Turbulence measurements under extreme conditions : cryogenic fluids

- Scope : give some flavour of why and how to perform turbulence measurements in low temperature fluids

  - ✓ Fluid : Helium liquid, gaseous and superfluid
  - ✓ Cryogenic : T_{flow} as low as a few K
  - ✓ Flows : open flows
    - o *Axisymetric Jet flow (GReC experiment) @ CERN in Geneva*
    - o *Grid flow (TSF experiments) @ CEA in Grenoble*

Turbulence measurements under extreme conditions : Why cryogenic fluids ?

• Most exact (at least reliable) results and models on turbulence are *asymptotic* laws : in the *"limit of large Re numbers"*, with slow convergency (sometimes logarithmic).

• Main motivation : achievement of very high Reynolds numbers in well controled conditions (stationarity, reproducibility)

• Routes to Large Re flows : $\mathrm{Re} = \frac{UL}{\nu}$

✓ High U : limited by sound velocity

✓ Large L : e.g. geophysical flows, large wind tunnels (Modane)

o Total power consumption : $\varepsilon L^3 \propto U^3 L^2$ (@Modane : 20m^2x500m ~500 MW !)

o Large installations are hard to control ⇨stationarity ?

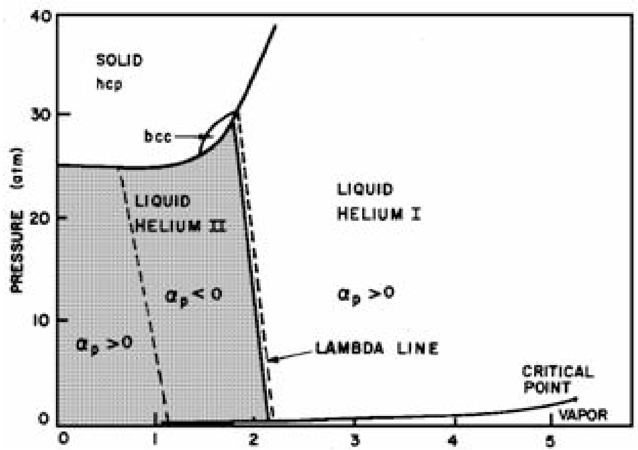
✓ Small ν : Helium the "Third Fluid"

Helium viscosity
273 K → $1.0\ \text{cm}^2/\text{s}$
2 K → $1.0\ 10^{-4}$ cm2/s
4 orders of magnitude

Fluid	T (K)	P (Bar)	ν (cm^2/s)
Air	293	1	0.15
Water	293	1	0.01
Helium I	2.2	SVP	1.8×10^{-4}
Helium II	1.8	SVP	8.9×10^{-5}
Helium gas	5.5	2.8	3.2×10^{-4}

Turbulence measurements under extreme conditions : Additional properties of He

- Mechanical properties : wide range of ν_{He} ⇨wide range of Re at constant geometry (U,L)
  - ✓ first cryogenic He jet flow @ CRTBT in Grenoble in the 1990's (Pr B. Castaing)
  - ✓ large cryogenic He jet flow (GReC project) @ CERN in Geneva in the 2000's
- Thermal properties of Helium : wide range of Ra (@CRTBT : B. Castaing and P. Roche)
- But He is also interesting for compressible turbulence (playing with the pressure)



- Helium superfluidity below T_λ=2.17K
  - ✓ quantum turbulence : quantified circulation $\kappa = \frac{h}{m_{He}}$
  - ✓ non viscous dissipation at small scales : vortex reconnection, Kelvin waves, mutual friction
  - ✓ Superfluid grid turbulence @ CEA in Grenoble : under development

The GReC experiment
1. People

- CERN : P. Lebrun, O.Pirotte, J-P.Dauvergne, A.Bezaguet, R.Van Weelderen

- CRTBT : B. Chabaud, S. Pietropinto (PhD), B. Hebral, Y. Ladam (Post-Doc), J-L. Bret (Elect Eng-CNRS)

- ENS-Lyon : B. Castaing, O. Michel

- LEGI : C. Poulain (PhD), J-P. Barbier-Neyret (Elec Eng-CNRS), Y. Gagne, C. Baudet

The GReC experiment
2. History

- 1990's : Cryogenic Helium Jet experiments at CRTBT (B. Castaing & B. Chabaud) in Grenoble.

- 1998-1999 : contacts with the CERN and design of the GReC experiment.
- 1999 : manufacturing of the nozzle, fluid connections, supports for the sensors, sensors (hot-wires, flow-meter, acoustic vortex sensor).

- 2000 : installation of the sensors, tests of the stability of the flow (set-up of the control loop by CERN), tests of the sensors
- 2001-2002 : data acquisitions ~ 3 x ~15-days campaigns

- Since 2002 : Data analysis, de-noising, turbulence statistics ...

The GReC experiment
3. Funding

- CERN
  - Man Power (flow control, refrigerator operation and maintenance)
  - Cryogenic facility Linde Refrigerator and Cryostat
  - Electrical Power and Helium

- Région Rhône-Alpes
  - Electronics, manufacturing, travels
  - one-year Post-Doctoral grant (Y. Ladam)

The GReC experiment
4. Flow Geometry

Why an Axisymetric Jet Flow ?

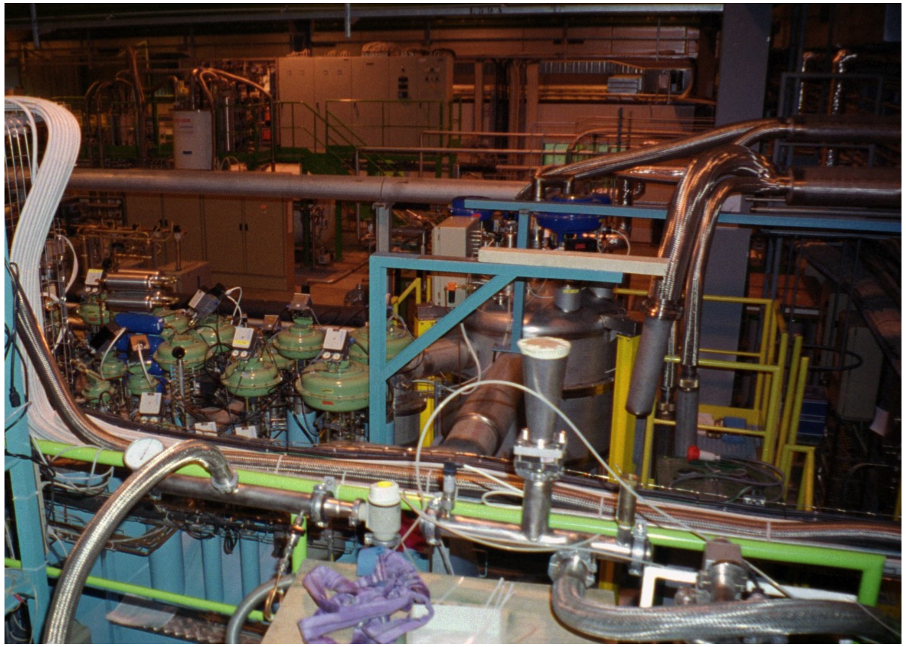
- High turbulence level ($u_{rms}/u_{avg} \sim 25\%$) ⇨Large Re
- Mean Flow velocity : Hot-Wire anemometry, Taylor hypothesis
- Fully documented properties : e.g. large scale flow profiles, ...
- Known anisotropy, axial evolution (longitudinal inhomogeneity)

- Self-similarity of the large scale flow ("looking-glass" property)
  - ✓ $(L_{int}, \lambda_{Tayl}, \eta_{Kolm}) \propto (z-z_o)$
  - ✓ $(u_{avg}, u_{rms}) \propto (z-z_o)^{-1}$
  - ✓ (Re, R_λ) = Ctes whatever the downstream distance z/D_{nozzle}

- Dimensions constrained by the size of the CERN Cryostat

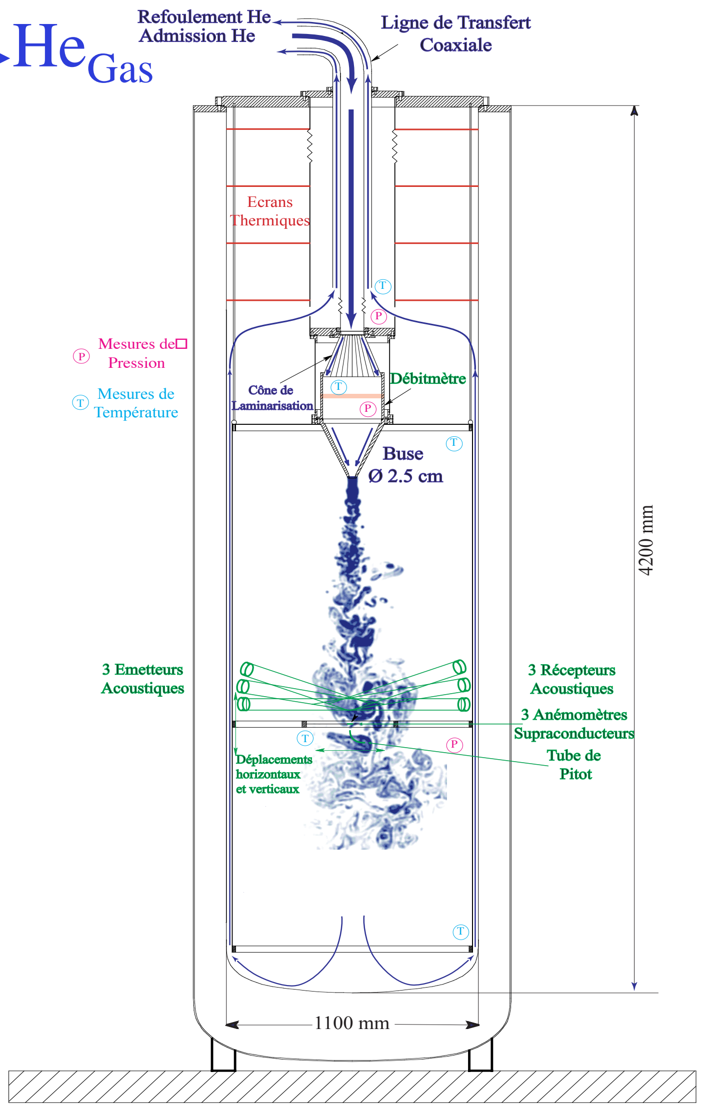
The GReC experiment

5. Experimental Set-Up



He_{Liq} Coaxial Line + Heating → He_{Gas}

Flow Set-Up



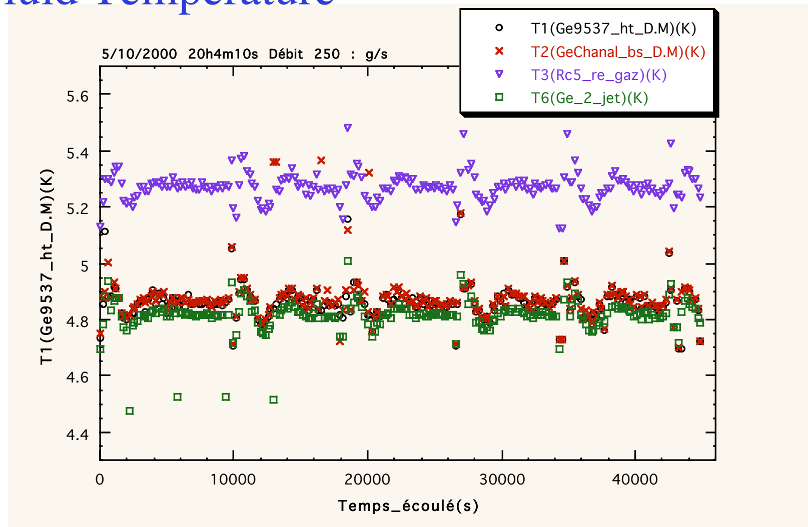
Helium Production

- Linde refrigerator : Refrigeration Power **6 kW**
  overall Electrical Power consumption : **several MW !**
- Gaseous Helium Flow Rate @ 4 K : **20g/s -> 300g/s**
  from heating of Liquid Helium @ 2,7 K
- T and Q regulation : heating control in the coaxial transfer line
- Loop back on (P, T, Q) measured in the jet flow

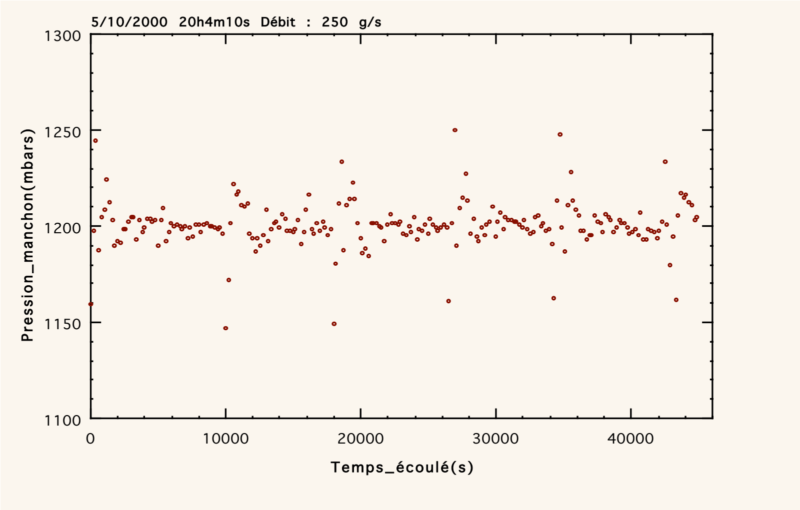
The GReC experimental set-up

The GReC experiment
7. Stability

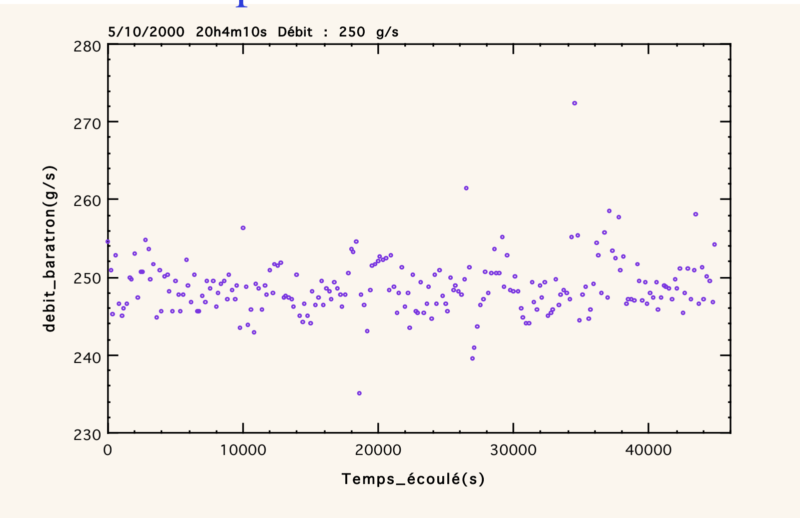
Fluid Temperature



He Flow rate



Pressure Drop

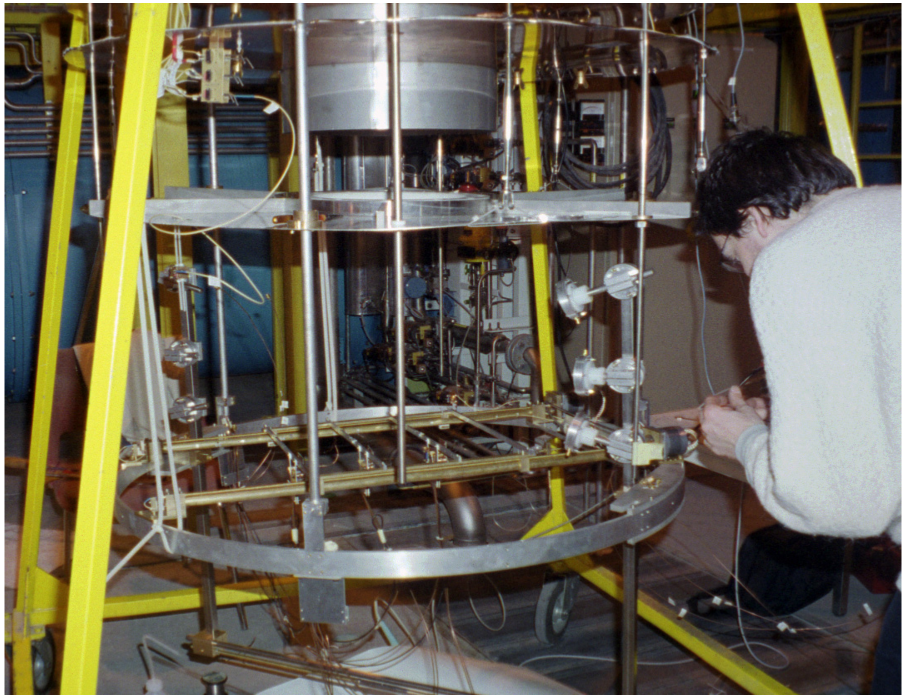


Large Scale Fluctuations : ~ a few %

Stability over Long Times : ~ 1 day

The GReC experiment

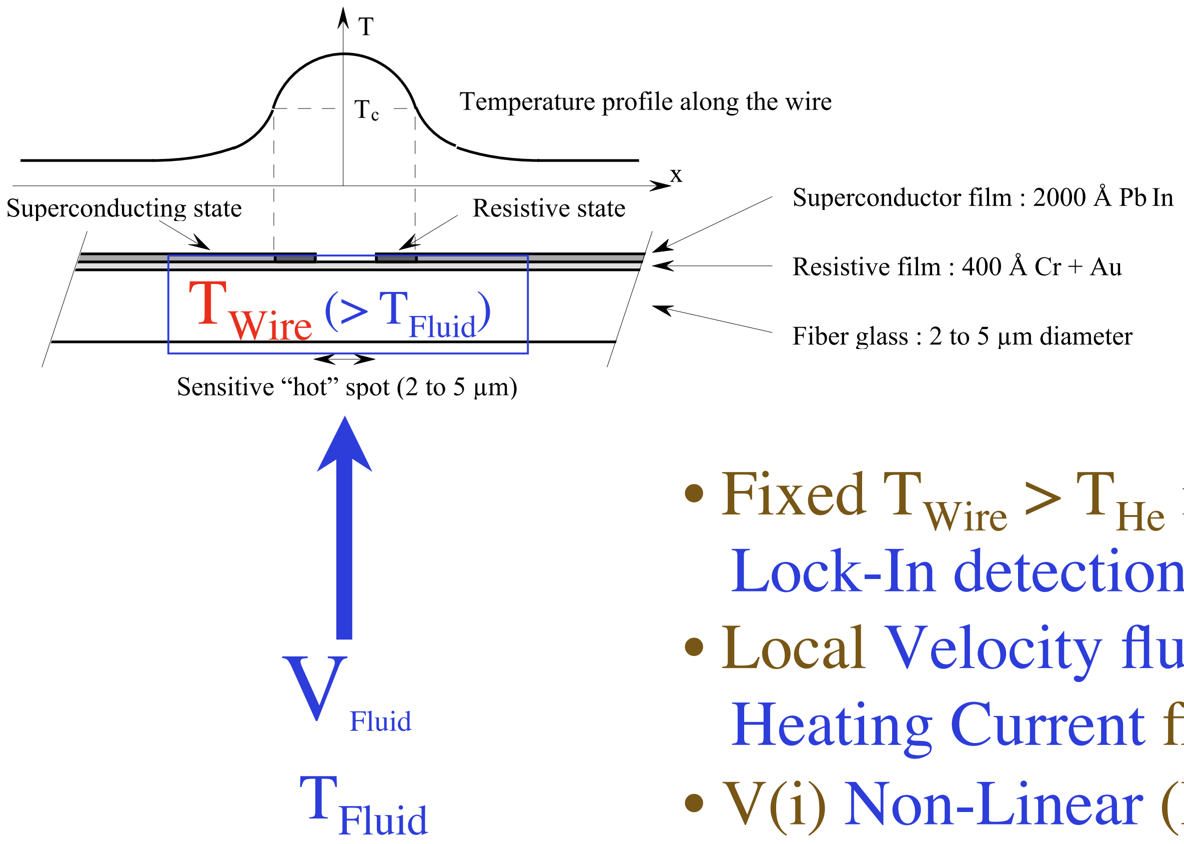
8. Instrumentation



- "Hot-Wire" superconducting anemometer
  Eulerian Velocity measurements
- Acoustic Scattering sensors
  Spectral Vorticity measurements
- Pitot tube
  Mean and rms velocity measurements
- Thermocouples
  Temperature monitoring
- All sensors mounted on a moving ring
  to probe various downstream distances

The GReC experiment

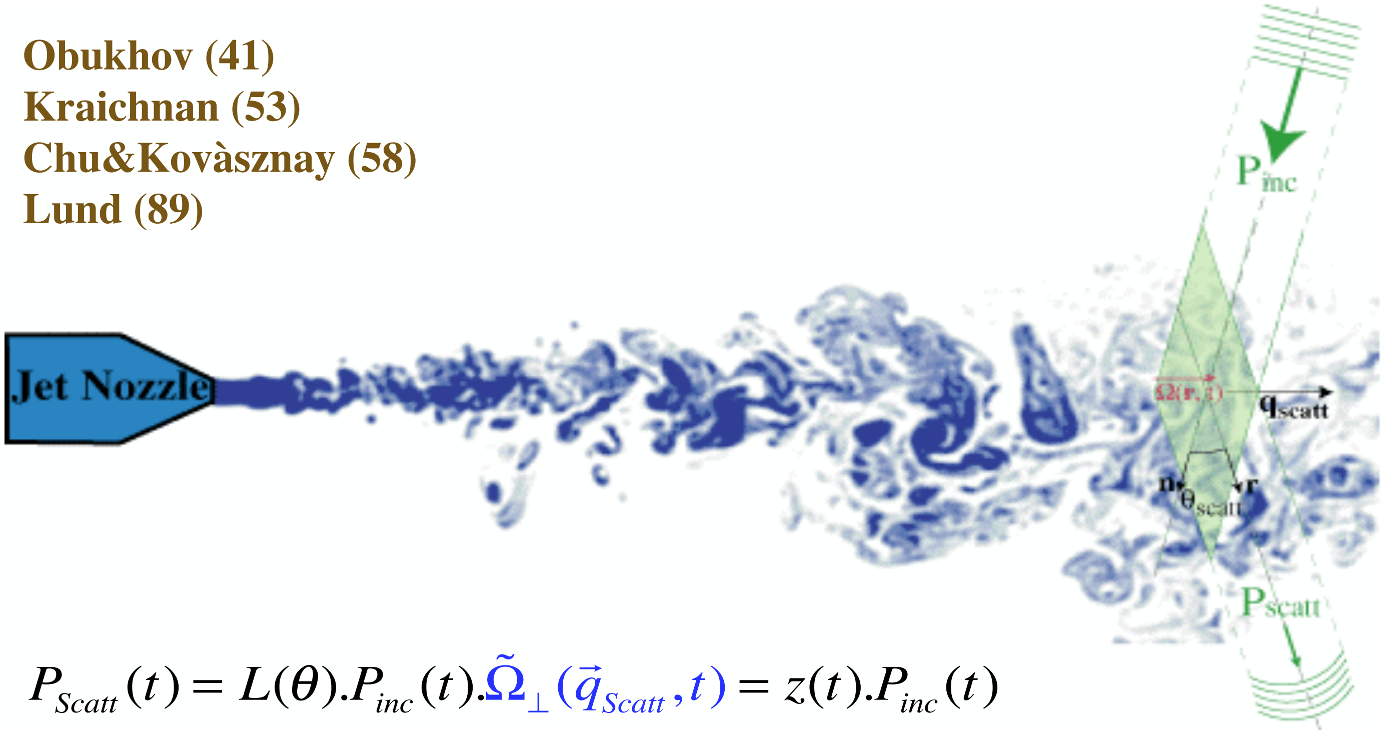
9. Superconducting Hot-Wire



- Fixed $T_{Wire} > T_{He}$ measured with a 10 MHz Lock-In detection.
- Local Velocity fluctuations measured through Heating Current fluctuations (up to 1 Mhz).
- V(i) Non-Linear (Kings Law) ⇨need for Calibration for each Flow Rate
- Aging sensors

The GReC experiment
10. Spectral Vorticity measurements

Obukhov (41)
Kraichnan (53)
Chu&Kovàsznay (58)
Lund (89)



$$P_{Scatt}(t) = L(\theta).P_{inc}(t).\tilde{\Omega}_{\perp}(\vec{q}_{Scatt},t) = z(t).P_{inc}(t)$$

- Direct : one vorticity component
- Spectral : spatial Fourier modes
- Non intrusive : remote sensing
- Small Scale statistics: velocity gradients
- Non Local : V_{Scatt}

$$\tilde{\Omega}_{\perp}(\vec{q}_{scatt},t) = \iiint_{V_{scatt}} \Omega_{\perp}(\vec{r},t).e^{i\vec{q}_{scatt}\vec{r}} d^3r$$

$$q_{scatt} = 4\pi \frac{\nu_o}{c} \sin\left(\frac{\theta_{scatt}}{2}\right)$$

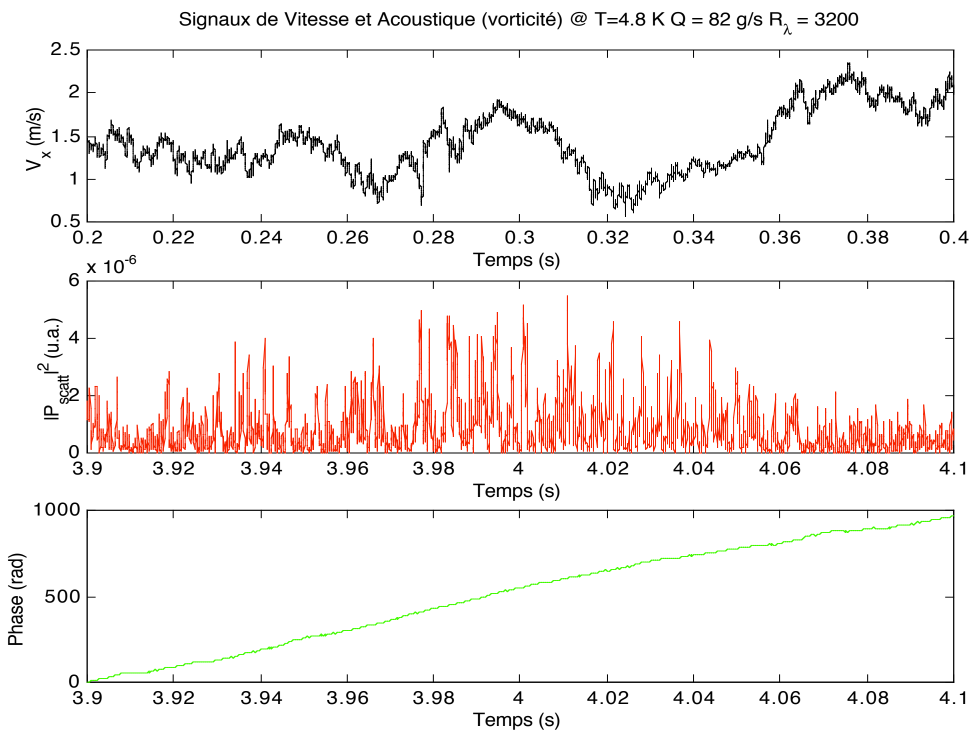
The GReC experiment
11. Signal acquisition

- Multiple HP E1430 digitizers (bus VXI)
- Large Band-Width : up to 4 MHz
- High Precision : up to 23 (18 bits alias-free ⇨ 110 dB)
- Large sample records (2 10^9) : up to 1000 s continuously

Eulerian Velocity

Acoustic Intensity
(vorticity fluctuations)

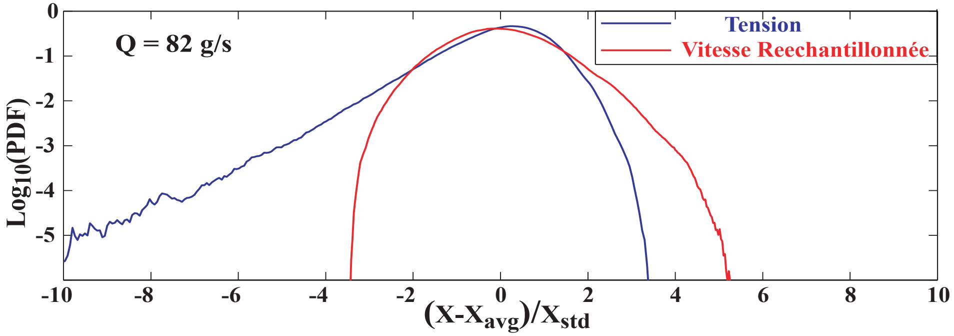
Acoustic Doppler Shift
(vortices advection velocity)

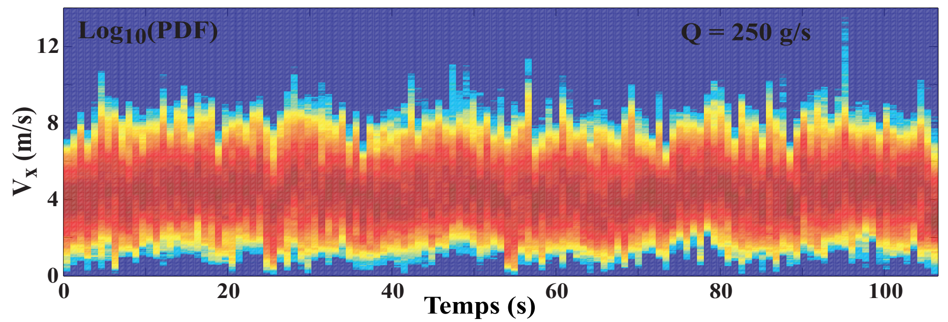


The GReC experiment

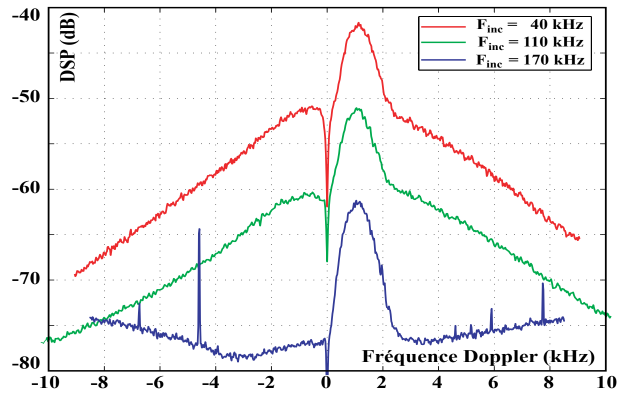
12. Signal Conditioning and Calibration

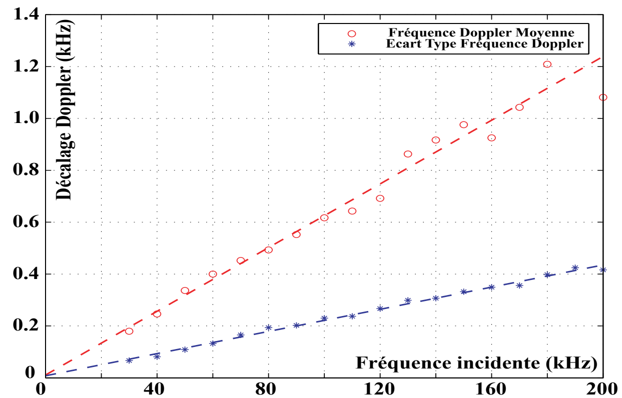
Hot Wire One Point Velocity Statistics





Acoustic One Point Velocity Statistics (Doppler Frequency shifts)





- Stationary Statistics over Long Times
- Gaussian Statistics of the Large Scale Velocity (turb level : ~ 25%)
- GReC Jet is a "Well Behaved" Axisymetric Turbulent Jet

The GReC experiment
13. Flow Reynolds Numbers and Scales

Helium Viscosity @ T_{op} ~ 4.7 K : $\nu_{He} = 8.10^{-8}$ (~ $\nu_{air}/230$!)

Mass Flow Rates : Q = 21 g/s up to 250 g/s

Mean Velocity (@50 D_{Nozzle}) : from 35 cm/s up to 4 m/s

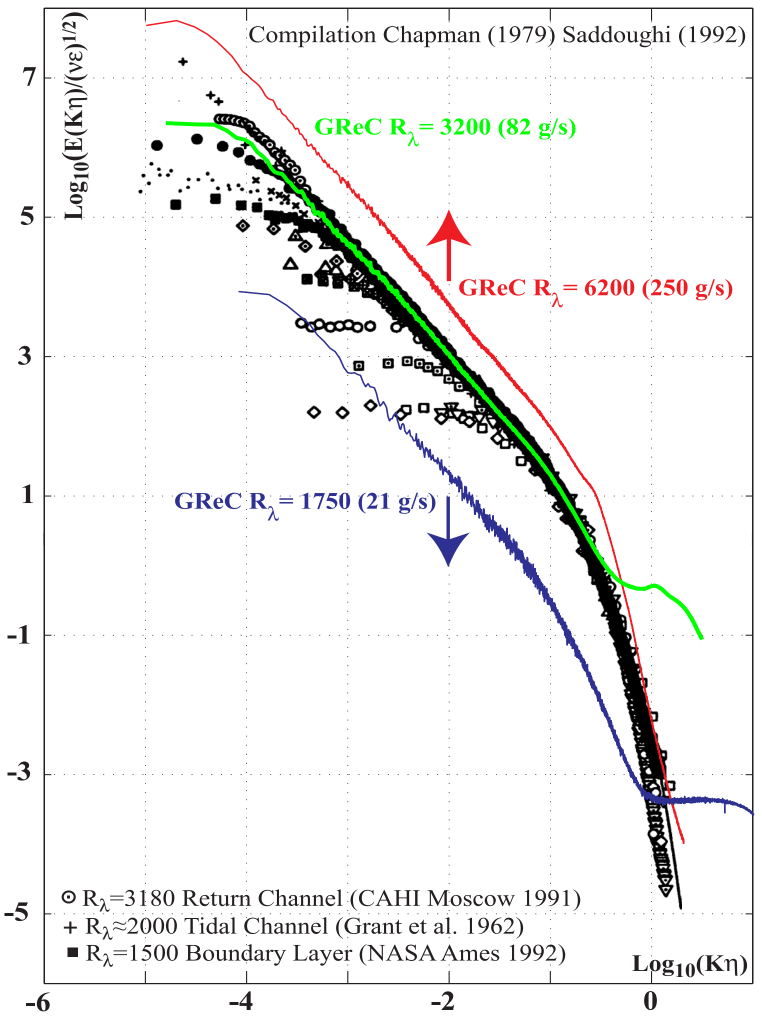
Reynolds numbers : Re = 8.10^5 up to 10^9
Taylor Reynolds numbers : R_λ = 1300 up to 6000

Integral Scale : L ~ 30 cm
Taylor Scales : λ = 1.7 mm down to 0.4 mm
Kolmogorov Scales : η = 20 µm down to 0.4 µm

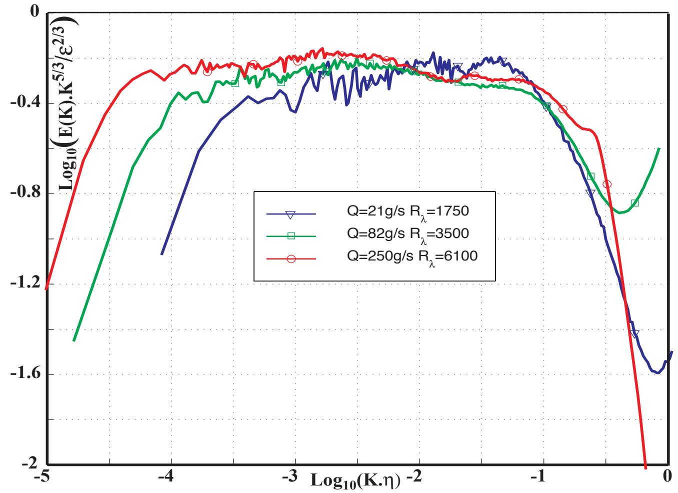
Time series up to 10^9 samples @ $F_{sampling}$ = 1.25 MHz

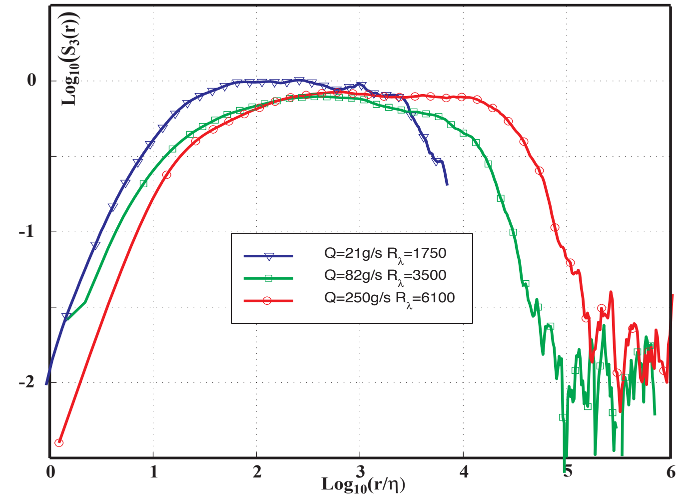
The GReC experiment
14. Scaling Laws inertial range

The -5/3 law (Kolmogorov 1941)



-5/3 and 4/5 laws (K41)



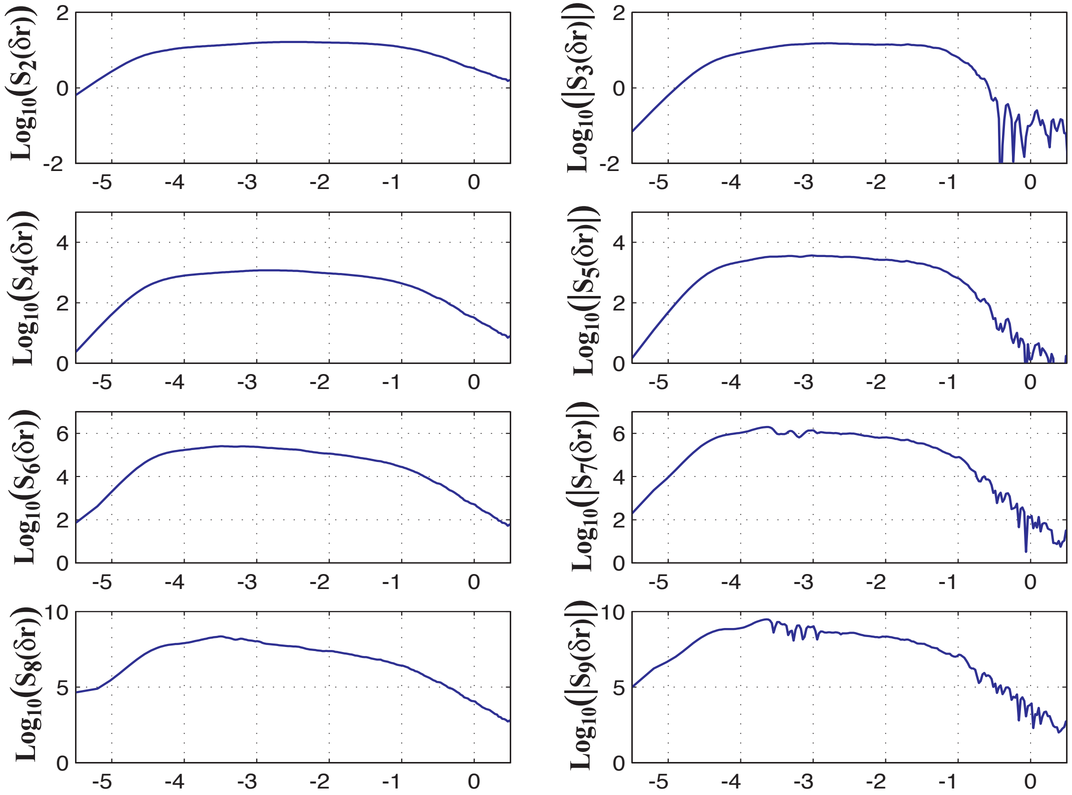


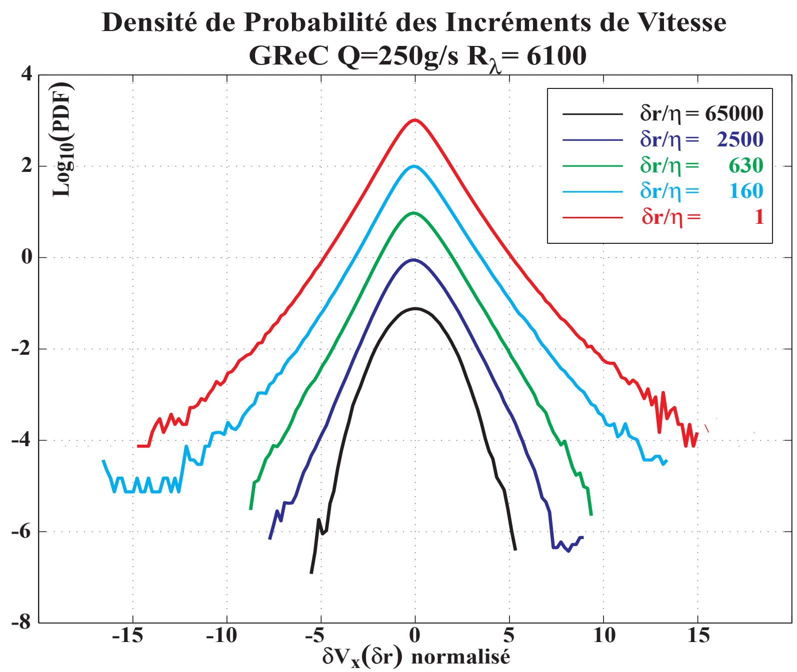
The GReC experiment

15. Higher Order Statistics : intermittency

Compensated (K41) Structure Functions @ $R_\lambda \sim 6000$

$$S_p(\delta r)\,/\delta r^{P/3} = \left|\left\langle (V_x(x+\delta r) - V_x(x))^p \right\rangle_x\right| / \delta r^{P/3}$$

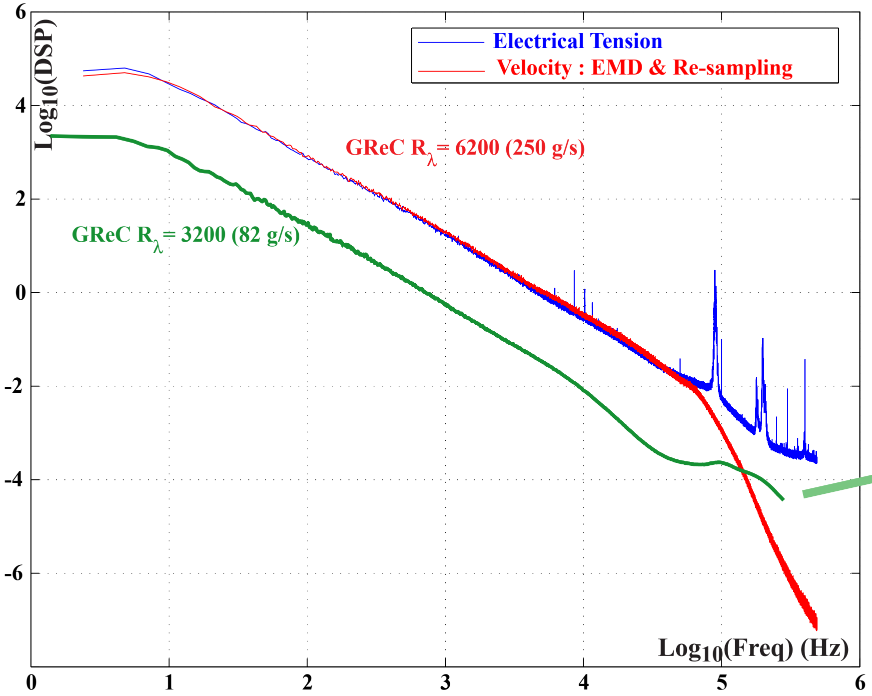




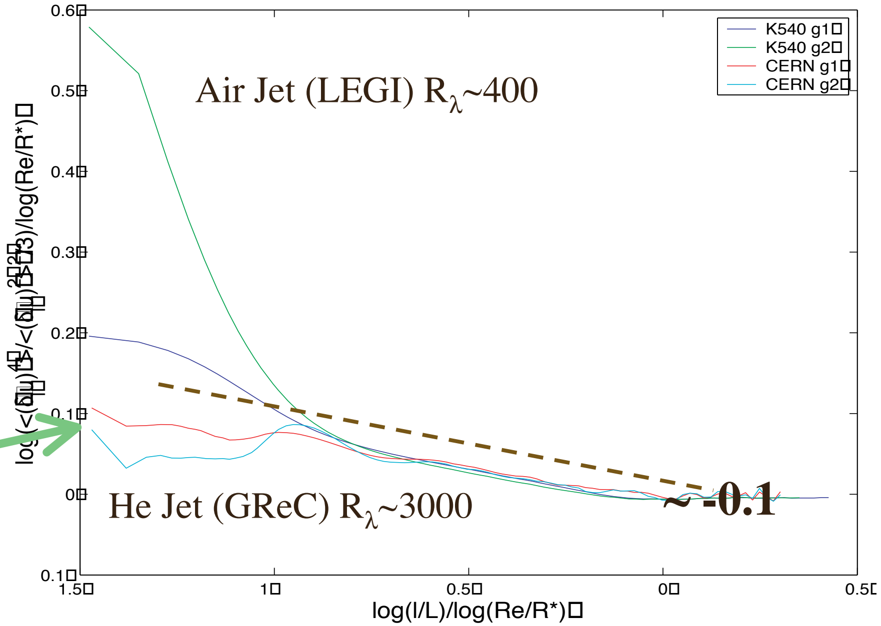
The GReC experiment

16. Noise Contamination

Denoising using EMD
(Empirical Mode Decomposition)



Scale resolved Noise Diagnostic
(Evolution of the Flatness GReC 82g/s)



Ref : "On the rapid increase of intermittency in the near-dissipation range of fully developed turbulence"
L. Chevillard, B. Castaing & E. Lévêque
Eur. Phys. J. B 45, 561–567 (2005)

- Noise : non linear and non stationary process
- Possible origin : current saturation in the supraconductor ($i > i_{crit}$)
- Still : capture of Inertial Range Intermittency (slope ~-0.1)

The GReC experiment

17. Conclusions

- GReC I experiment was intended to be preliminary (interrupted since 2002, but ready to start again)
- Preliminary Outcomes :
  - Feasibility of a well controled high Re turbulent jet @ CERN
  - Evidences of Inertial Range Intermittency
  - Identification of some instrumentation problems
- Works in progress
  - Super-fluid wind tunnel @ CEA in Grenoble CryoLoop
  - Atlas Pipe-Flow experiment @ CERN (Ph. Roche)
  - Developments of new small scale instrumentation in progress in Grenoble Hot-Wire, Second Sound (vortex counting), Acoustic Scattering (vorticity fluctuations), ...
- Prospective works
  - Atlas, GReC II, Large Convective Cell ...

The TSF experiment
1. Aims

- TSF : “Turbulence Superfluide français”

- Fully developped Grid turbulence

  ✓ Liquid Helium in the normal state ⇨Classical turbulence at $R_\lambda \sim 450$
  - o Grid turbulence ~ best approximation of Homogeneous Isotropic turbulence
  - o Low velocity fluctuations level : $u' / U \approx 3\%$
  - o High R_λ scales separation
  - o Scaling laws (structure functions), intermittency, ...

  ✓Liquid Helium in the superfluid state ⇨Quantum turbulence
  - o shape of the energy spectrum in the dissipative range ?
  - o do the dissipative process influence (modify) intermittency ?
  - o internal vs inertial intermittency ?
  - o mutual interaction of the normal and superfluid turbulent velocities ?
  - o dynamic of superfluid vorticity lines (second sound probe, P. Roche).

The TSF experiment
2. People

- CEA (Commissariat à l'énergie atomique) :
  B. Dubrulle and F. Daviaud : *CEA/Saclay*
  P. Diribarne, P. Thibault, Bernard Rousset and Alain Girard : CEA/Grenoble (SBT)

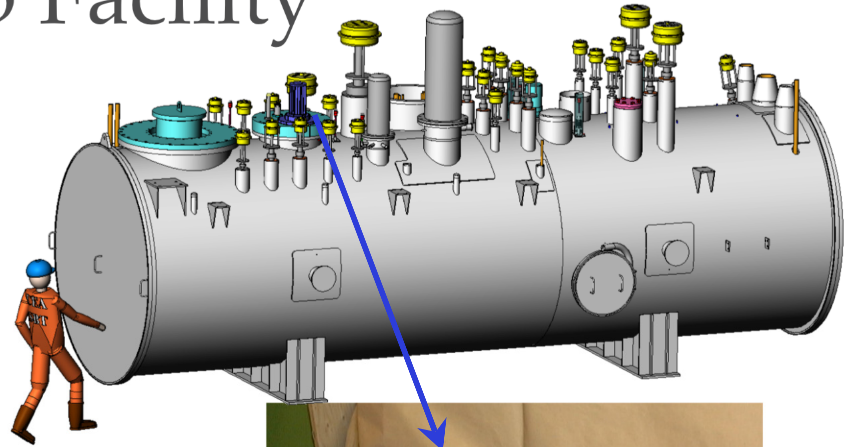
- Institut Néel (CNRS) :
  P. Roche

- Ecole Normale Supérieure de Lyon :
  L. Chevillard (CNRS) and Pr B. Castaing (head of the project)

- Laboratoire des Ecoulement Géophysiques et Industriels (UJF-INPG-CNRS)
  Y. Gagne and C. Baudet

- Funding : Agence Nationale de la Recherche, Projet TSF

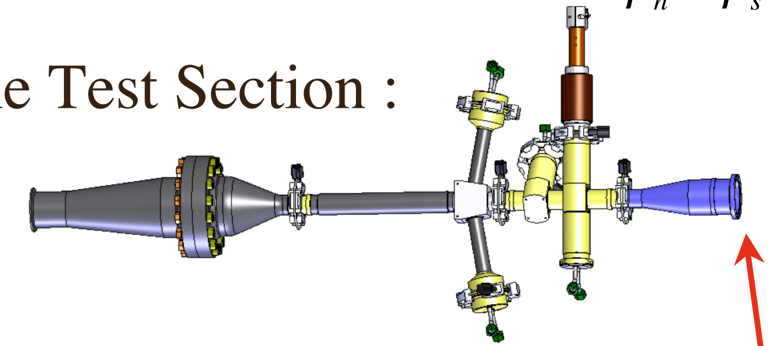
The TSF experiment
3. The CryoLoop Facility



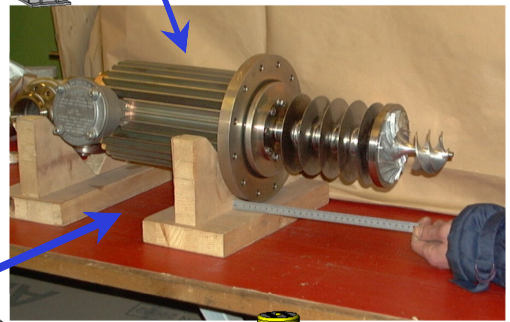
Flow rate 750 g/s achieved at a temperature of 1.9 K

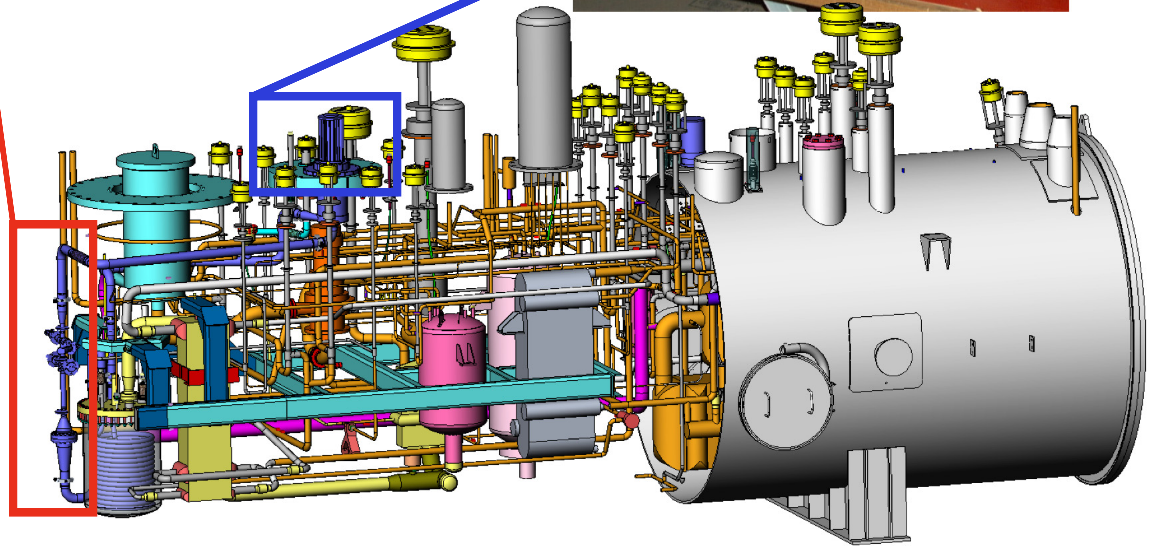
- ✓ 400 W of cooling power around 2 K
- ✓ Square Grid mesh size : 3.9 mm in 27.3 mm Pipe
- ✓ 2.2 K > T > 1.64 K ⇨ $0 \leq \dfrac{\rho_s}{\rho_n + \rho_s} \leq 80\%$

The Test Section :



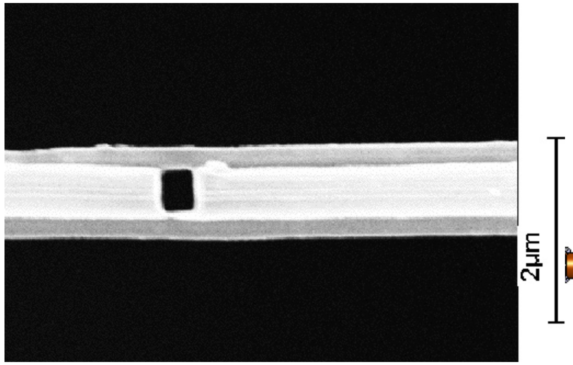
The Atlas pump :

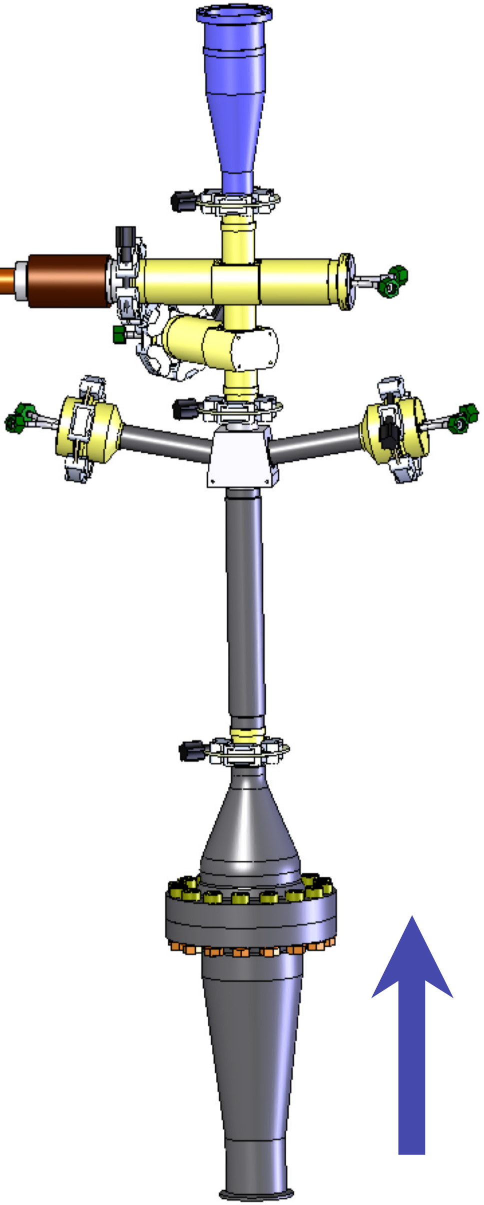




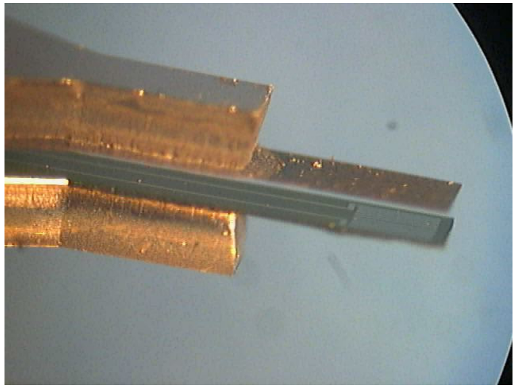
The TSF experiment
4. Sensors

- Eulerian Velocity measurement
  with supra-conductor hot-wire
  only for the normal fluid
  (need a viscous boundary layer !)
  and Pitot tube
  P. Diribarne & P. Thibault





- Second sound Vorticity probe
  Thermal propagative waves
  only for the super-fluid
  P. Roche



- Acoustic scattering probe
  Spectral vorticity measurements
  in both normal and super fluids
  Y. Gagne & C. Baudet

The TSF experiment
5. Stability tests

- Normal phase

- Q_{He} ~ 400 g/s

- Superfluid phase