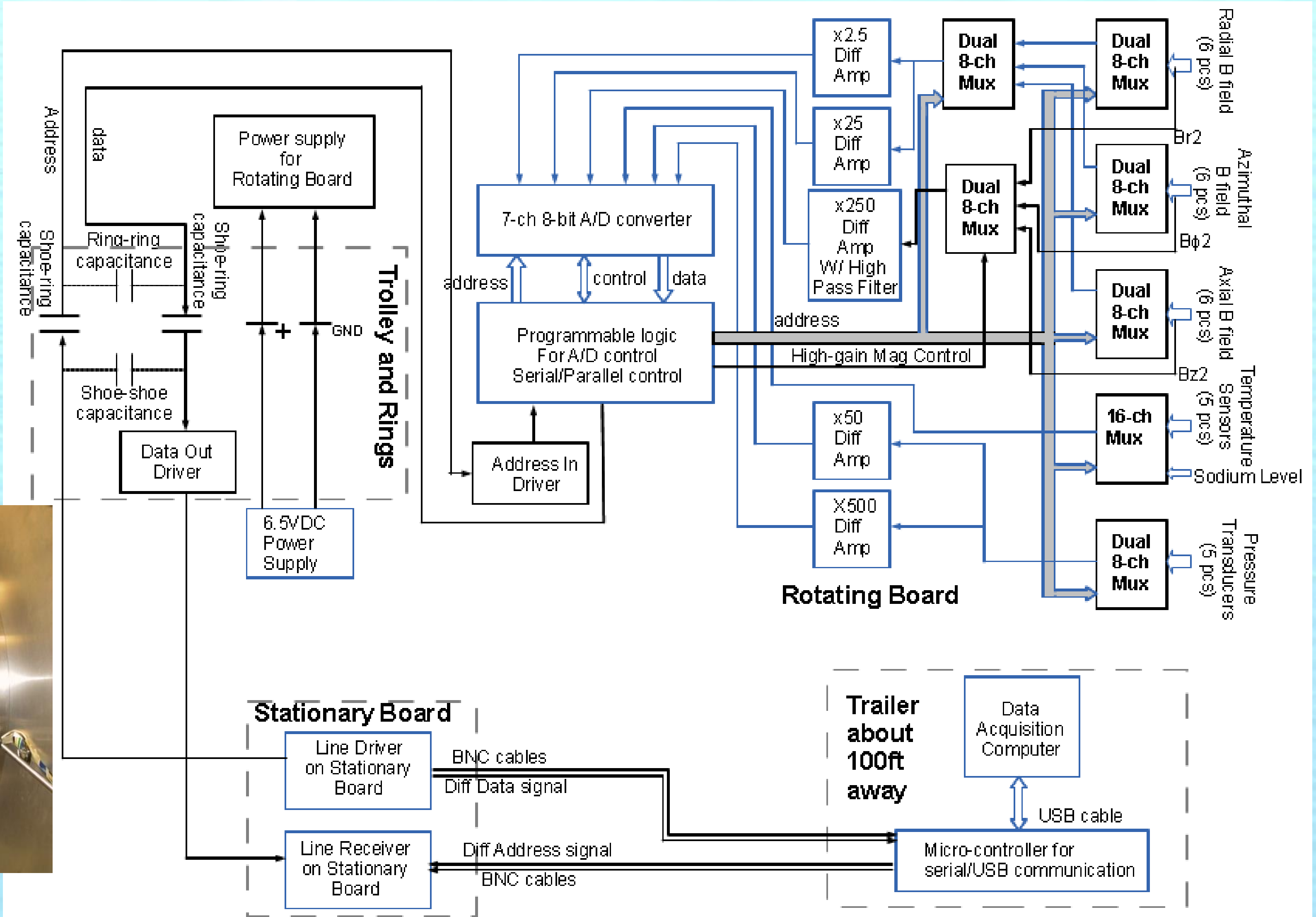


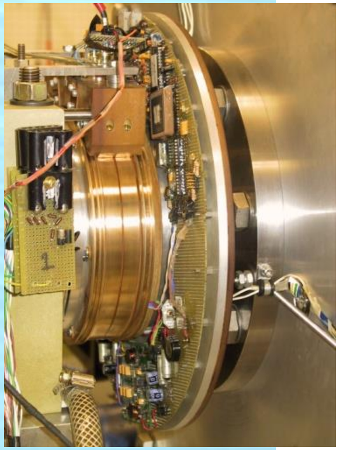
FSG15N1A Force Sensors are used to measure:
the DC motor torque = Ekman flow torque = turbulence torque.

The torque on the spinning outer cylinder can be measured through a gimbaled dc motor



Signals from sensors in the rotating frame are digitized and transmitted though capacitive coupling.

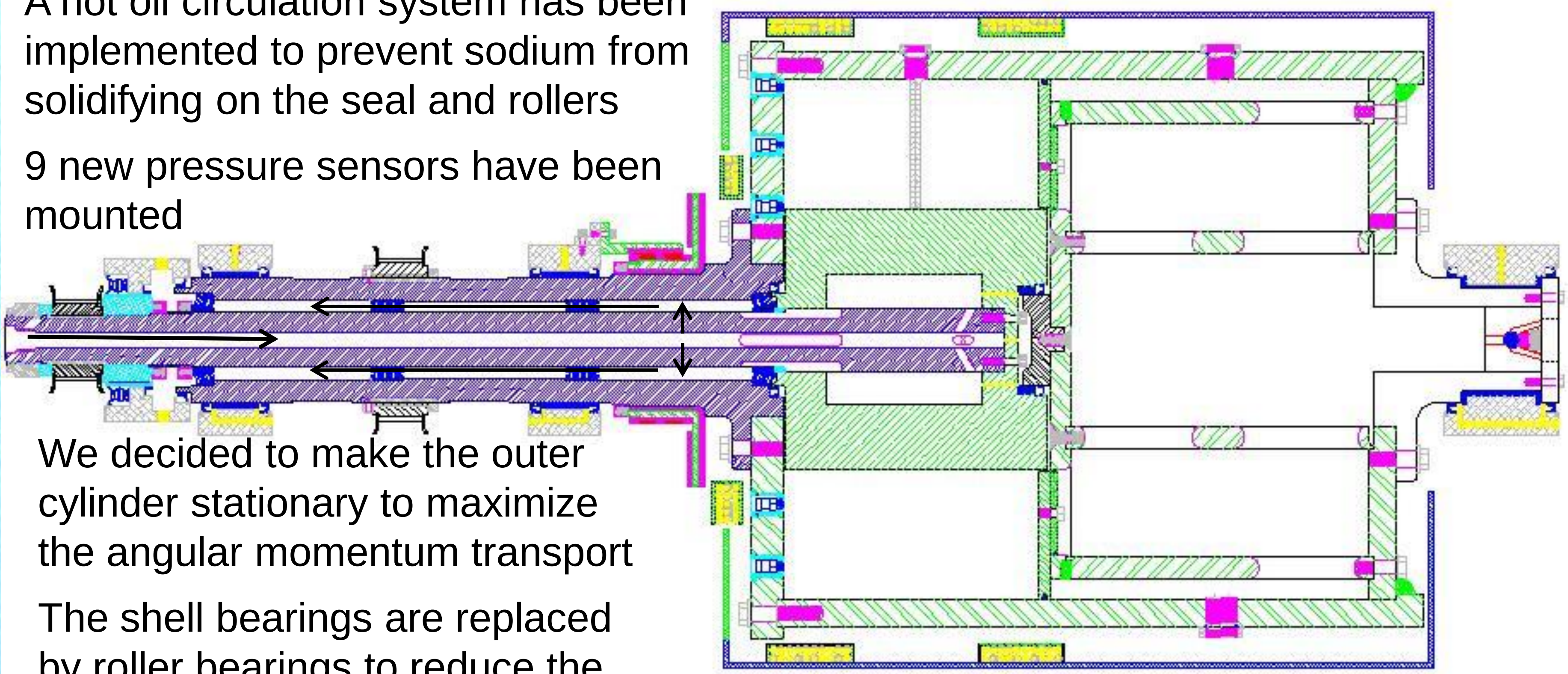




The experimental apparatus had been refitted during 2013

A hot oil circulation system has been implemented to prevent sodium from solidifying on the seal and rollers

9 new pressure sensors have been mounted



We decided to make the outer cylinder stationary to maximize the angular momentum transport

The shell bearings are replaced by roller bearings to reduce the friction.

8-bit DAQ system was replaced by an NI 16-bit DAQ system for the current purpose.

We also improved our methods for storing, filling, heating and dumping Na.