Large scale facilities to compare superfluid and normal fluid turbulence behavior at high Re

B. Rousset, C. Baudet, M. Bon Mardion, M. Bourgoin, A. Braslau, C. Bret, B. Castaing, L. Chevillard, F. Daviaud, P. Diribarne, B. Dubrulle, J. Duplat, Y. Gagne, B. Gallet, M. Gibert, A. Girard, B. Hébral, E. Herbert, S. Kharche, I. Moukharski, J. Peinke, P. Roche, B. Saint-Michel, J. Salort, F. Sy among many others…

Summary:

- Motivations to compare He II and normal helium turbulence and limitations
- Solutions to reach ultimate Re numbers in He I and He II and its consequences
- Brief presentation of passive grid flow at high Re
- The giant von Karman facility SHREK
- Some results obtained in SHREK using global measurements (Local measurements are presented in another session by Pantxo D. and Philippe R.)
- Brief presentation of oscillating grid flow allowing 3D Particle Tracking Velocimetry at moderate Re number

Ultimate high Reynolds number at laboratory scale : $Re = \frac{V.L}{\nu}$

$$\eta = \left[\frac{\nu^3}{\varepsilon}\right]^{\frac{1}{4}} \quad \text{so} \quad \varepsilon_{(W/kg)} = \frac{\nu^3}{\eta^4} \quad \text{or} \quad \varepsilon'_{(W/m^3)} = \frac{\rho\,\nu^3}{\eta^4} \quad \text{and} \quad \frac{L}{\eta} = Re^{\frac{3}{4}}$$

For a defined geometry L and a given Re number, dissipated power scales as

$$\varepsilon'_{(W/m^3)} \sim \rho\,\nu^3$$

fluid	viscosity ν (m^2/s)	density ρ (kg/m3)	$\rho.\nu^3$	Power (W)
He I 2.3K-1bar	2.01E-08	147.8	1.20E-21	400
Air	1.50E-05	1.2	4.05E-15	1.35E+09
Water	1.00E-06	1000	1.00E-15	3.34E+08
SF6 at 15bar room T°	1.50E-07	92	3.11E-19	1.04E+05
Air at 240bar room T°	9.62E-08	263	2.34E-19	7.82E+04

Comparison of He II and He I turbulence in the same facility and (if possible) with the same sensors:

~~Counterflow~~

isothermal flow

~~Second sound alone~~ ~~hot wire alone~~

global sensor at room temperature
(torquemeters, calorimetric measurements)

or microcantilever, micropitot, wall pressure sensors…

or isodense particles + visualization

Working with large velocities without cavitation and/or boiling:

- Flows generated in liquid helium usually operate inside a saturated bath. Kinetic energy $\rho V^2/2$ should be compensated potential energy $\rho.g.h$, to prevent cavitation ($g.h > V^2/2$ is safe due to absence of germ in helium). This limits maximum velocity to avoid cavitation. Typically, local velocity must remain under 5m/s.

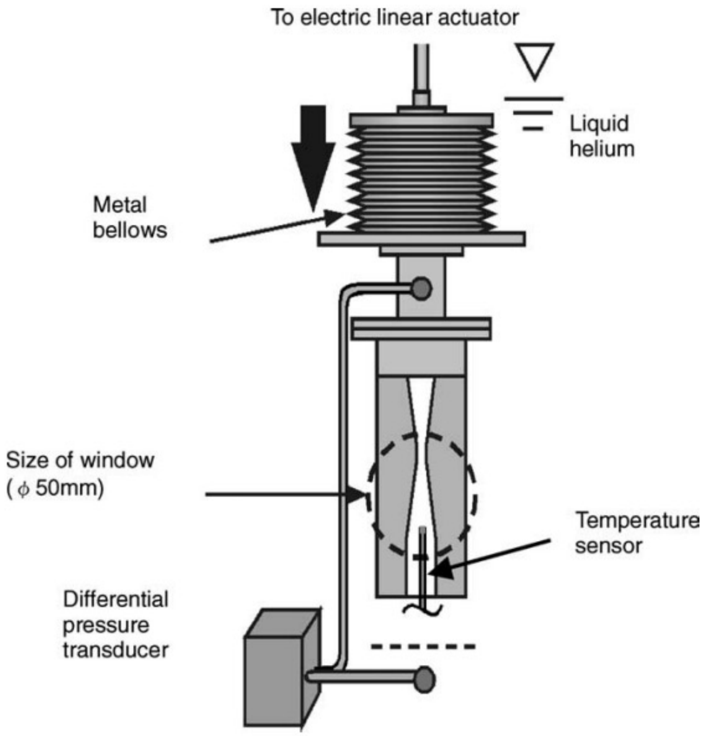


Fig. 1. Schematic illustration of the key area of the cavitation experimental system.

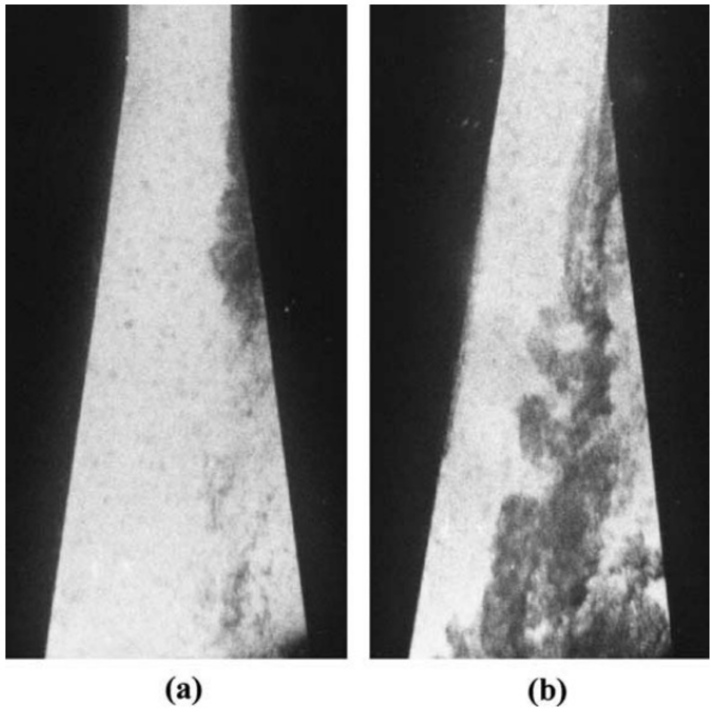


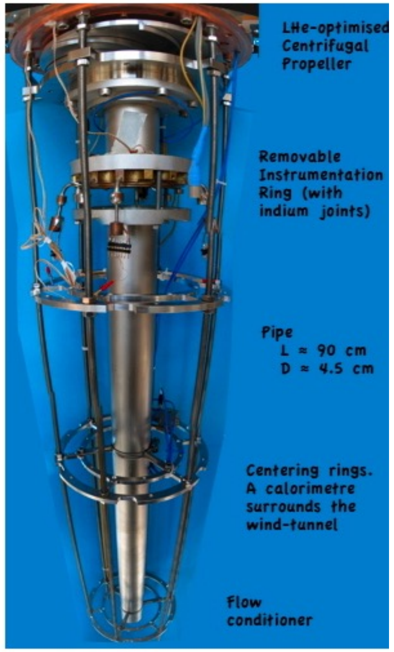
Fig. 8. Visualization pictures of cavitation of (a) He I (2.30 K) and (b) He II (2.10 K) flows in the inception state (P_i = 2.75 kPa).

Extracted from paper

« Comparison of cavitation flows in He I and He II »
by T. Ishii and M. Murakami ,
Cryogenics 2003

Working with large velocities without cavitation and/or boiling:

- Normal helium has a very poor heat conductivity and is subject to nucleate boiling as soon as some heat is released in the bath (wall heat loss, ball bearing friction loss, heat coming from Joule effect in case of resistive sensors..).



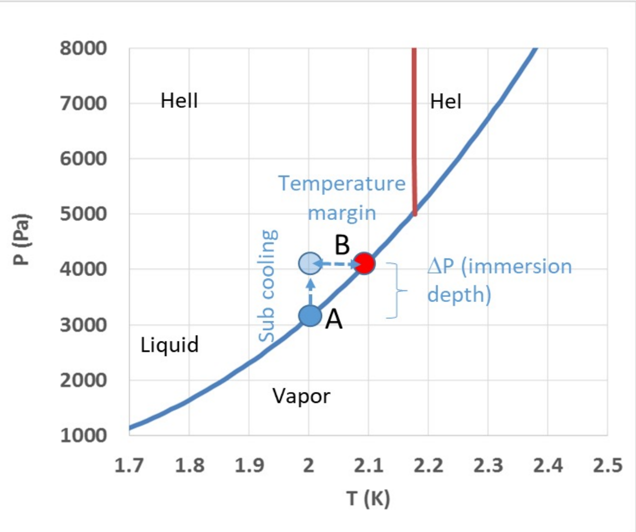
See Philippe R. for more details about Toupie

Liquid helium need to be subcooeld/pressurized by

@ hydrostatic pressure

@ decoupling pressure/T° via double bath

SHREK experiment (detailled afterward)



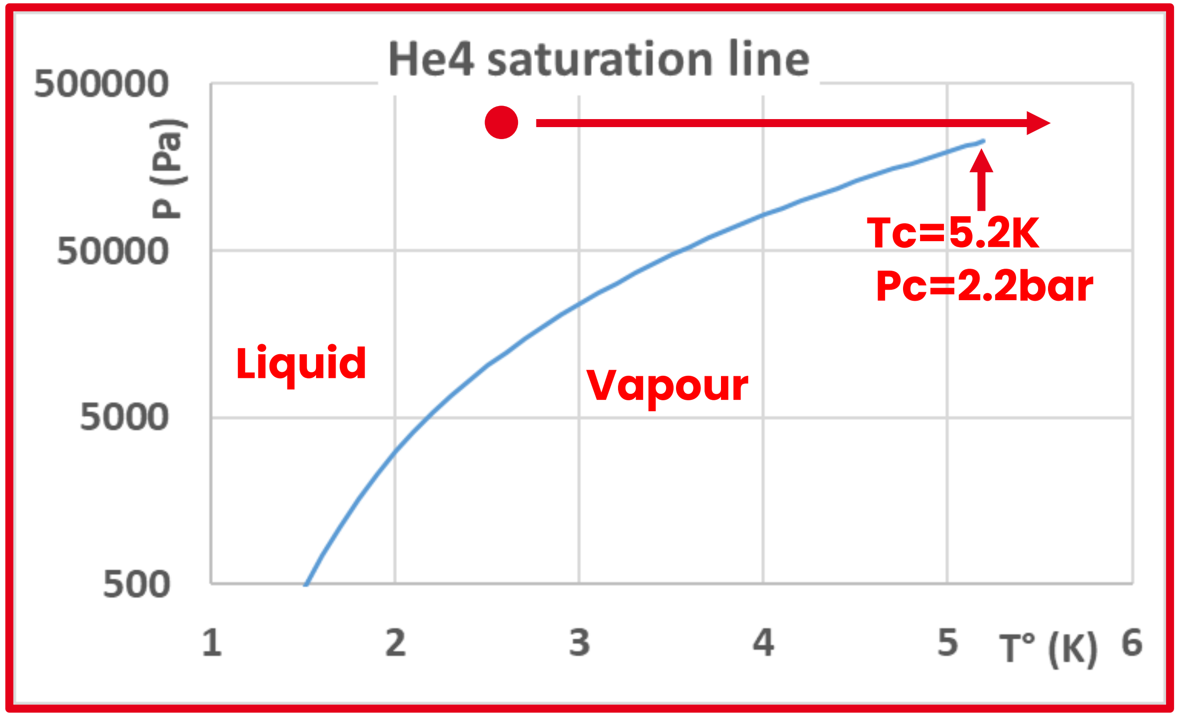
Working with large velocities without cavitation and/or boiling:

Sensors as “hot wire” need to be overheated to operate.

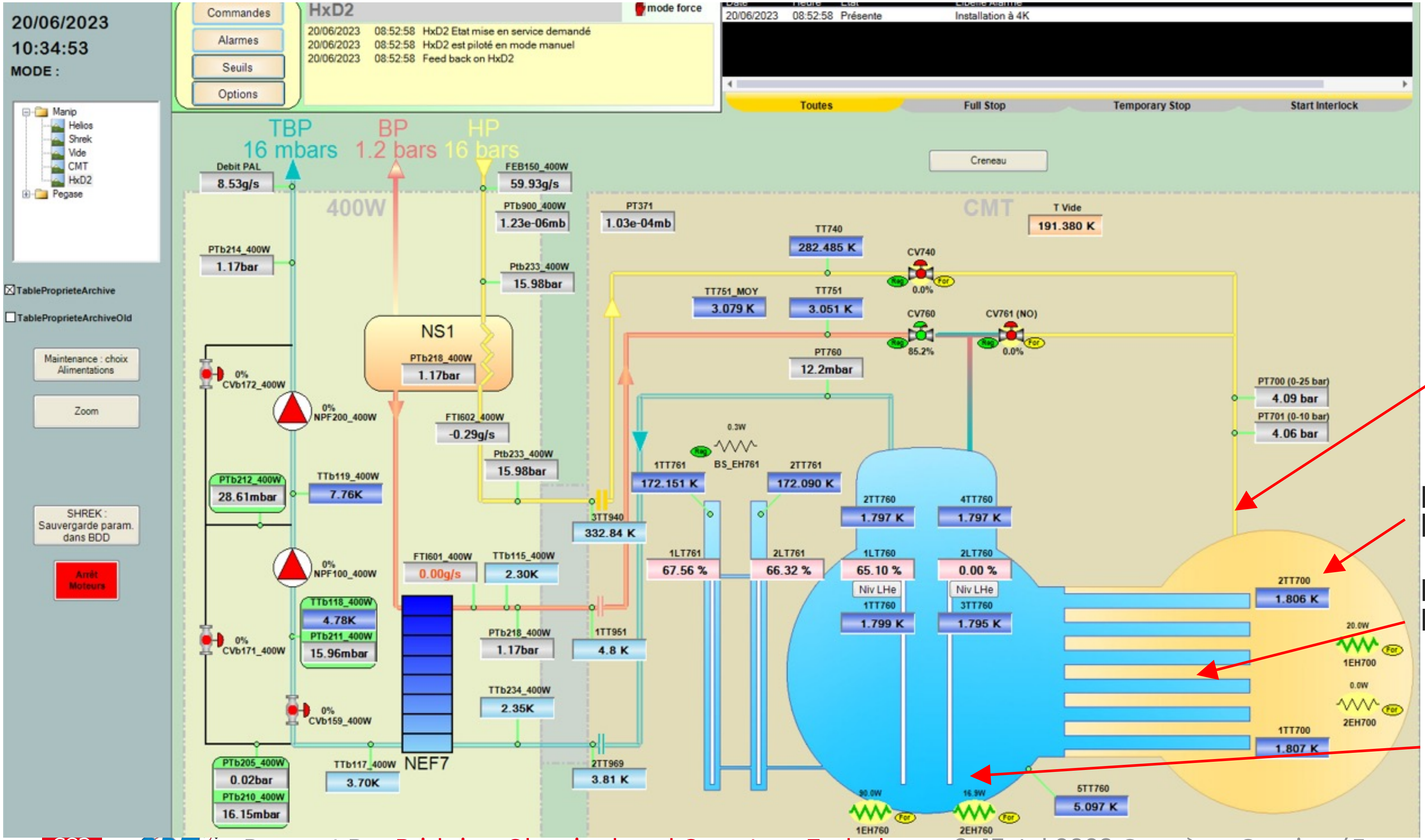
To avoid any risk of nucleate or film boiling, fluid should be at a pressure higher than critical pressure (2.2 bar for helium)

This corresponds to 140 m of equivalent liquid helium height, and can not be obtained by means of hydrostatic pressure at laboratory scale.

A dedicated pressurized bath connected to a cold source (saturated bath) must be used. Pressure is decoupled from temperature, enabling the same fluid density to be achieved at different temperatures, whether in normal helium or superfluid.



Working with large velocities without cavitation and/or boiling:



Example of He II double bath : test of a heat exchanger for HL-LHC

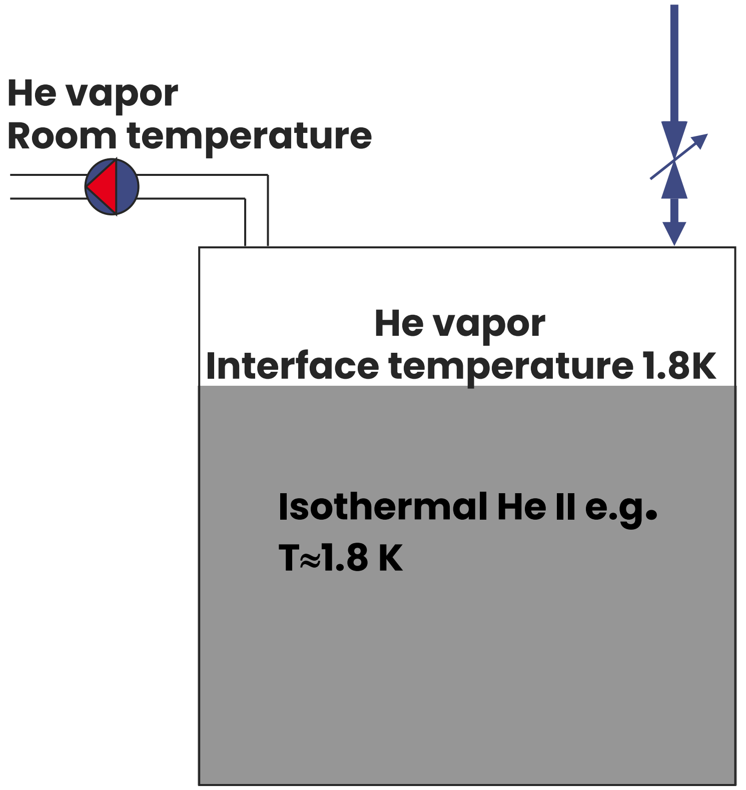
Filling line (and connection to pressure sensor, safety valves…)

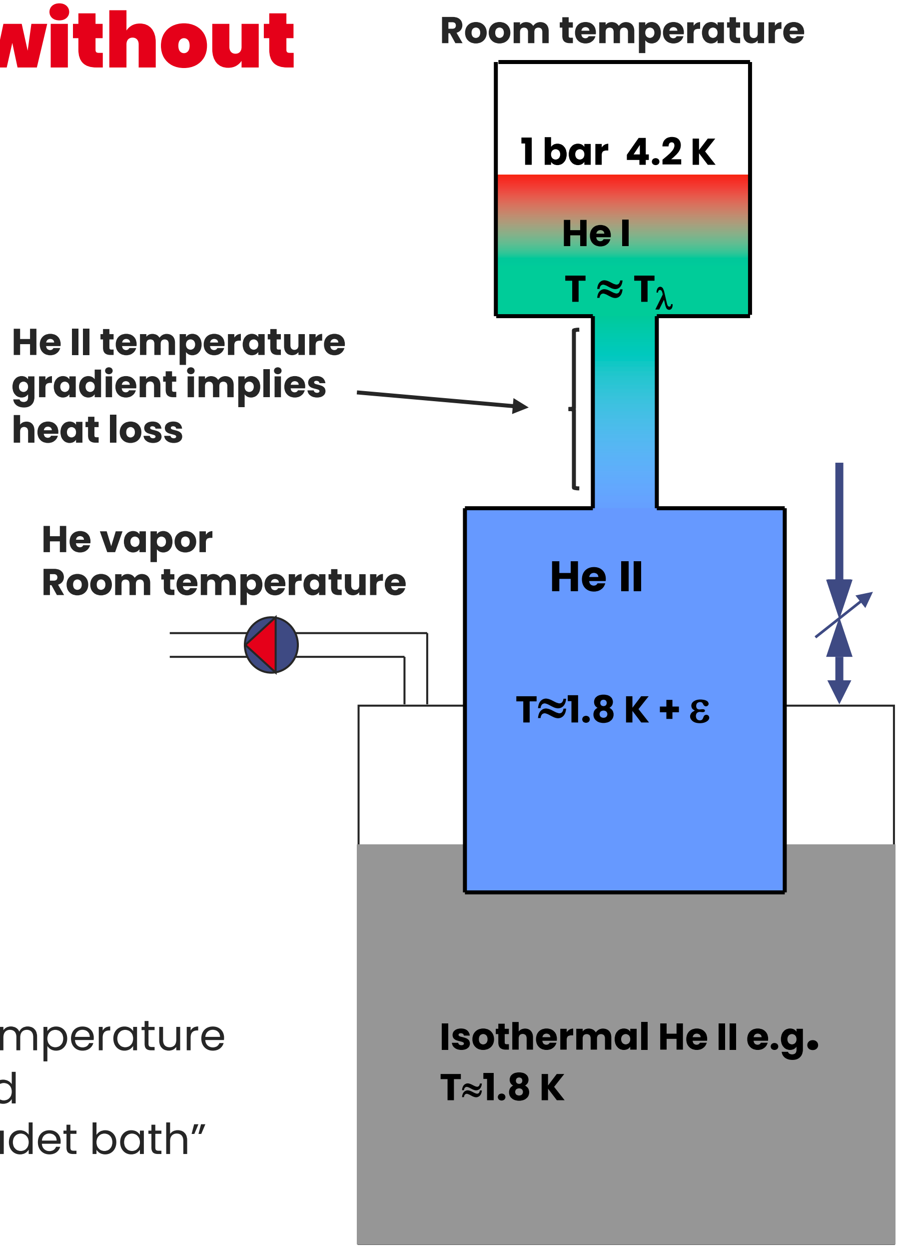
Pressurized subcooled He II bath

Pressurized He II/saturated He II heat exchanger

Saturated He II bath (cold source)

Working with large velocities without cavitation and/or boiling:





Main problem of double bath concerns the connection with temperature higher than $T\lambda$ (safety valve, pressure measurement, filling and pressurization pipes) and justify that this technic named "Claudet bath" was only employed recently and remains rare.

Working with large velocities without cavitation and/or boiling:

Inside He II, assuming 1D heat flow, ΔT obeys to the law :

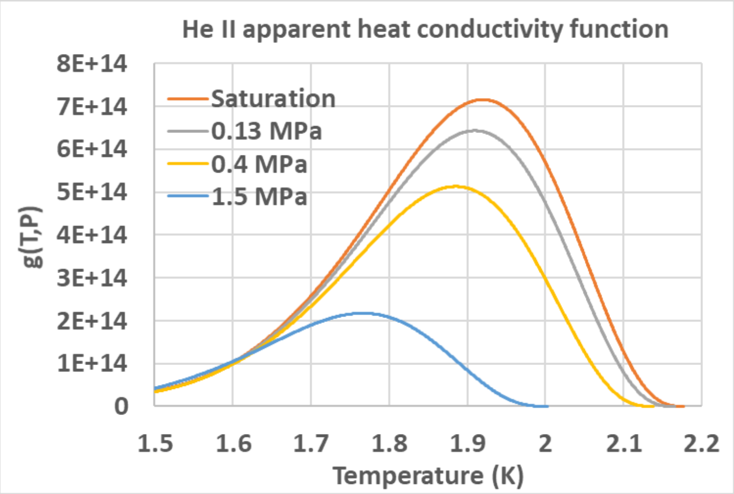
$$q^{3.4}.\,dx = -g(T,P)dT$$

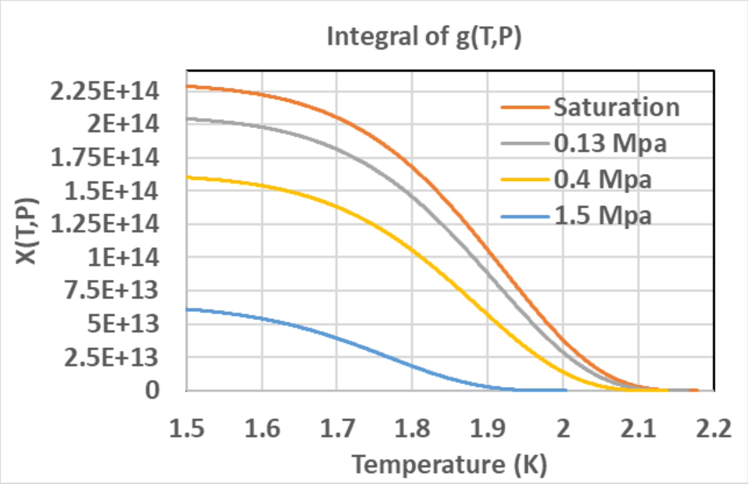
$$W^{3.4}.\,dx = -S^{3.4}\,g(T,P)\,dT$$

$$W^{3.4}.\,dx = -S^{3.4}\int_{T(0)}^{T(L)=T_\lambda} g(T,P)dT$$

$$W = -\frac{S}{L^{\frac{1}{3.4}}}\left(\int_{T(0)}^{T(L)=T_\lambda} g(T,P)dT\right)^{\frac{1}{3.4}}$$

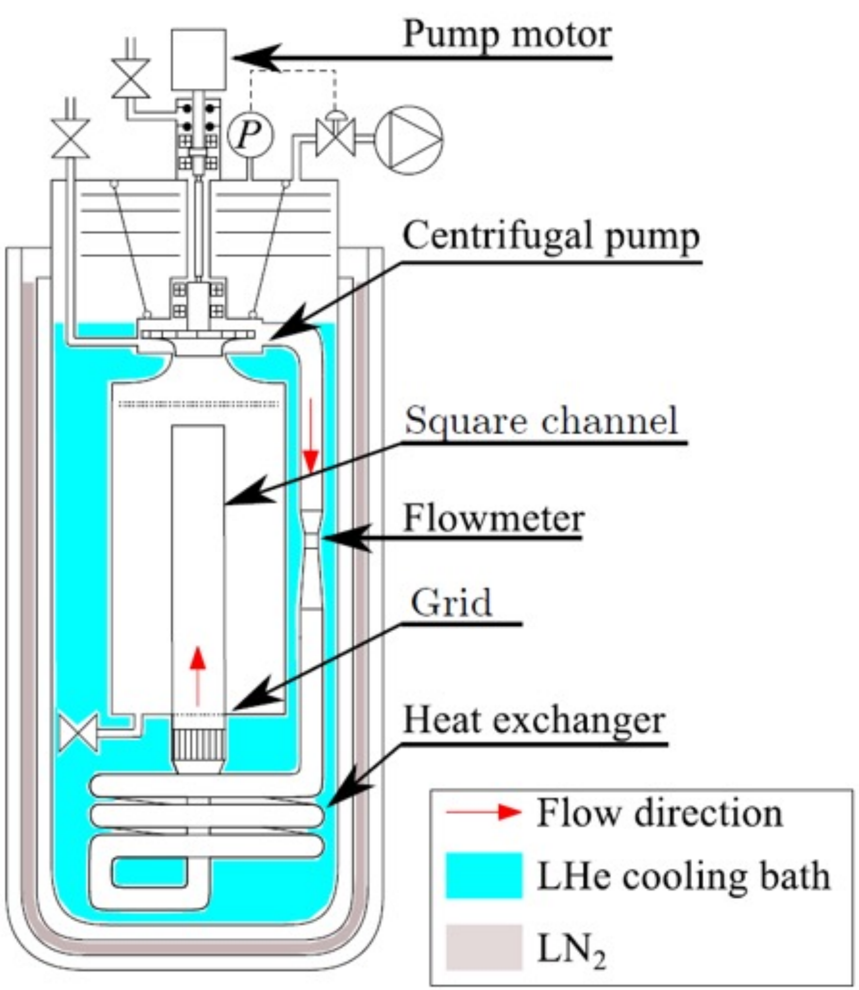
Must be very small

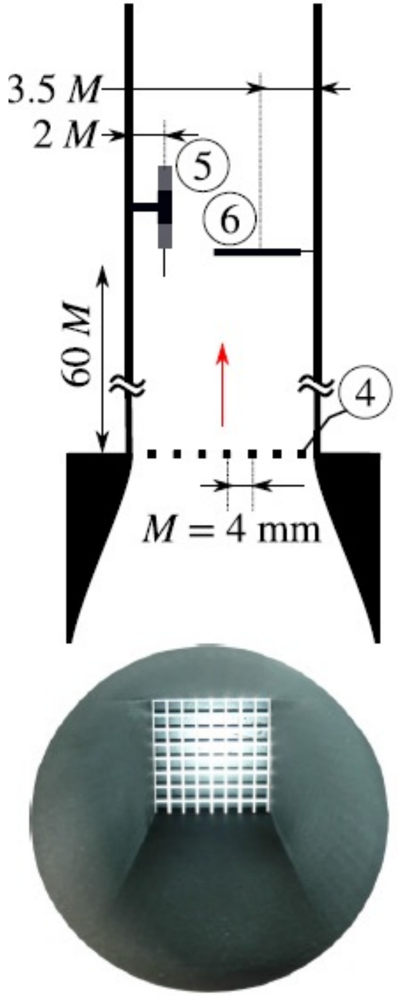




Main problem of double bath concerns the connection with temperature higher than Tλ (safety valve, pressure measurement, filling and pressurization pipes) and justify that this technic named “Claudet bath” was only employed recently and remains rare.

Passive grid flow : Hegrid





Flow properties :

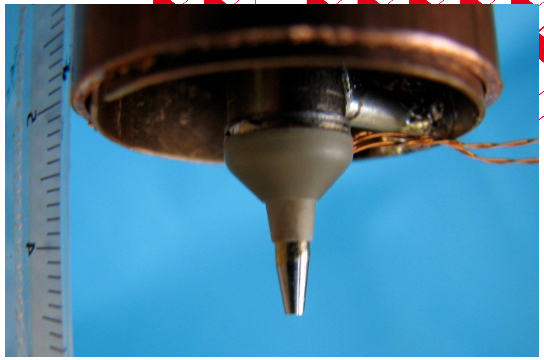
- 32 mm square channel.
- Grid mesh $M = 4$mm
- Integral length scale of order M
- Small turbulence ratio

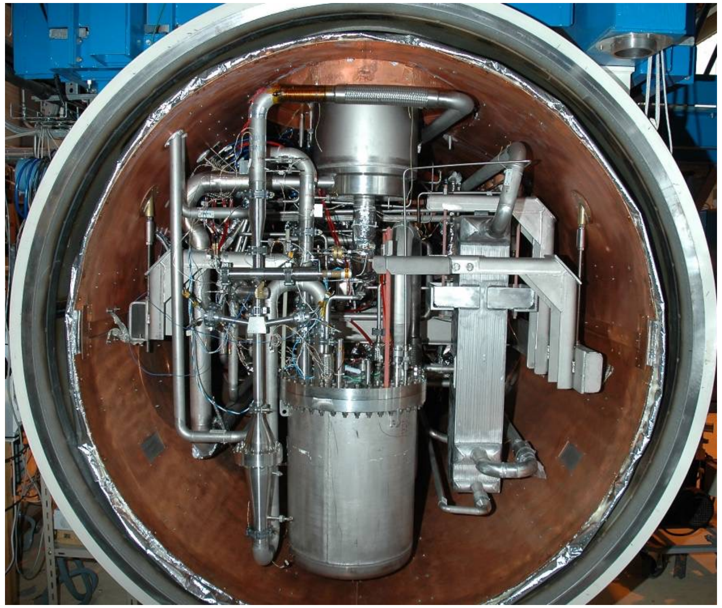
Hegrid experiment provide insight about behavior of miniature heaters (like "hot wire") in a subsonic He II flow

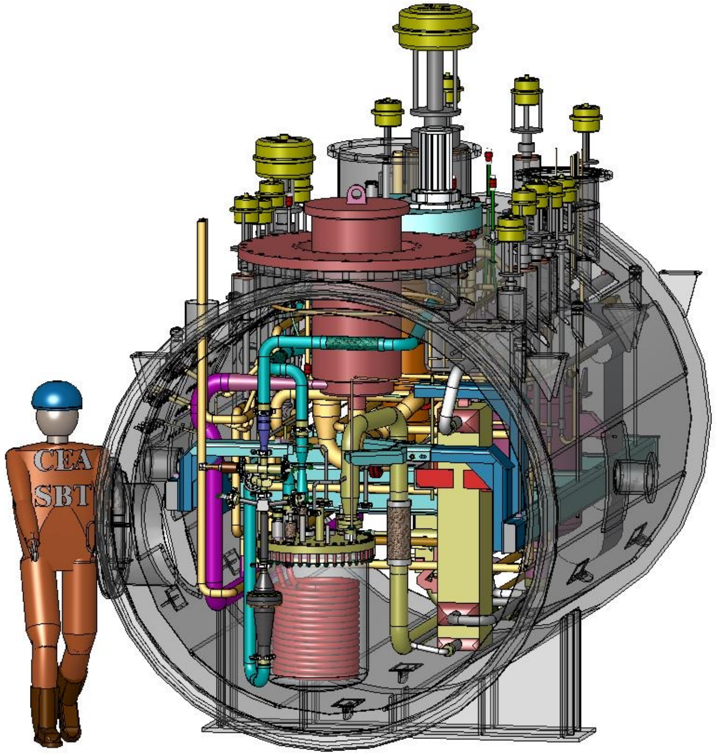
See the designer/user Pantxo D. for more details

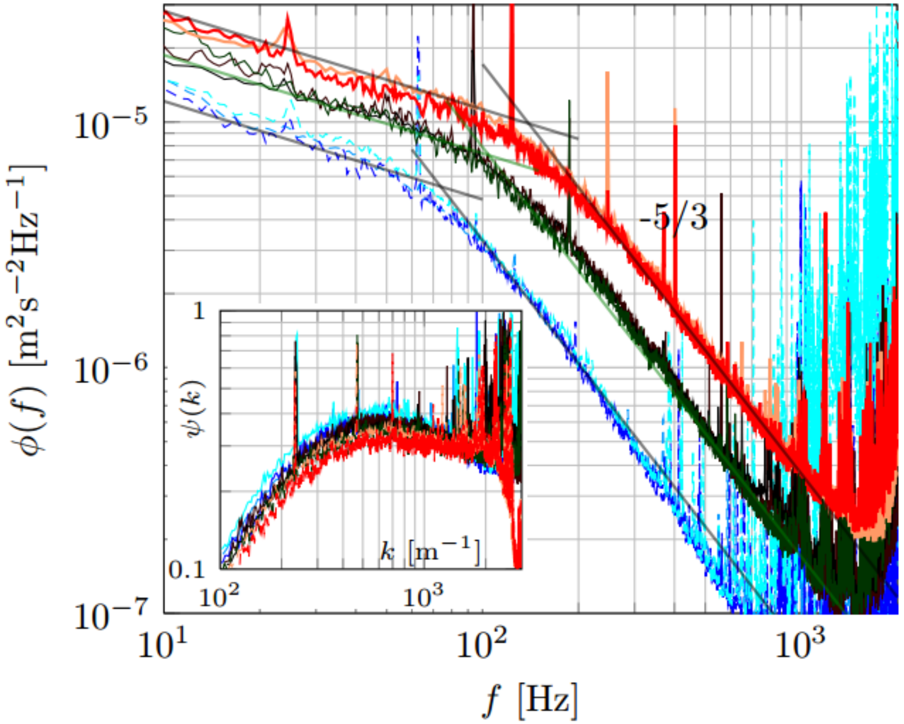
Passive grid flow : TSF

- Rλ (calculated for He I) up to 350 was achieved

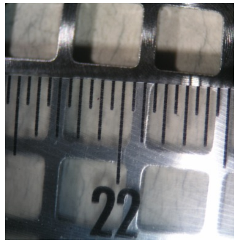




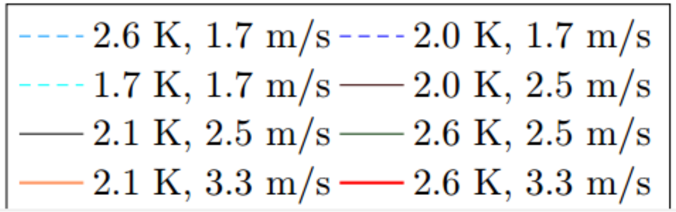




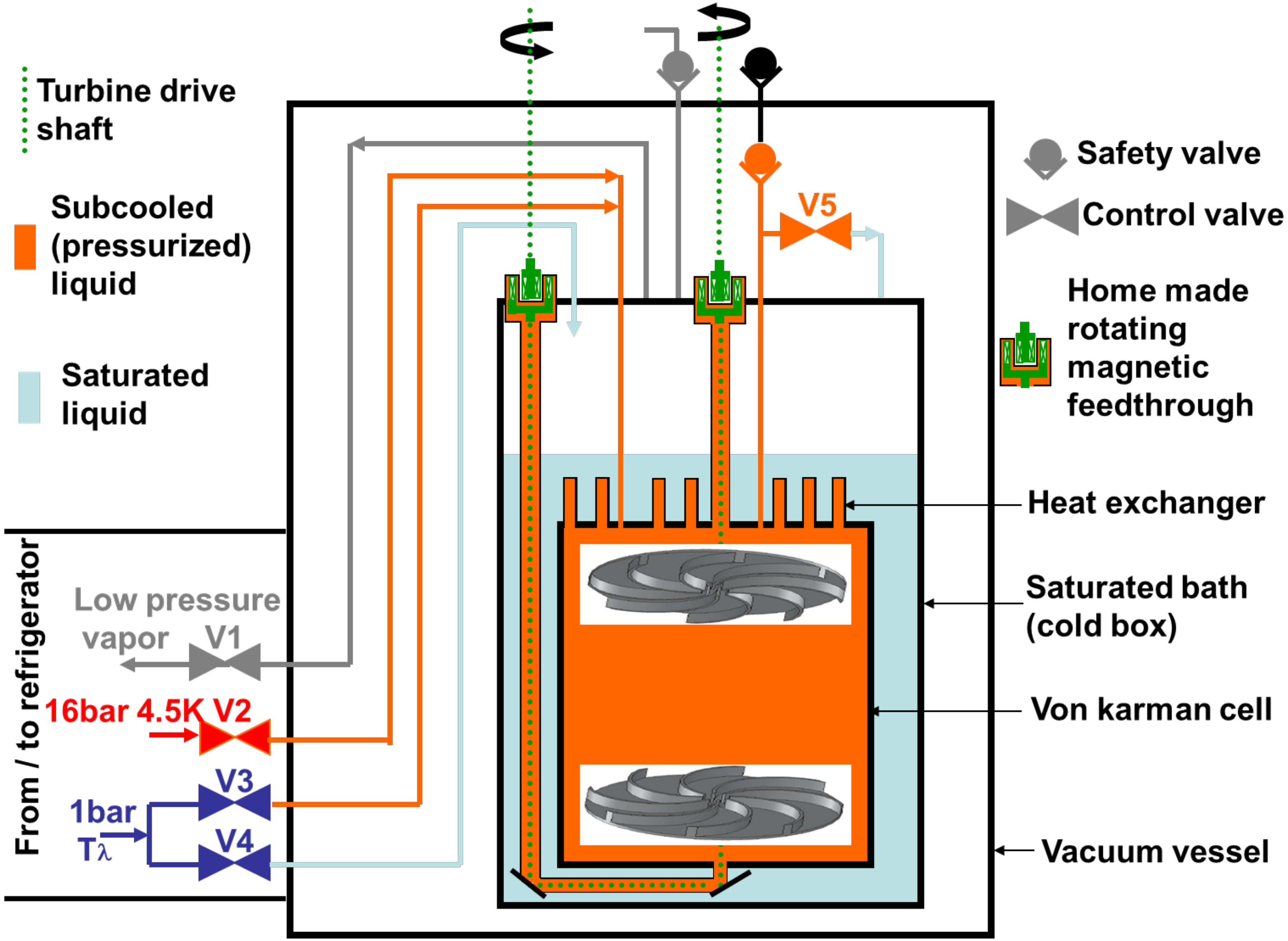
Detail of the grid



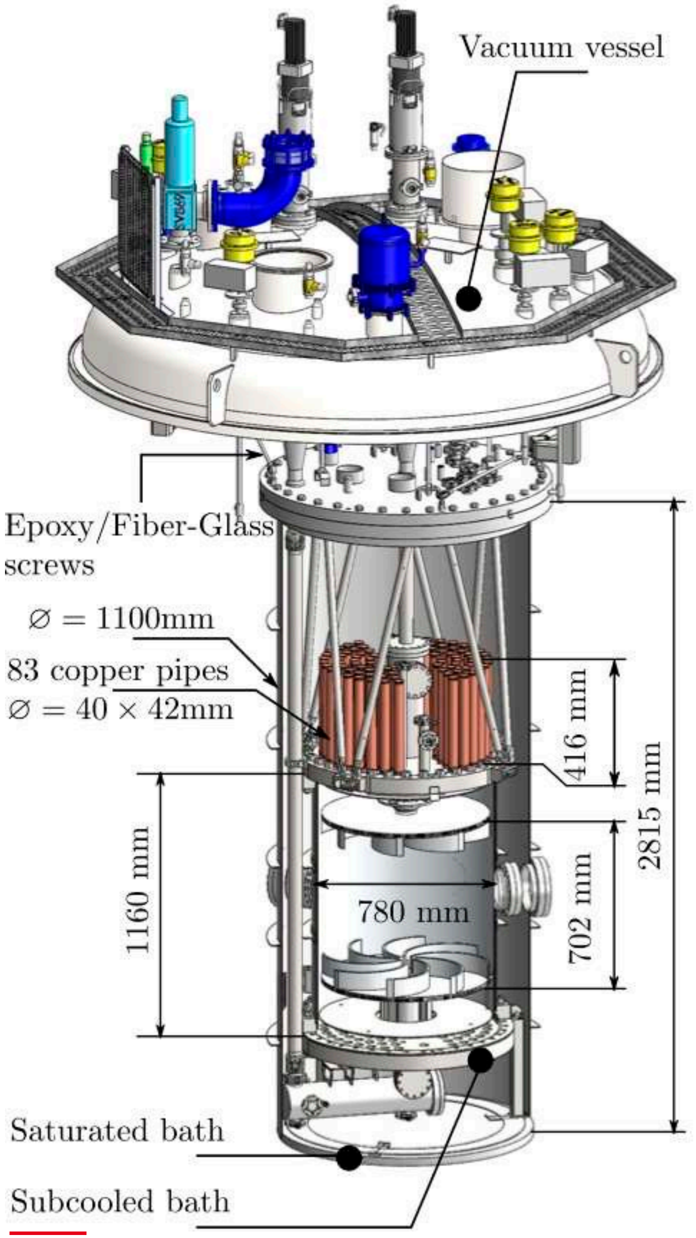
DSP based on micro-pitot measurements (courtesy of Julien Salort)



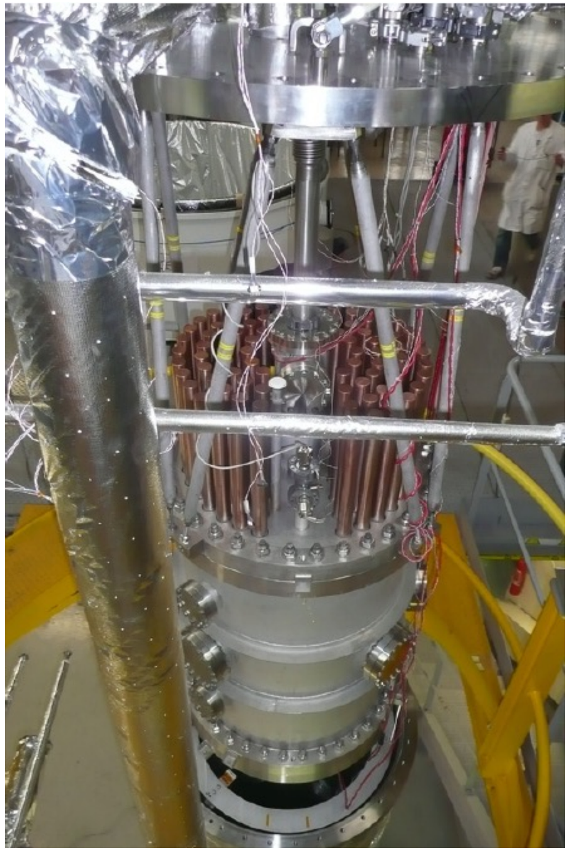
Giant von Karman flow : SHREK conceptual design



SHREK control parameter allowing to reach Rλ=10000

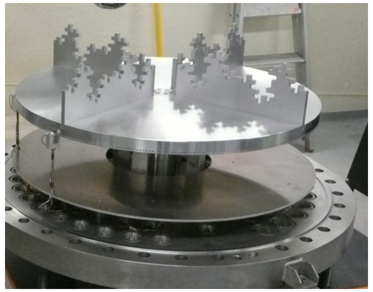


2 propellers rotating co/counterclockwise at the same/different frequencies $f1$ and $f2$. **Control parameters :** $\theta = \dfrac{f1 - f2}{f1 + f2} \in [-1; 1]$



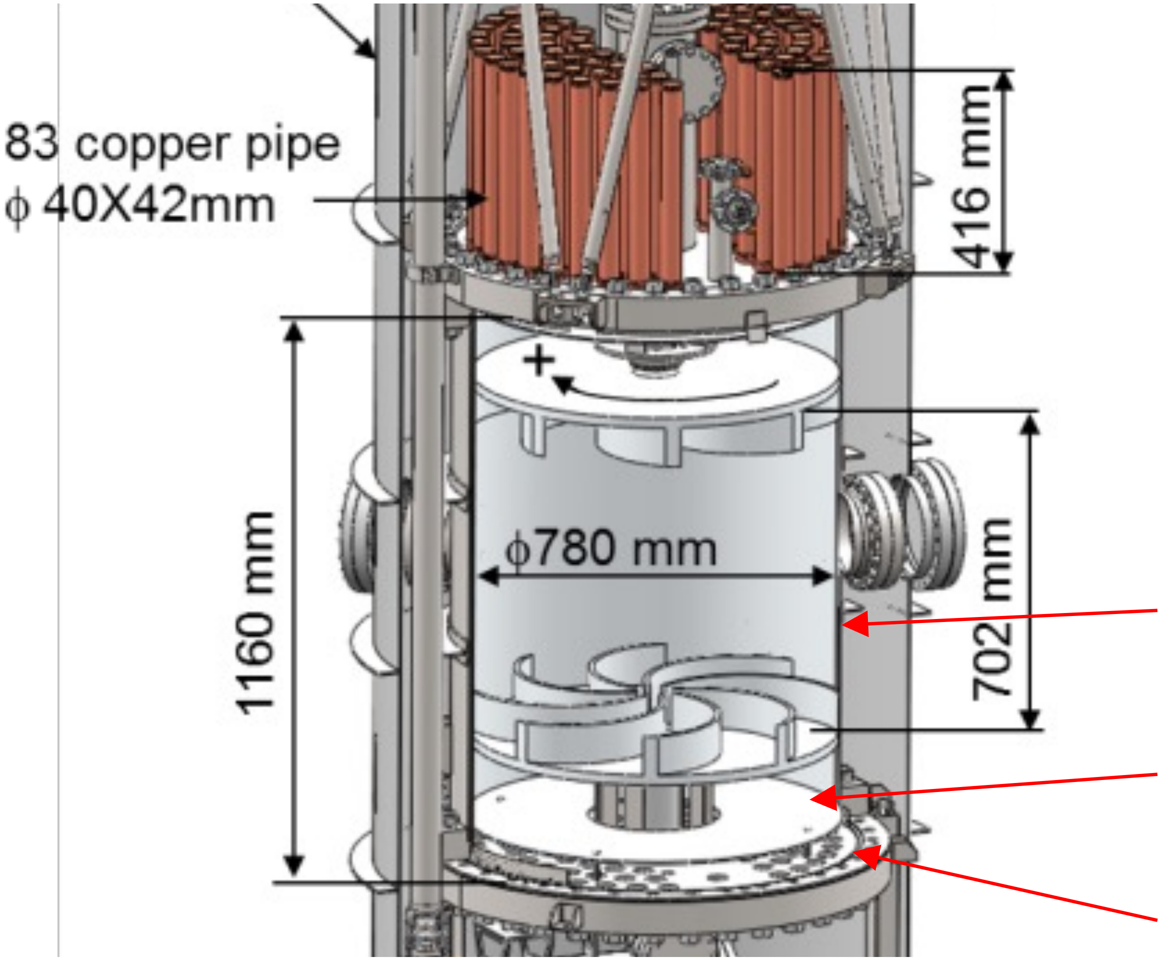
$f1 \in [-2; 2]$hz $\longrightarrow$ $Re = \dfrac{\rho.2\pi f R^2}{\mu} \leq 10^8$

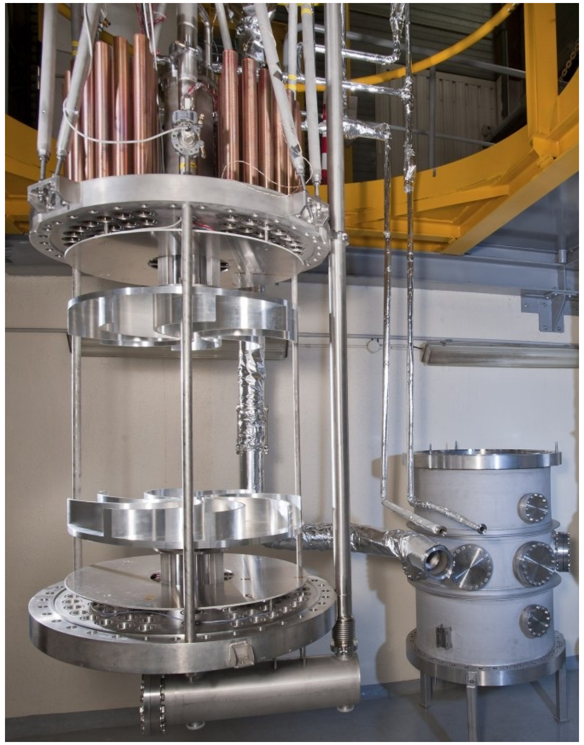
$1.6 \leq T \leq 4.2K$ $\quad$ $1 \leq P \leq 4 Bars$



Different types of propellers are available : curved blades, radial straight blades, radial fractal blades…

Giant von Karman flow : SHREK



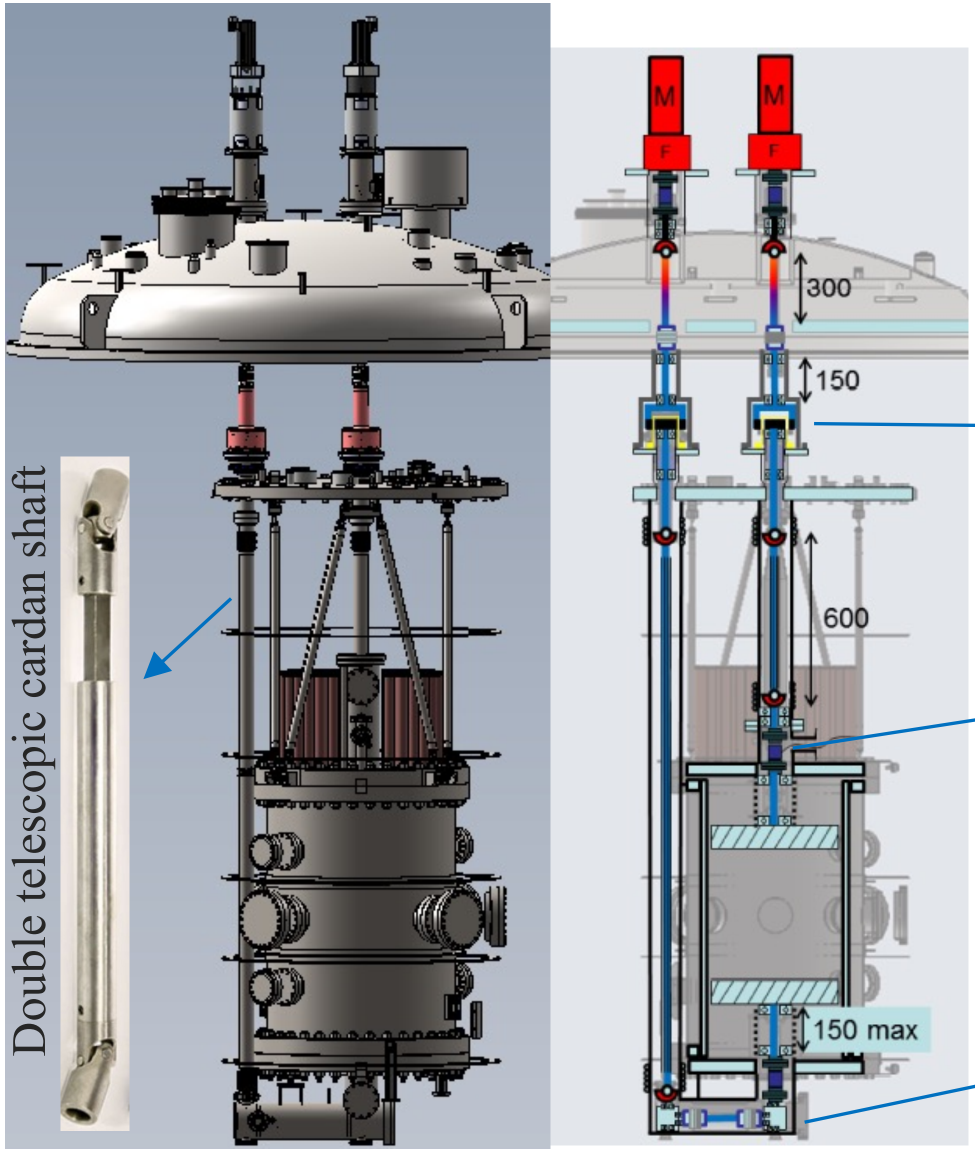


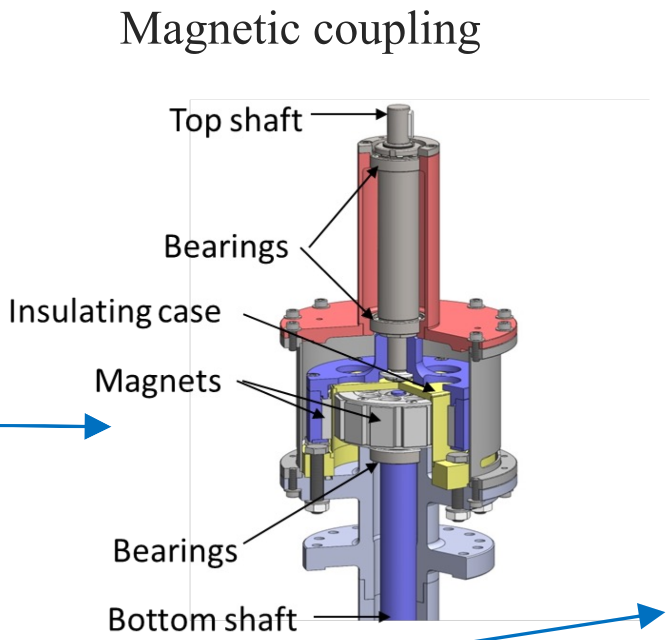
An aluminum sleeve is inserted, to avoid flow perturbations due to lateral flanges

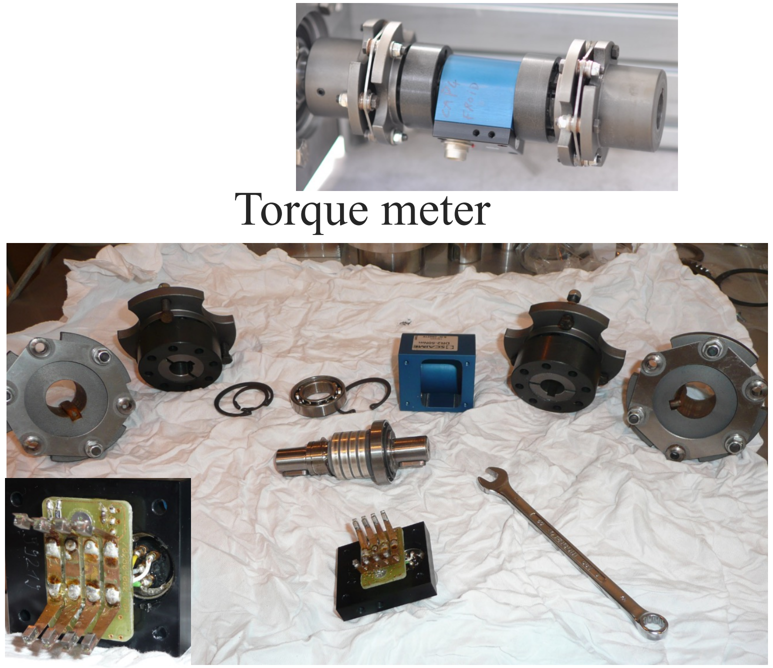
Static plate used for hydraulic purpose and support of electrical heater at the rear side

To insure a perfect symmetry, blind holes are drilled at the bottom plate to mimic the entrance of the top plate heat exchanger

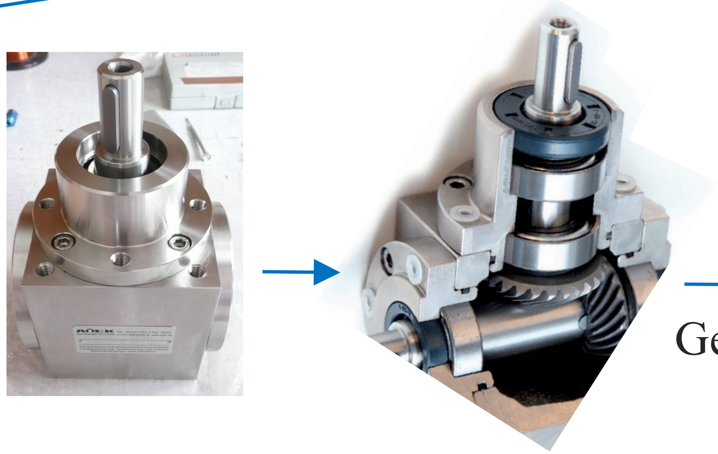
SHREK : some technological details





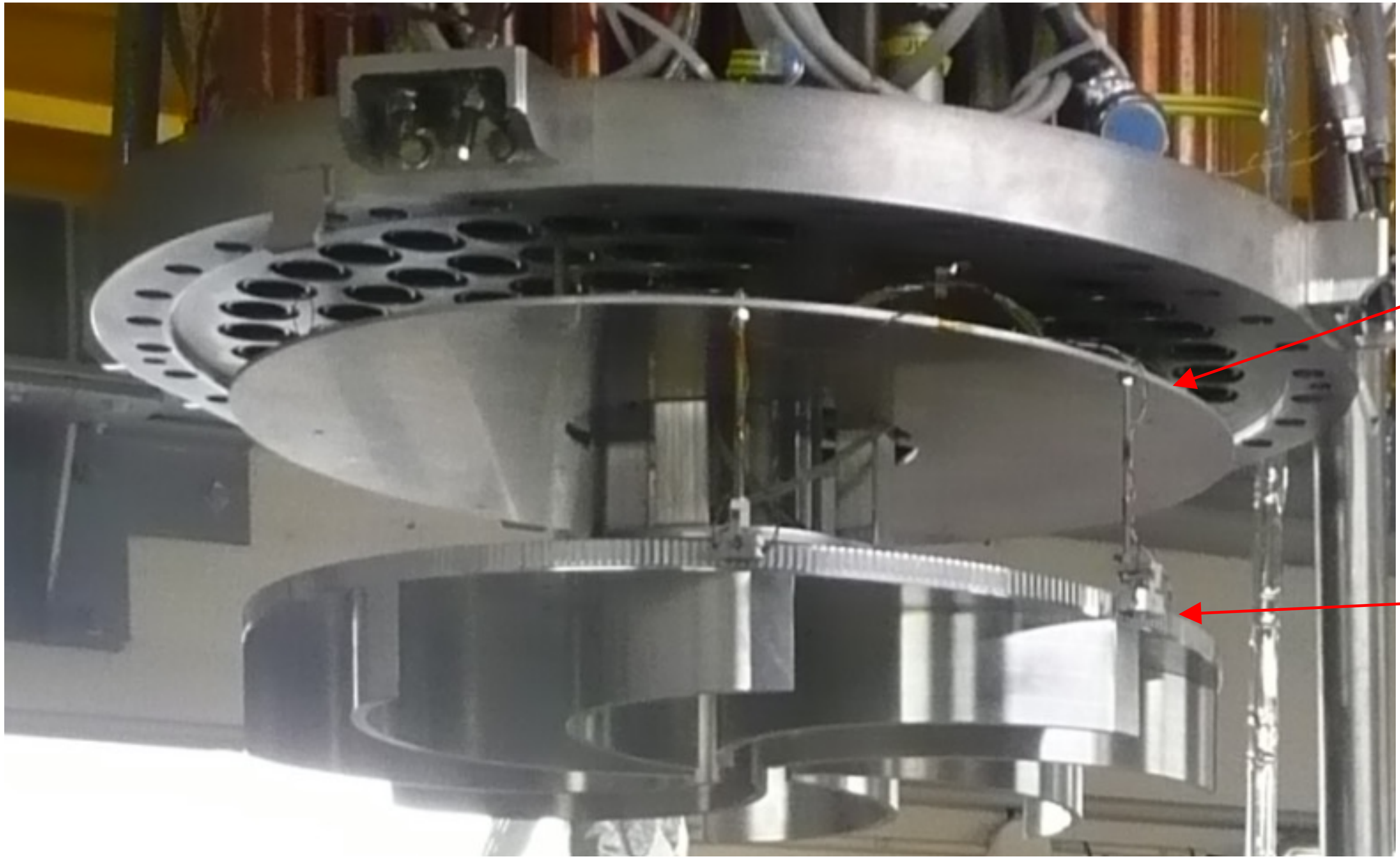


Torque meter



Gearbox

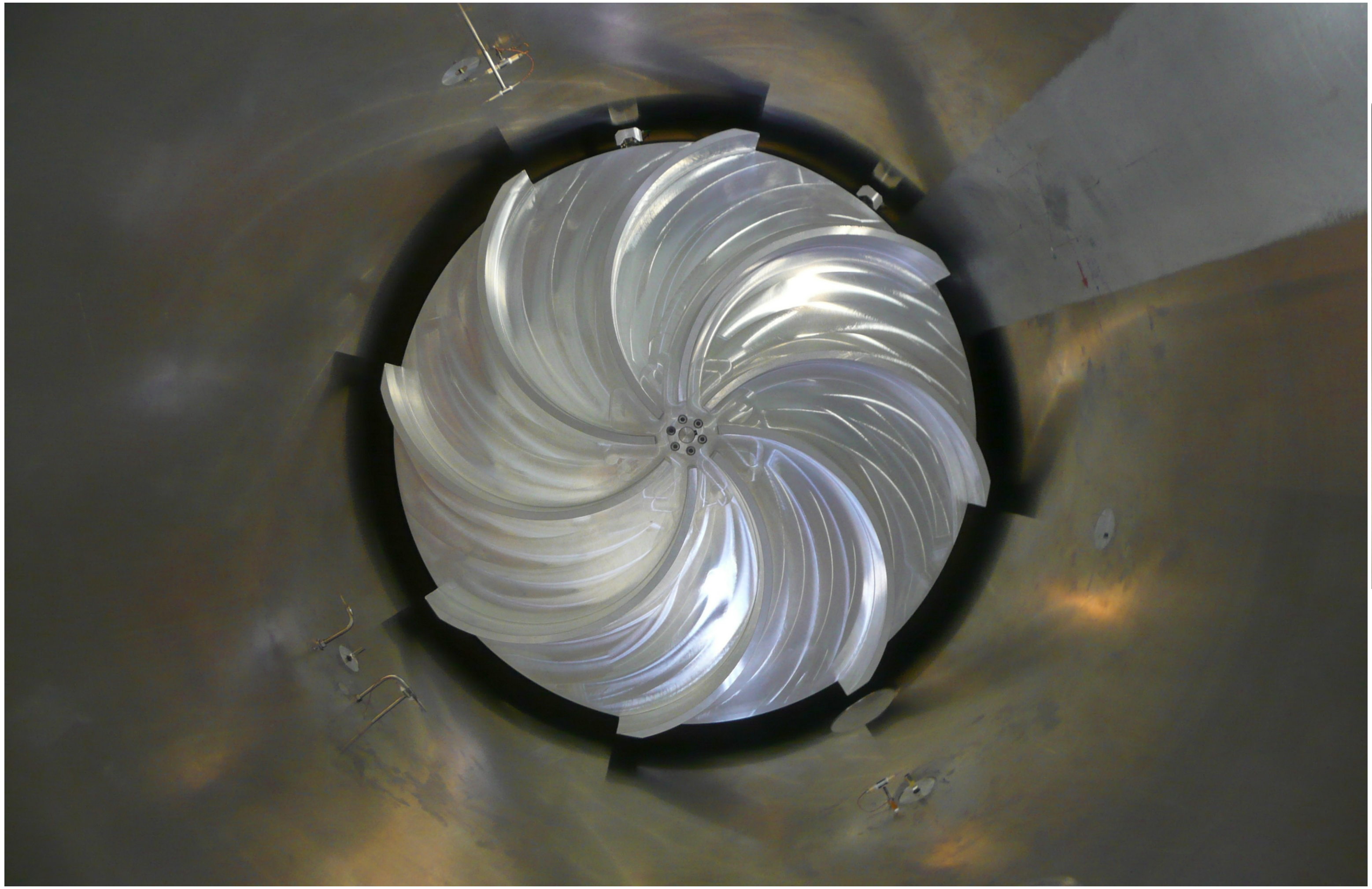
Giant von Karman flow : SHREK

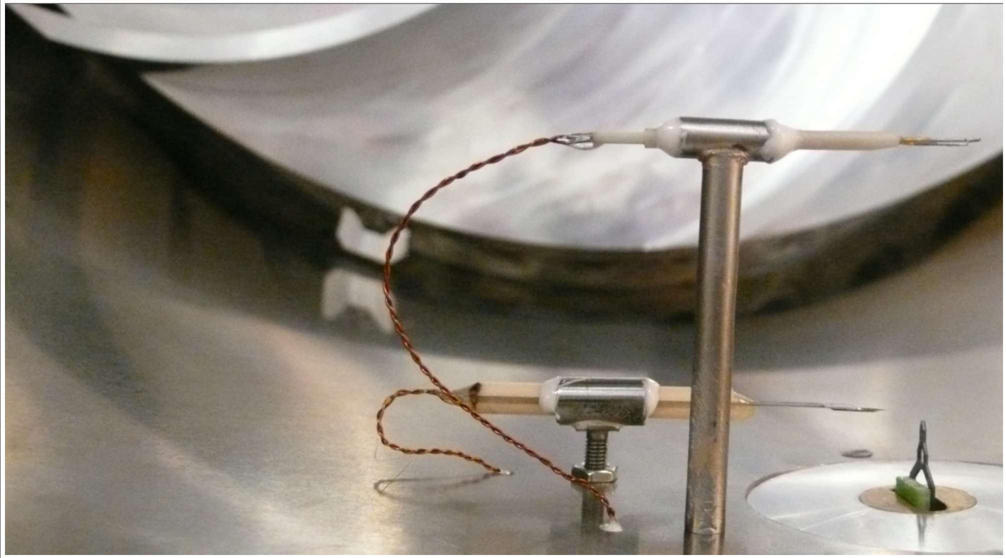


Static plate used for hydraulic purpose and support of electrical heater at the rear side

All-degree slots for illumination/reflection diode/photodiode for rotation frequency measurement

Giant von Karman flow : SHREK

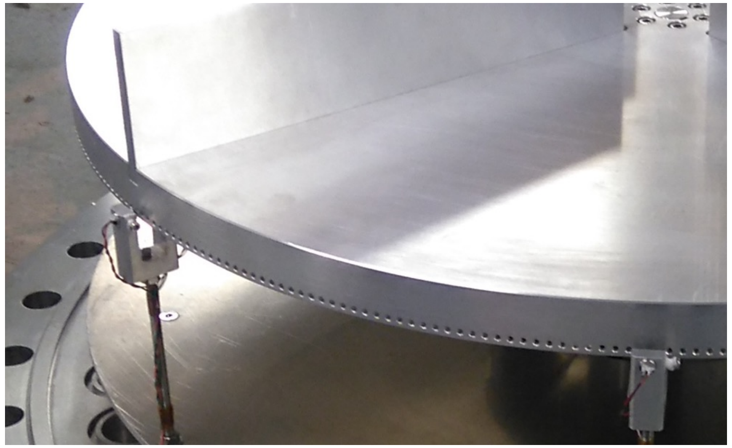


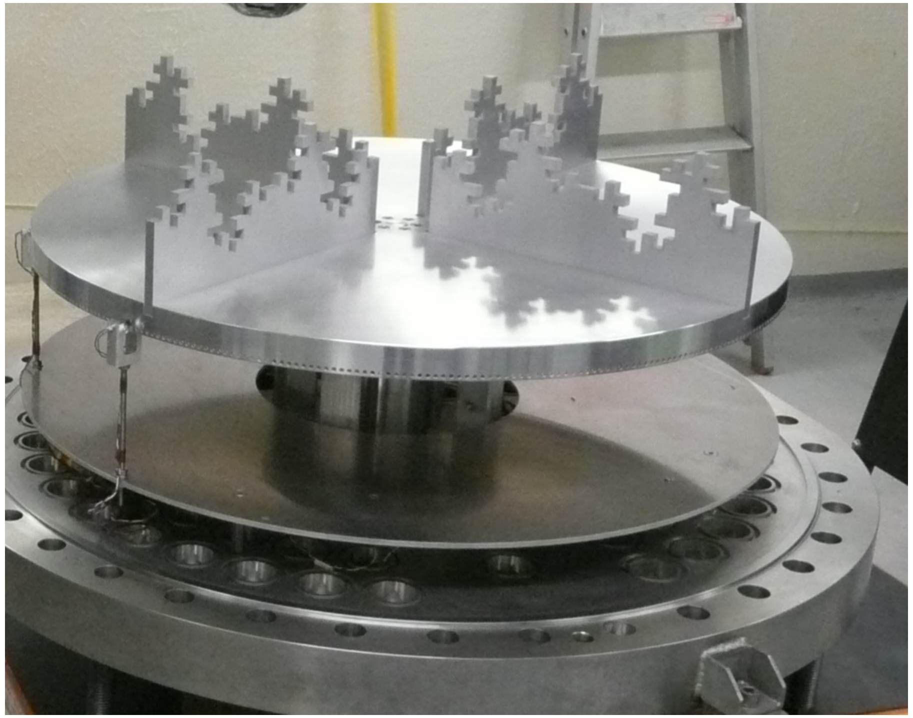


Aluminum sleeve equipped with small Eulerian sensors

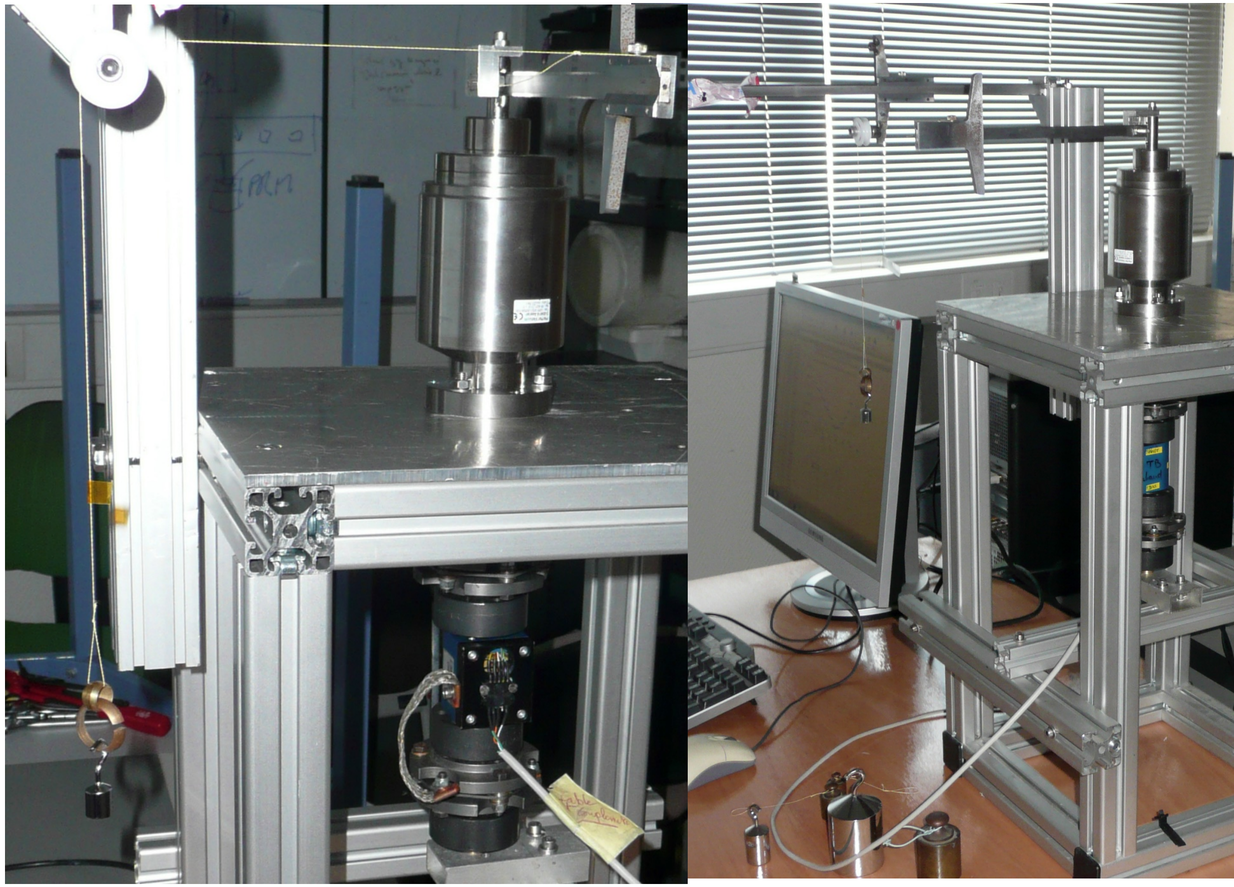
SHREK : various configurations

Various blade shapes were tested. Different rotational frequency measurements were also used.
Optical diodes or capacitive sensors are employed to "track" uniformly distributed holes at each degree.



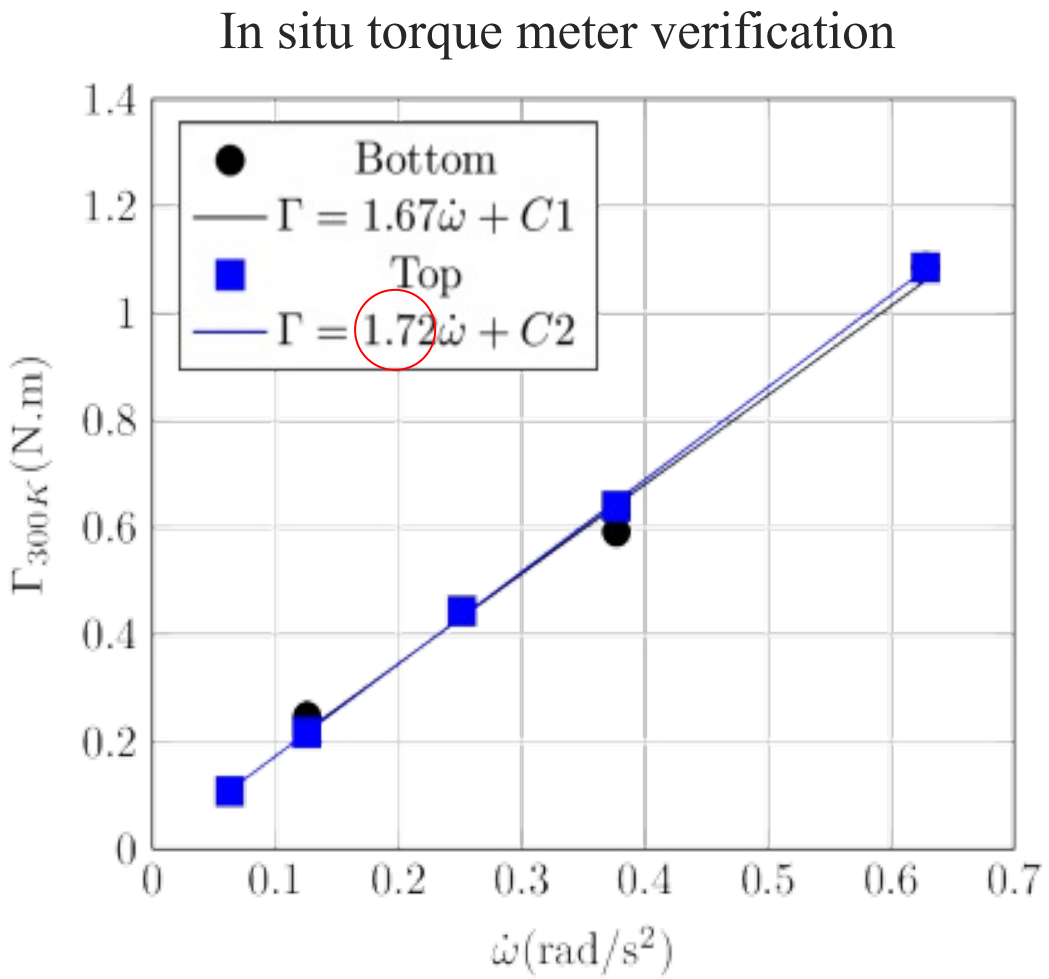


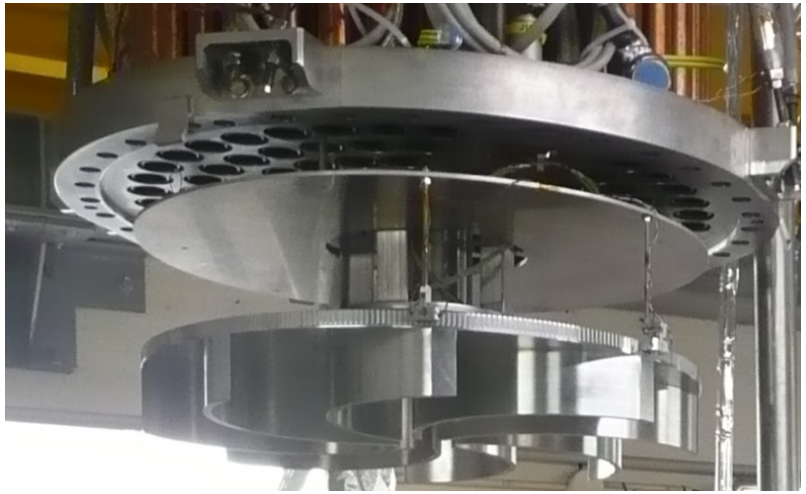
SHREK : global measurements (Torque meter calibration)



SHREK assembly before every run

SHREK : global measurements (Torque meter in-situ "calibration")



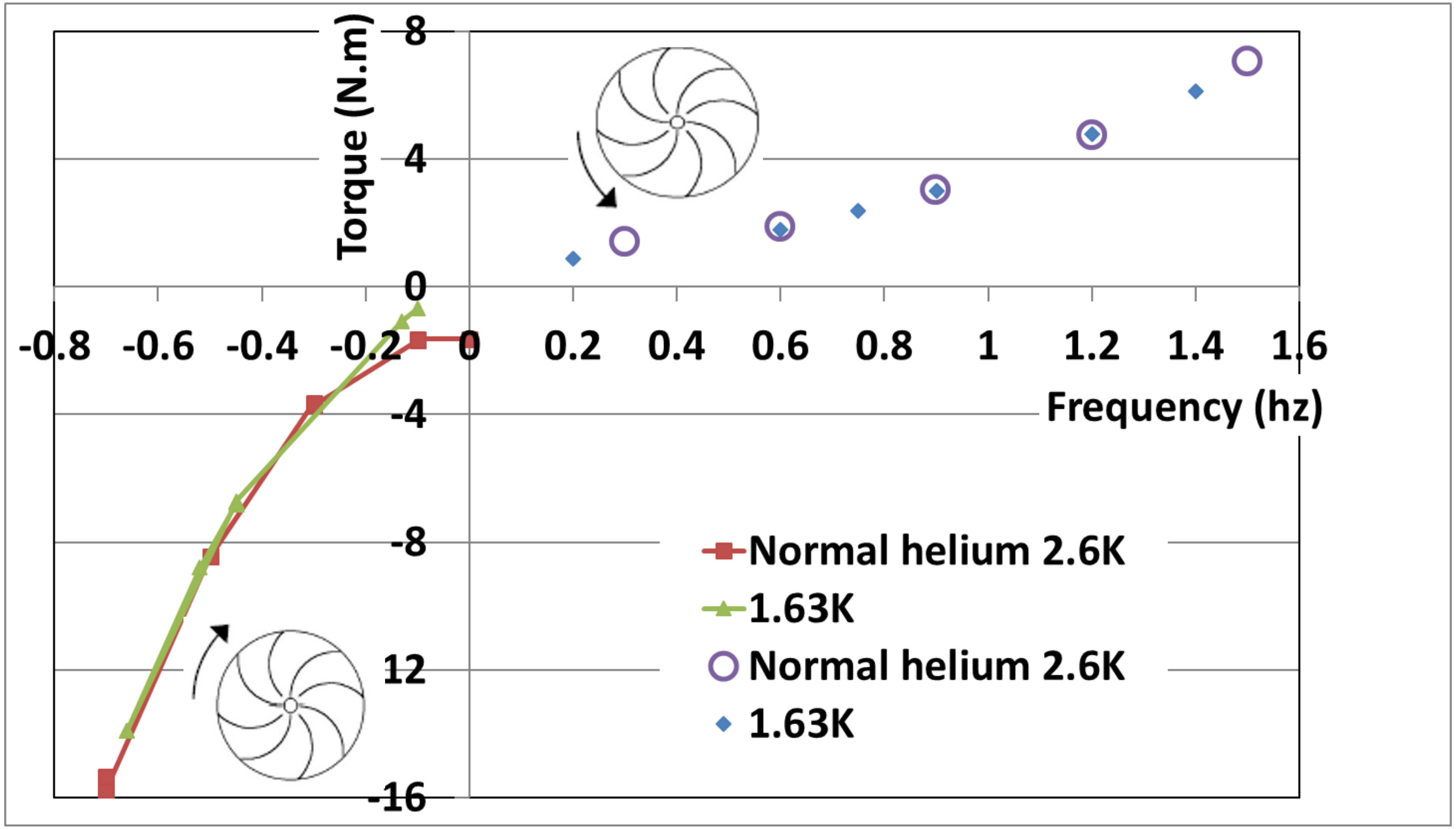


$$\Gamma_{300K} = I\dot{\omega} + \Gamma_{static} + \Gamma_{fluid}$$

1.7kg.m² is the moment of inertia calculated using solidworks CAD software

SHREK : global measurements (torque meter results)

The propellers rotate in counter rotation at the same frequency (f)



$$\omega_i = 2.\pi.\,f_i$$

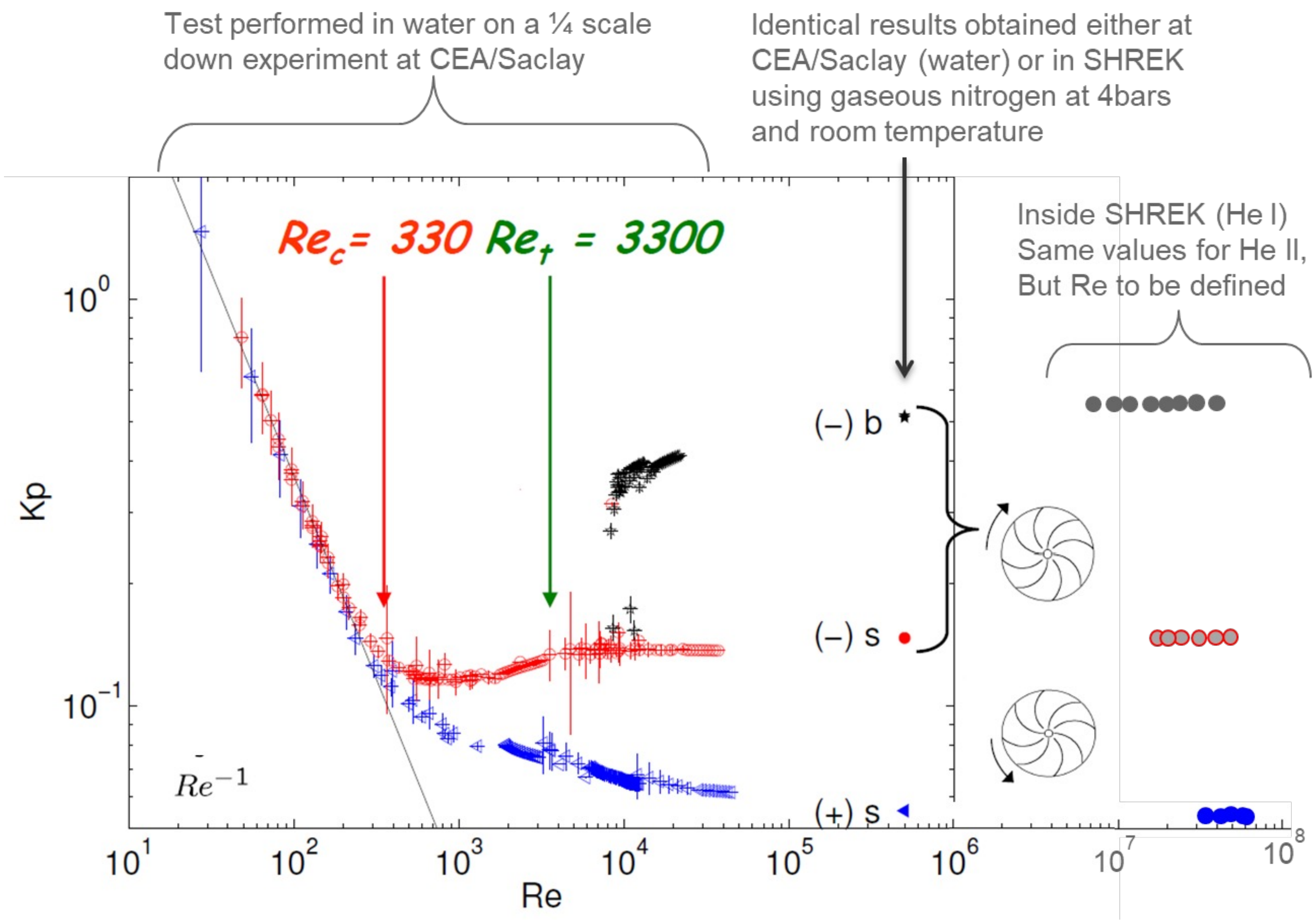
$$\langle \varepsilon \rangle = \frac{\Gamma_1 \omega_1 + \Gamma_2 \omega_2}{M_{fluid}}$$

$$M_{fluid} = \rho_{fluid}.V$$

$$\rho_{he(1.63K,4bar)} = 152\ kg/m^3$$
$$\rho_{he(2.6K,4bar)} = 152\ kg/m^3$$

These non local measurements indicate that total injected kinetic energy flux is identical for He II and He I.

SHREK : global measurements (torque meter results)



$$\omega_1 = \omega_2 = \omega$$

$$Re = \frac{\omega R^2}{\nu}$$

$$K_p = \langle \varepsilon \rangle_{adim} = \frac{(\Gamma_1 + \Gamma_2).\omega}{2.\rho.R^5.\omega^3}$$

SHREK : global measurements

Closed flow allow measurements of both injected and dissipated power providing SNR is high enough.
It also required « statistically stationnary turbulence » and absence of any drift during the measurements.

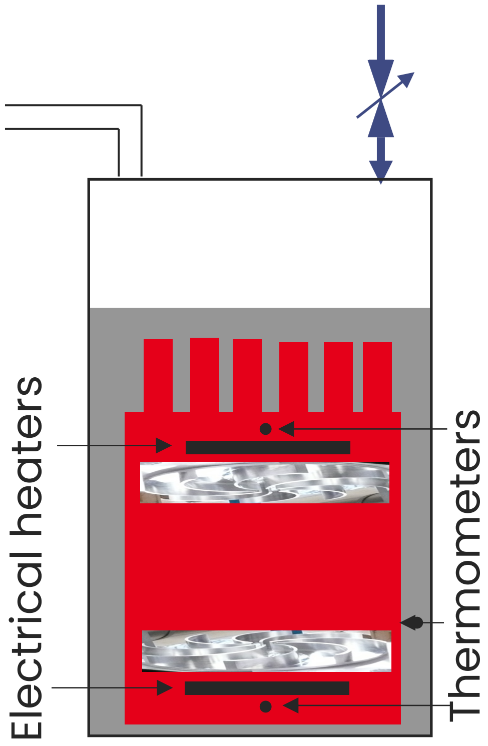
Injected kinetic energy flux $\langle \varepsilon \rangle = \dfrac{\Gamma_1 \omega_1 + \Gamma_2 \omega_2}{M_{fluid}}$

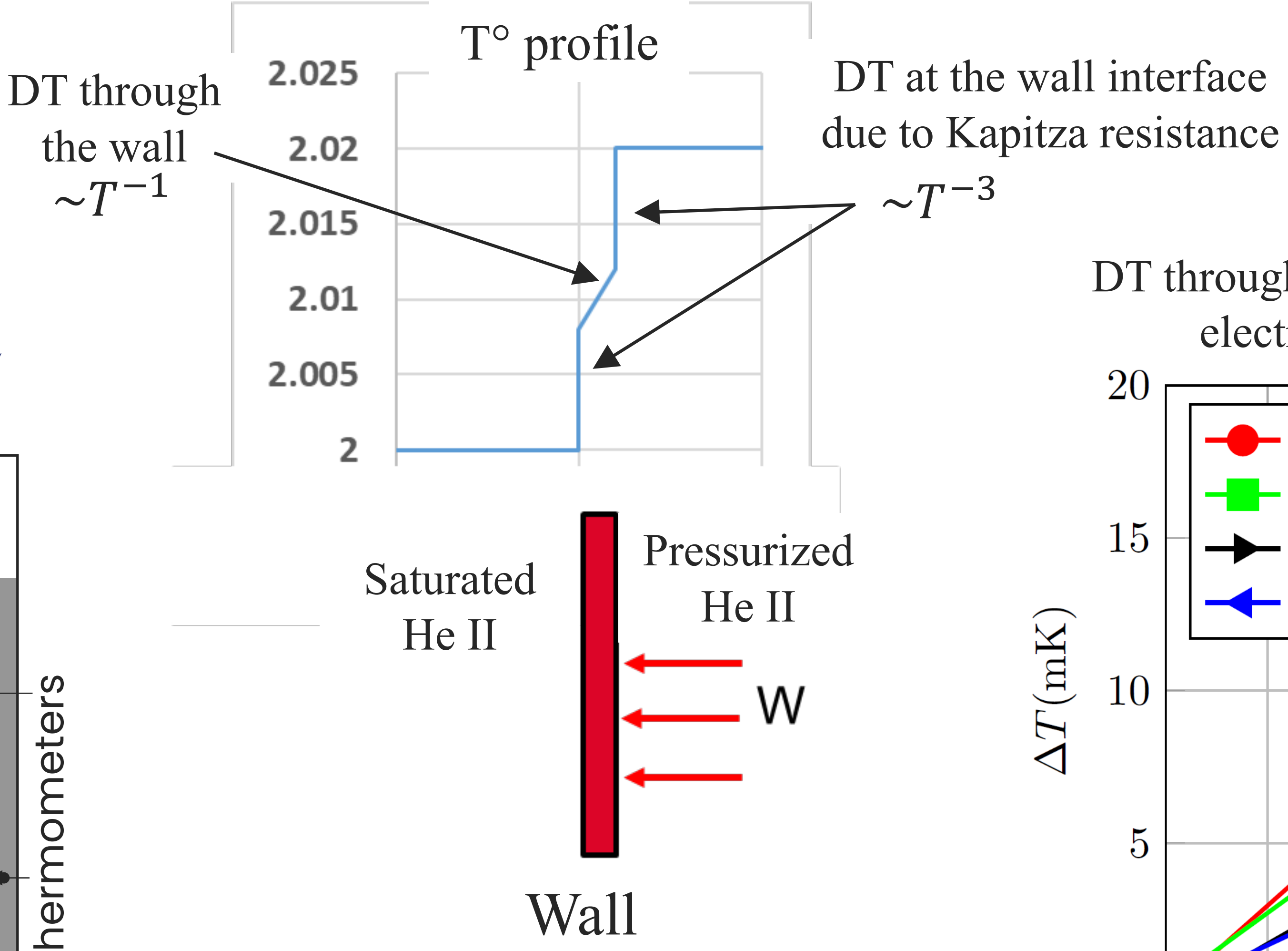
Dissipated kinetic energy flux $\langle \varepsilon \rangle = \dfrac{W}{M_{fluid}}$

Dissipated power W can be access by vapour mass flow produced by the cold source to absorb energy coming from the internal flow, but usually it is very tricky as other loss (radiation and conduction losses, evolution of external environment...) induces very low SNR.

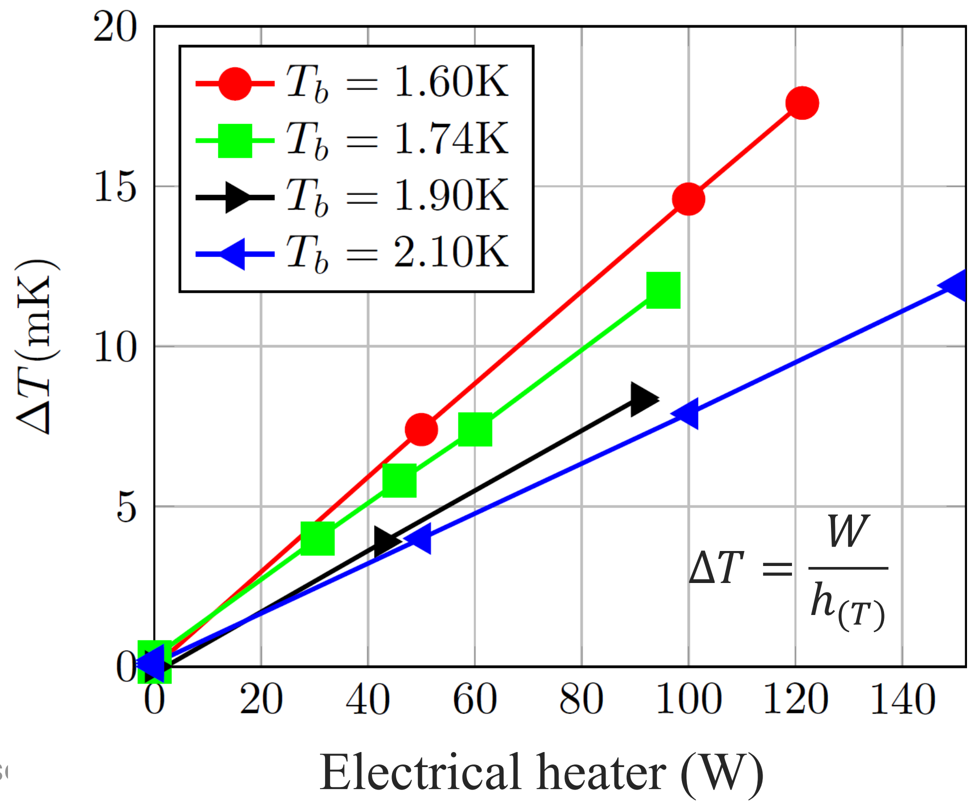
Another solution is possible in superfluid with the « Claudet bath » configuration.

SHREK : global measurements (power dissipation calibration using heaters)





DT through Shrek heat exchanger for different electrical powers and temperatures

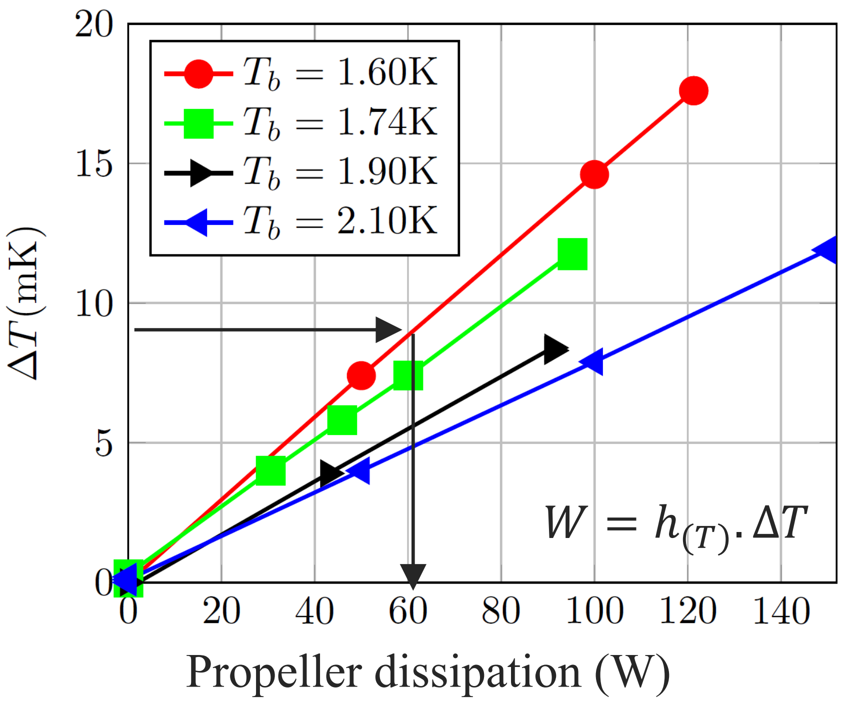


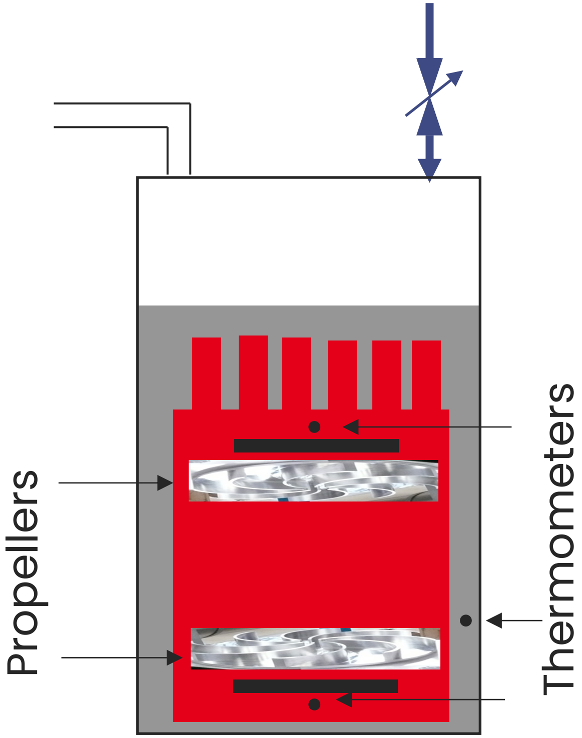
SHREK : global measurements (power dissipation measurements)

Using electrical heaters and propellers are rest, we have established the law $\Delta T = \dfrac{W}{h_{(T)}}$

With no electrical power and propellers running, power dissipated by propellers is calculated with $W = h_{(T)}.\Delta T$ no matter existing heat loss on saturated bath

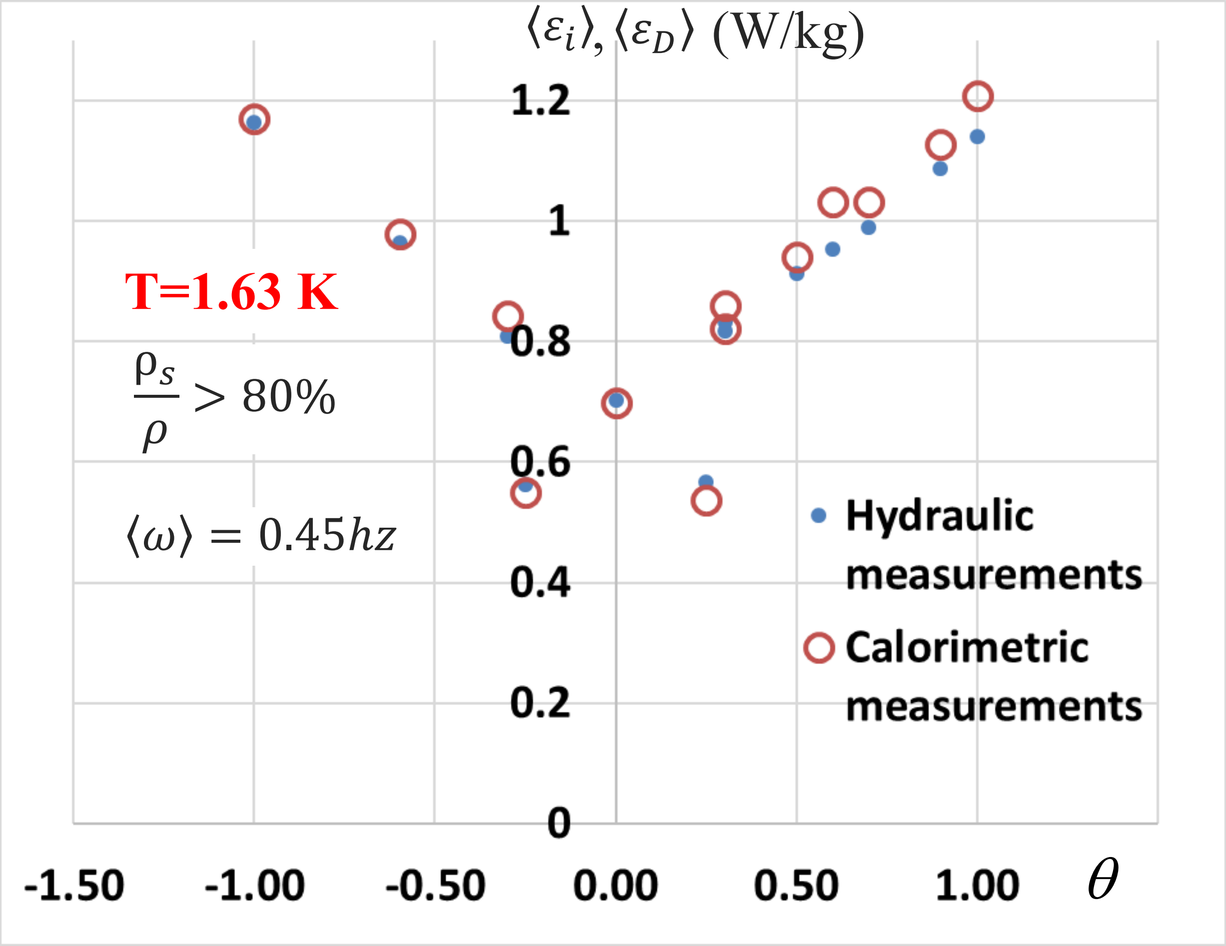
Furthermore, saturated bath surrounding the von Karman cell allow to minimize heat loss





SHREK : global measurements

$$\varepsilon_{(W/kg)} = \frac{\nu^3\, Re^3}{L^4}$$



Injected kinematic power :

$$\langle\varepsilon_i\rangle = \frac{\Gamma_1\omega_1 + \Gamma_2\omega_2}{M_{fluid}}$$

Γ_i Torque measurement on propeller i

ω_i Frequency measurement on propeller i

$$\langle\varepsilon_D\rangle = \frac{W}{M_{fluid}}$$

W Calorimetric measurement

Mean rotation frequency : $\langle\omega\rangle = \frac{\omega_1 + \omega_2}{2}$

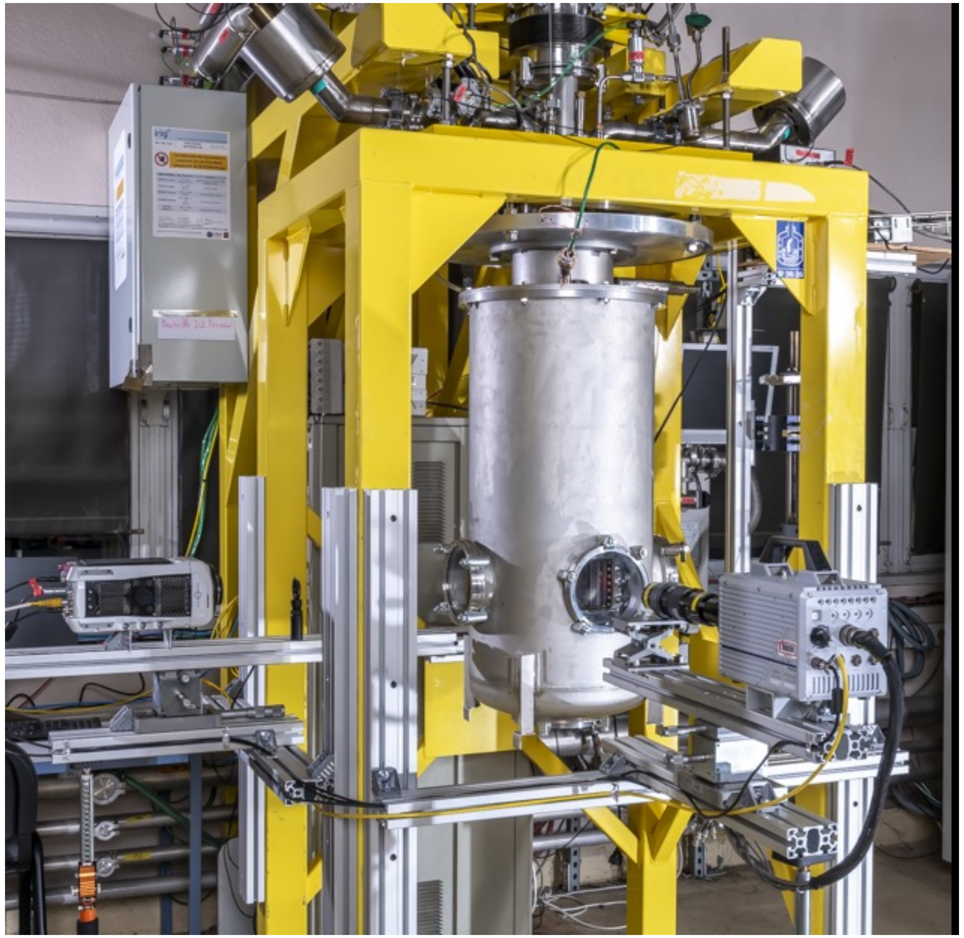
Relative rotation frequency of top and bottom propeller $\theta = \frac{\omega_1 - \omega_2}{\omega_1 + \omega_2}$

Ultimate convergence statistic without any flow change :

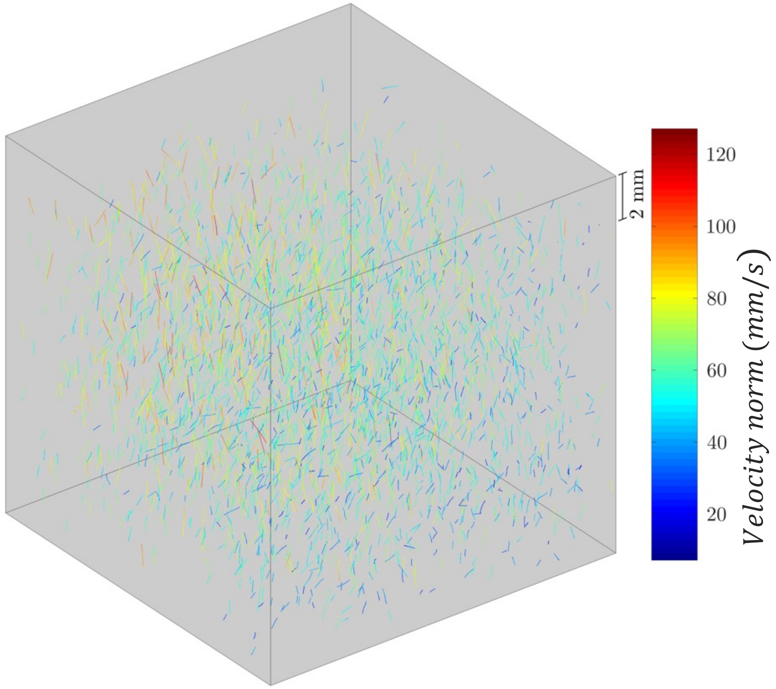
The SHREK facility is capable of continuous operation under stable conditions (temperature control better than 0.1mK), which has made it possible to achieve unprecedented statistical convergence. The very high number of Re and the long recording time (several days possible) ensure a very large number of vortex turnarounds. This was used by the Oldenburg team (Joachim Peinke and co-workers) to test the validity of the integral fluctuation theorem.

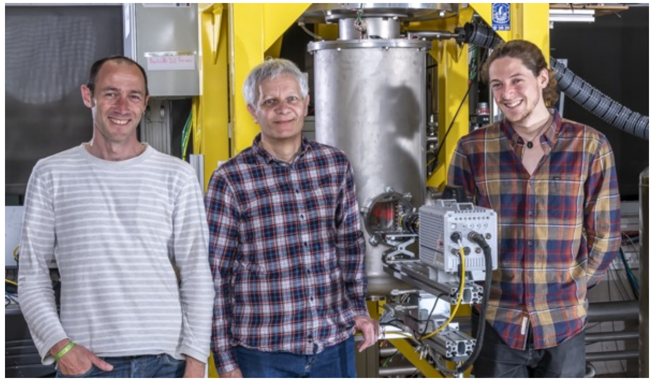
I take also this opportunity to remind us that SHREK results could be available for other post processing if it can help to increase our knowledge. As an example, Alain Pumir and co-workers asked us for use the SHREK data in order to test a new procedure “Stochastic Interpolation of Sparsely Sampled Time Series via Multipoint Fractional Brownian Bridges”. They kindly acknowledge the SHREK collaboration in their paper.

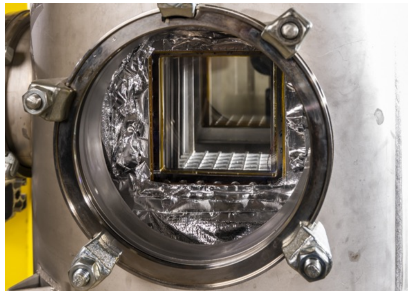
3D lagrangian measurements to study He II oscillating grid turbulence (preliminary results) : part of Clement Bret Phd



$3D\ Trajectories:\ T° = 1.6K,\ \ f_{motor} = 6hz$
$A_{motor} = 14mm \rightarrow Re_\lambda = 400$
$FPS = 3000, voxels = 800X800X800\ pixels^3$







Conclusion

It is possible to realize large experiments and obtained ultra high Reynolds number using liquid helium

Once the difficulties of working at low temperature are overcomed, results can be more accurate and gives larger statistic than in classical fluid due to a better temporal stability

Superfluid and normal helium flows at identical total density can be produced and studied in the same facility with same sensors, providing under cooling (pressurized bath) is used.

In the inertial range and for inertially driven flows, superfluid helium behaves as a classical fluid. Furthermore, this is also the case for the overall dissipation, even if the mecanism responsible for the superfluid dissipation remains to be studied.

Main results obtained with micronic Eulerian sensors will be presented by Pantxo and Philippe

Turbulence in He I and He II isothermal flow : Total dissipation

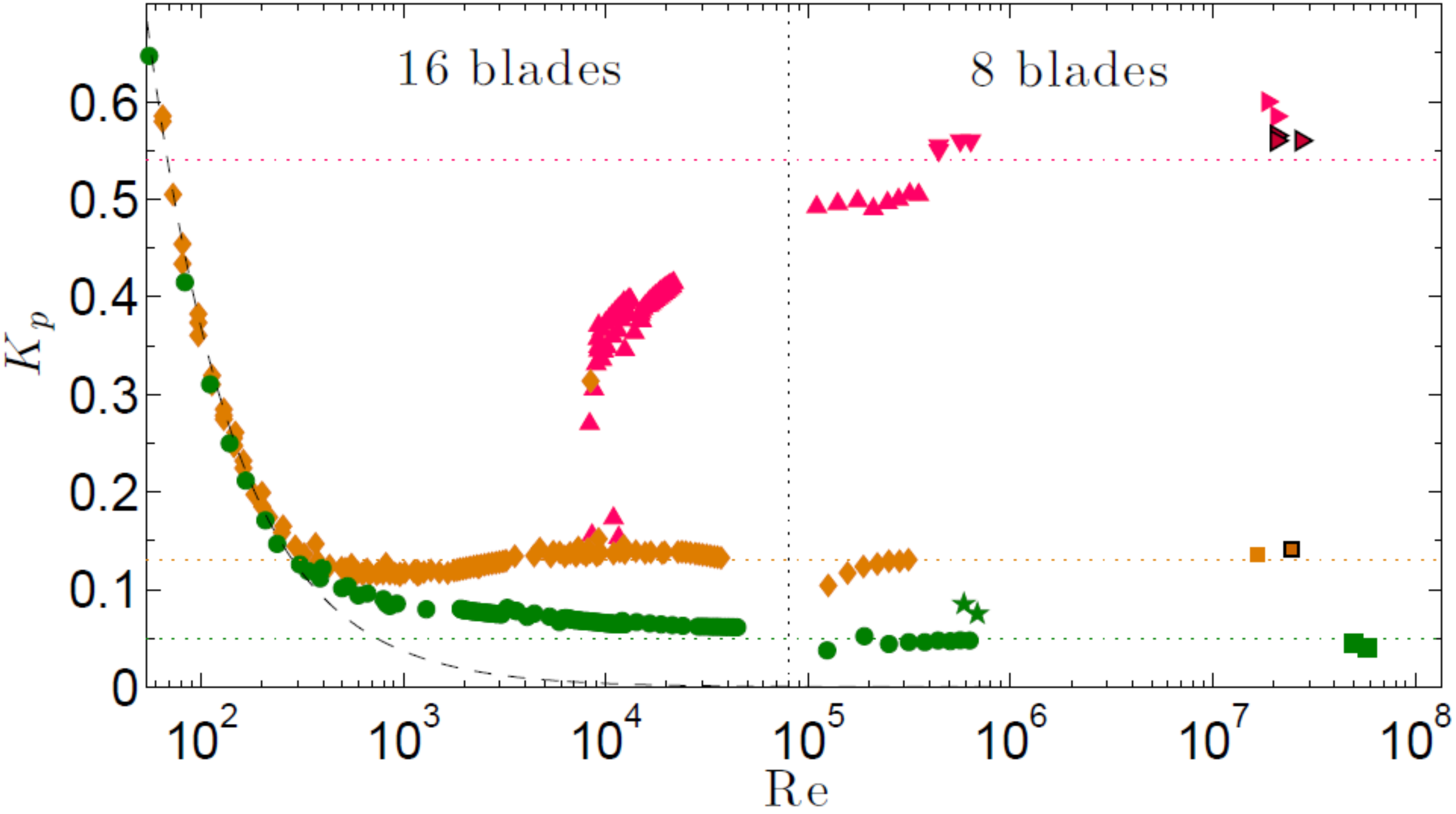
- Dire que le fait que les lois dans le domaine inertiel en -5/3 pour la cascade de Kolmogorov et le transfert d'énergie cinétique sontréalisées avec des capteurs locaux. Ces mesures locales dans un écoulement pas nécessairement THI à grande échelle pourraient éventuellement introduire des biais.

Des mesures comparatives entre He I et He II de la puissance totale injectée et/ou de la puissance totale disssipée pour une condition identique sont ainsi un complement important.

- Les résultats de SHREK avec conditions identiques (fréquence géométrie densité fluide) et avec des capteurs identiques non intrusifs dont la mesure (éventuellement faite à temperature ambiante) ne dependant pas de la T° ou de la nature du fluide (couplemètre à T° ambiante et mesures calorimétriques) montre l'equivalence entre He I et He II.

- Sinon insister sur le fait que l'installation SHREK très fort Re permet d'avoir des puissance dissipées suffisantes pour des mesures calorimétriques aisées car dissipation >>pertes thermiques et aussi stabilité sur des temps très longs pas de dérive (type dérive en T° de composants ou de l'écoulement…)

SHREK : global measurements (torque meter results)



$$\omega_1 = \omega_2 = \omega$$

$$Re = \frac{\omega R^2}{\nu}$$

$$K_p = \langle \varepsilon \rangle_{adim} = \frac{(\Gamma_1 + \Gamma_2).\,\omega}{2.\,\rho.\,R^5.\,\omega^3}$$