Ultrasonic Doppler velocimetry in liquid gallium

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INTRODUCTION

A wealth of optical methods is available to visualize or measure flows in transparent liquids. These methods cannot be used in opaque liquids such as liquid metals.

Our involvement in a french project of experimental dynamo provided the motivation to devise a non–intrusive method to measure velocity in liquid metals. Our approach is to to rely on small heterogeneities in physical properties of the fluid to backscatter acoustic waves. The flow velocity is then derived from the Doppler shift of these scattered waves. With a single ultrasonic probe and a pulsed signal, one obtains **a profile of the component of the flow velocity along the shooting direction**. This method has rarely been used in liquid metals. Only successful tests in mercury have been reported (Takeda, 1987).

In this poster, we present flow velocities in liquid gallium obtained with the pulsed Doppler velocimeter *DOP1000* of Signal Processing. **Our set–up consists of a cylinder filled with liquid gallium at the top of which spins a small crenelated disk. We thus produce a nearly two–dimensional axisymmetric vortex**. According to previous studies (Brito et al., 1995, 1996), our set–up is very appropriate for making a **quantitative test of the pulsed Doppler shift method in liquid gallium** because the vortex is well–behaved, reproducible, and nearly axisymmetric, yet turbulent.

DOPPLER EFFECT PRINCIPLE

In the pulsed Doppler shift ultrasonic technique, a pulse of collimated ultrasounds is shot into the fluid. One then listens for the echoes that come back from particles in the fluid. **The delay time of the echo provides the distance of the particle**, while **the corresponding Doppler shift provides its velocity**. In a few milliseconds, a profile of fluid velocities is obtained.

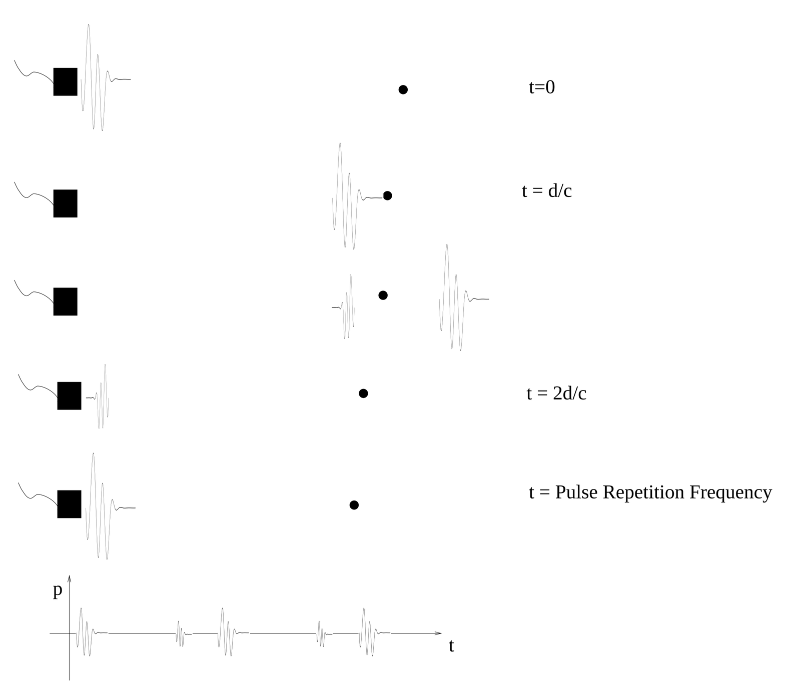

Figure 1: Principle of Doppler effect applied to the DOP1000 apparatus.

EXPERIMENTAL SET-UP

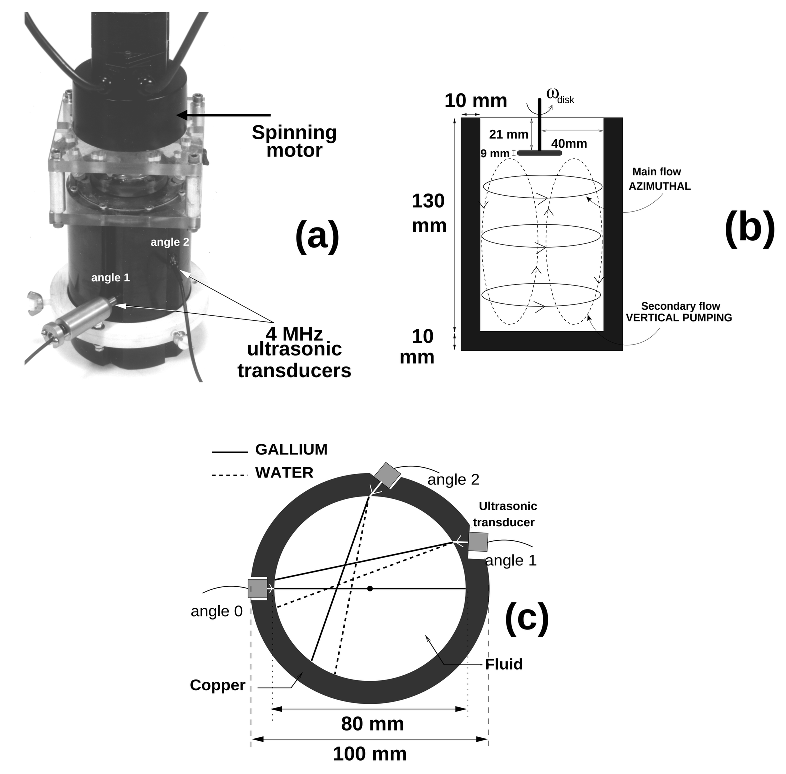

Figure 2: a) Photograph of the copper cylinder (coated with a black cataphoretic thin film) and motor that entrains a crenelated disk near the top of the cylinder. Two 4MHz ultrasonic transducers are pressed on flat slits machined at three different angles (angles 0, 1, 2). b) Vertical cross–section of the cylinder with a schematic view of the fluid flow. c) View from the top of the cylinder. The lines indicate the cords followed by the ultrasonic beams in liquid gallium (solid line) and water (dashed lines) for the three different angles (Snell-Descartes' law).

PHYSICAL PARAMETERS

	Symbol	Unit	WATER	LIQUID GALLIUM	LIQUID SODIUM	COPPER
Density	ρ	kg/m^3	1000	6090	990	8900
Kinematic viscosity	$\nu = \frac{\mu}{\rho}$	m^2/s	$1.14 \cdot 10^{-6}$	$3.1 \cdot 10^{-7}$	$0.5 \cdot 10^{-6}$	
Sound velocity	c	m/s	1500	2860	2550	4760

Table 1: Physical properties of liquid gallium (30^{o}C), sodium (100^{o}C), water and copper relevant to the experiment.

ECHO MODE

The amplitude of the echoes in the cylinder as a function of distance for water, gallium and sodium using the *echo mode* of the *DOP1000* are shown in figure 3. The transducer is positioned at angle 0 (see figure 2), and the time between two emissions has been chosen so as to record ultrasonic waves that have bounced back and forth on the side walls of the cylinder. Nice peaks are clearly visible that correspond to waves that have bounced at the liquid–copper interface once or more.

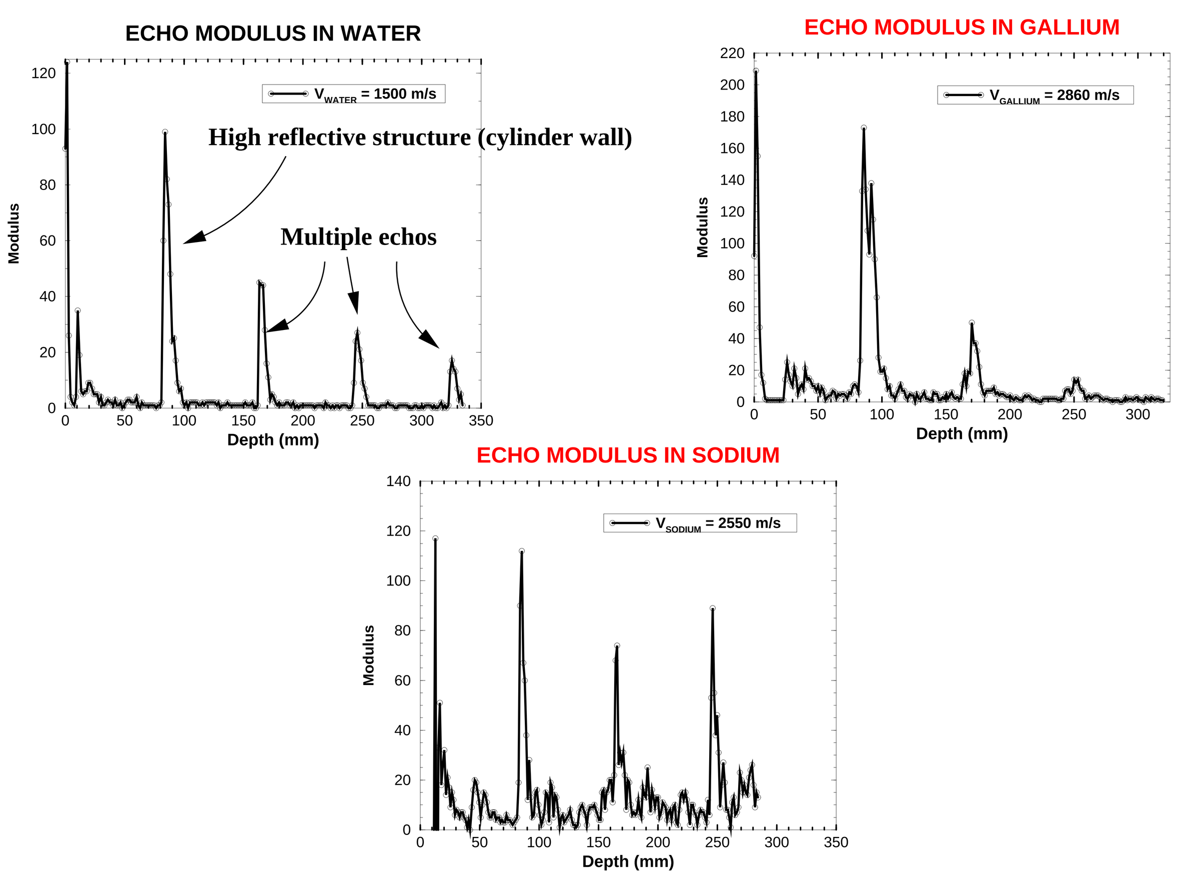

Figure 3: Ultrasonic echoes (arbitrary units) as a function of distance in mm registered in a vortex of water, gallium and sodium.

VELOCITY PROFILES

Figure 4 shows velocity profiles measured at mid–depth of the cylinder from angle 1 in vortices of water (a) and gallium (b). The profiles are consistent with the properties of the flow as sketched in figure 2b:
- the profiles are symmetric with respect to the mid–point of the beam in the cylinder (axisymmetric flow).
- the projection of the velocity along the beam is maximum at the mid–point.
- this maximum velocity increases with the imposed angular velocity of the disk.
- the velocity jumps abruptly from zero in the copper wall to its value in the liquid across a very thin vertical viscous boundary layer.

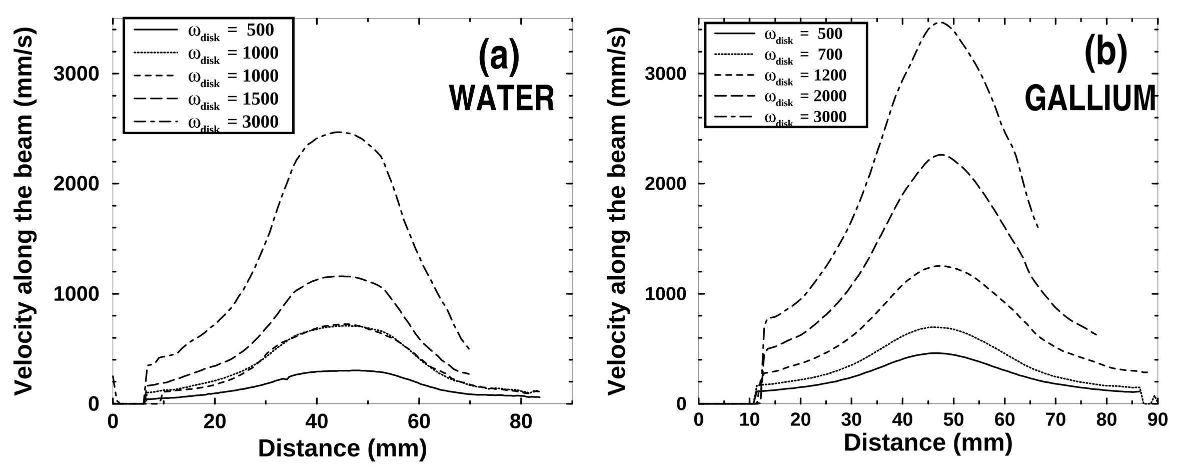

Figure 4: Velocity profiles as a function of distance measured at mid–depth of the cylinder from angle 1, in vortices of water (a) and gallium (b). Angular velocities of the disk ω_{disk} are in rev min^{-1}.

TREATMENT OF VELOCITY PROFILES

It is shown how we convert the raw velocity data recorded by the *DOP1000* velocimeter into time–averaged profiles of the angular velocity ω as a function of radius. Figures 5a-d show the successive steps of the processing, and figure 5e illustrates the projection of the measured velocity V_{dop} into the azimuthal velocity component V_θ.

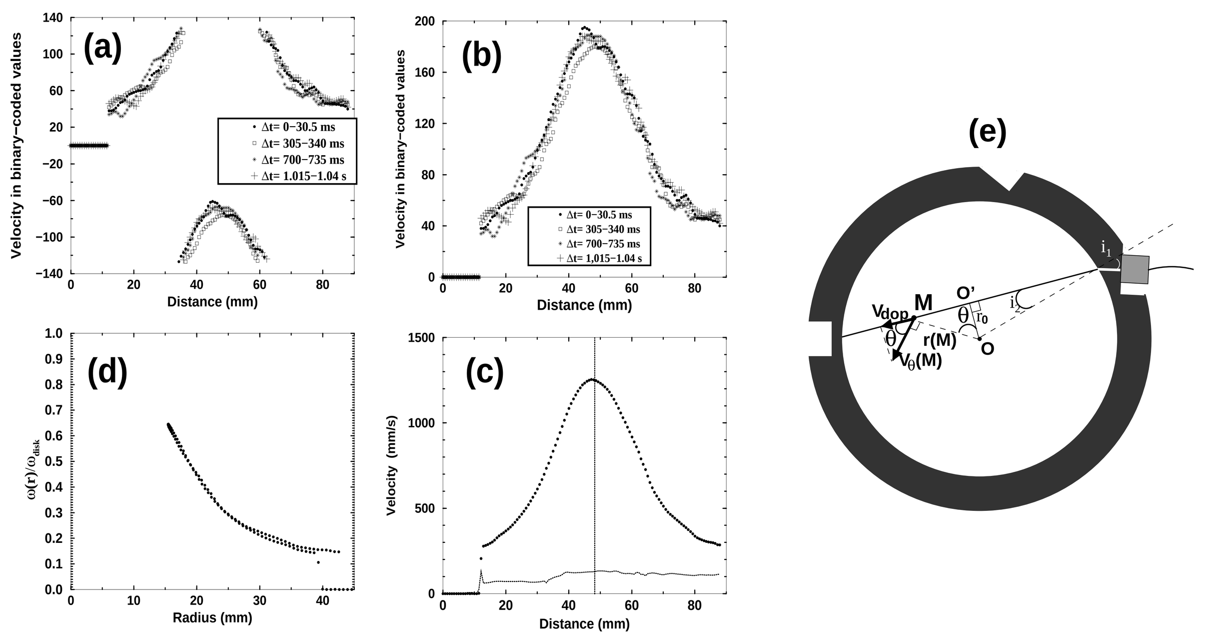

Figure 5: Successive steps of the processing of a velocity file recorded by the *DOP1000* during an experiment with liquid gallium and $\omega_{disk} = 1200$ rev min^{-1}. (a) Original binary–coded velocity values as a function of distance for 4 profiles. (b) "Unfolded" profiles. (c) Time–averaged profile in physical units (mm/s), obtained by taking the mean of the 256 successive individual unfolded profiles. The continuous line at bottom of the figure is the root mean square dispersion about that mean profile. The vertical bar is the symmetry point O'. (d) Time–averaged angular velocity $\omega = V_\theta/r$ scaled with ω_{disk}, as a function of radius. (e) View from the top of the cylinder. The *DOP1000* measures the component of the velocity along the beam, V_{dop}. O' is the mid–point of the cord. $V_\theta(M)$ is obtained by projecting $V_{dop}(M)$ on the perpendicular to OM.

ANGULAR VELOCITIES

Radial profiles of the angular velocity $\omega(r)$ can be retrieved from the raw velocity profiles, as shown in the treatment of velocity profiles. The profiles extend from the minimum radius at the mid–point of the beam to the outer wall.

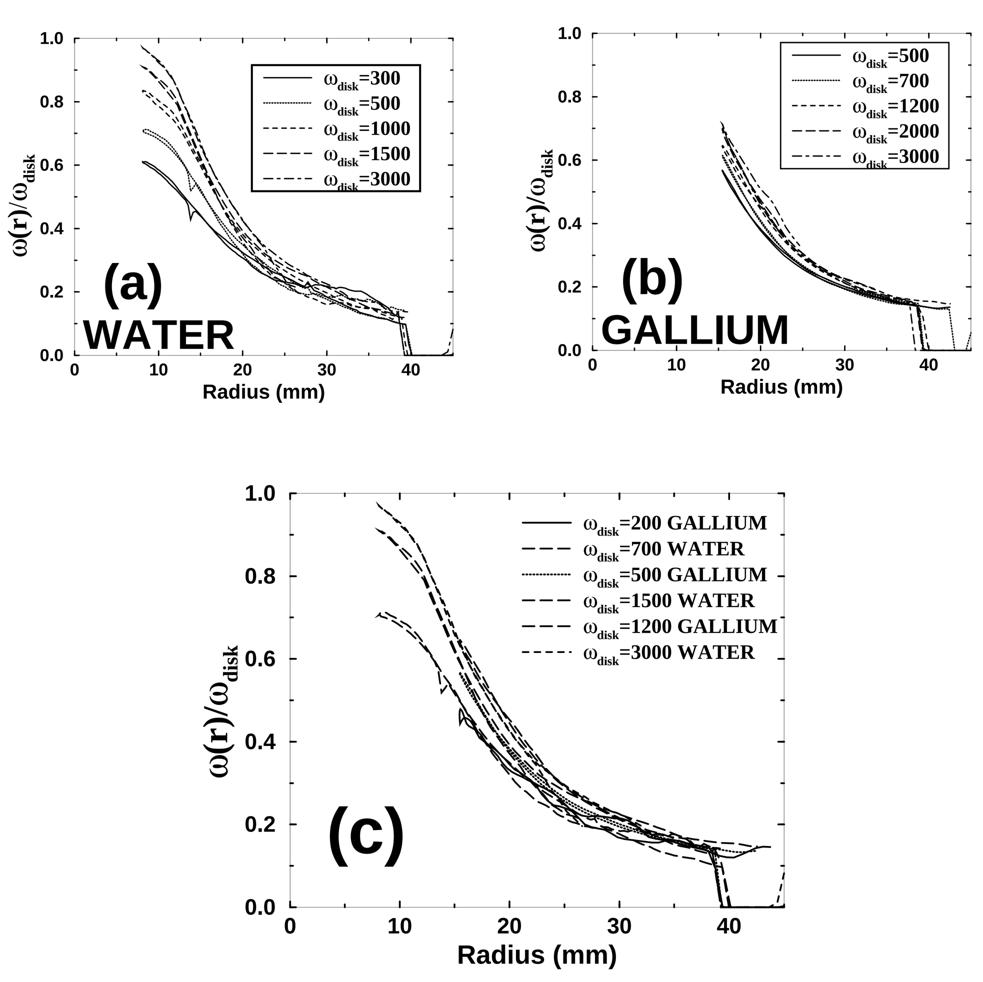

Figure 6: Normalized angular velocity profiles $\omega(r)/\omega_{disk}$ in vortices of water (a) and vortices of gallium (b). (c) Comparison of water and gallium angular velocity profiles. Angular velocities of the disk ω_{disk} are in rev min^{-1}.

First, we note that the two branches superpose remarkably well as a function of radius for both gallium and water, demonstrating that the fluid flow is indeed axisymmetric.

Figure 6c) shows that profiles for water with an imposed velocity ω_{disk} match perfectly those for gallium with ($\omega_{disk}/3$): the relevant dimensionless number for our experiment is the Reynolds number $Re = \frac{\omega_{disk} r_{disk}^2}{\nu}$, where r_{disk} is the radius of the disk, and ν the kinematic viscosity of the liquid. Since the kinematic viscosity of liquid gallium is about three times smaller than that of water (see table 1), the profiles that superpose have the same Reynolds number.

Note that Reynolds numbers extend from $7 \cdot 10^3$ to 10^5 in water experiments, and from $2.5 \cdot 10^3$ to $4 \cdot 10^5$ in gallium experiments.

METHODOLOGICAL ASPECTS

Although one advantage of the ultrasonic Doppler velocimeter is that is does not require any calibration, there are a few phenomena that can introduce biases in the measurements. The biases can be in distance and in velocity. Biases in velocity happen in particular when the echoes from the particles in the liquid are too strong and saturate the signal. This can be solved by adapting the filter applied to the signal (**TGC** parameter). Another subtle cause of bias in velocity lies in the choice of the Pulse Repetition Frequency (*PRF*). The *PRF* gives the time between two ultrasonic emissions. **Bad choices of the DOP1000 parameters can introduce quite large errors in measurements velocity** (see Brito et al.,2000).

For gallium, additional problems come from the formation of oxides that affect the transmission of the ultrasonic waves. The main difficulties are linked to the exceptional affinity of liquid gallium with oxygen. **As soon as oxides have had time to develop enough, it becomes impossible to obtain reliable profiles with the ultrasonic velocimeter**. There are two options to avoid problems with gallium oxides : either always operate gallium under an oxygen–free atmosphere, or remove the oxides (see Brito et al., 2000).

The cylinder material is also crucial for gallium measurements. it is important to avoid cluttering of oxides on the walls. Although we tested 3 different cylinders (polycarbonate, nylon and copper), the oxydes irremediablement clutter inevitably after few minutes of experiments. The parade we found for obtaining reliable and lasting velocity measurements was to coat the walls of the copper cylinder with a 2 μm–thick cataphoretic film. With this coating, oxides do not stick to the walls. Starting with purified liquid gallium, we can typically **run the experiments for about one hour without encountering troubles due to oxides**.

MEASUREMENTS IN LIQUID SODIUM

We have performed ultrasonic velocimetry measurements in a vortex of liquid sodium at high temperature (150^{o}C) under argon atmosphere. These expriments were done at CEA (Commissariat à l'Energie Atomique) in Cadarache. We use a specific high temperature ultrasonic probe and three different cylinders: copper, copper coated with cataphorese and stainless steel.

Qualitatively, results in sodium are in good agreement with the velocity measurements done in water and gallium: the measured velocity increases with the velocity of the disk (figure 7). Quantitevely, discrepancy between velocities in sodium and velocities in gallium and water are important: like in gallium, our future studies will determine what is the best container material and what is the proper seeding to perform realiable ultrasonic velocity measurements in liquid sodium.

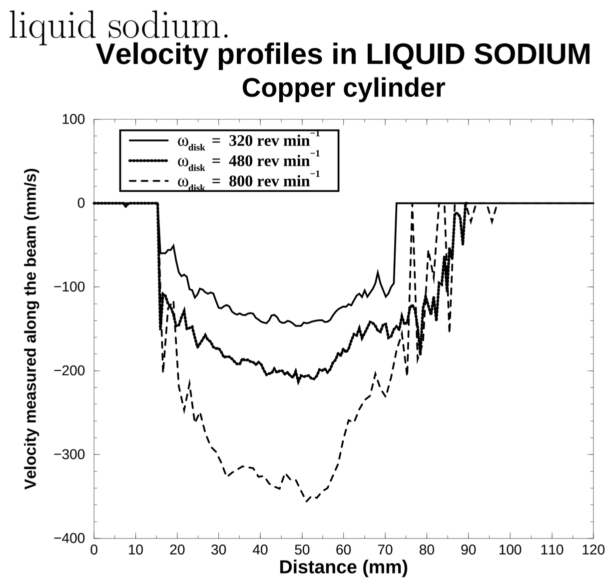

Figure 7: Measurements of velocity in a vortex of liquid sodium contained in a cylinder of copper

CONCLUSIONS

We have shown the first velocity measurements performed in a vortex of liquid gallium, using the pulsed Doppler shift *DOP1000* velocimeter. Reliable profiles have been obtained. Comparisons with earlier experimental results for the same set–up demonstrate the high quality of the velocity measurements.

Our results open new perspectives for the investigation of fluid flow in liquid metals. They should lead to developments in the context of experimental dynamos, where fast motions are set in large volumes of liquid sodium.

References

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