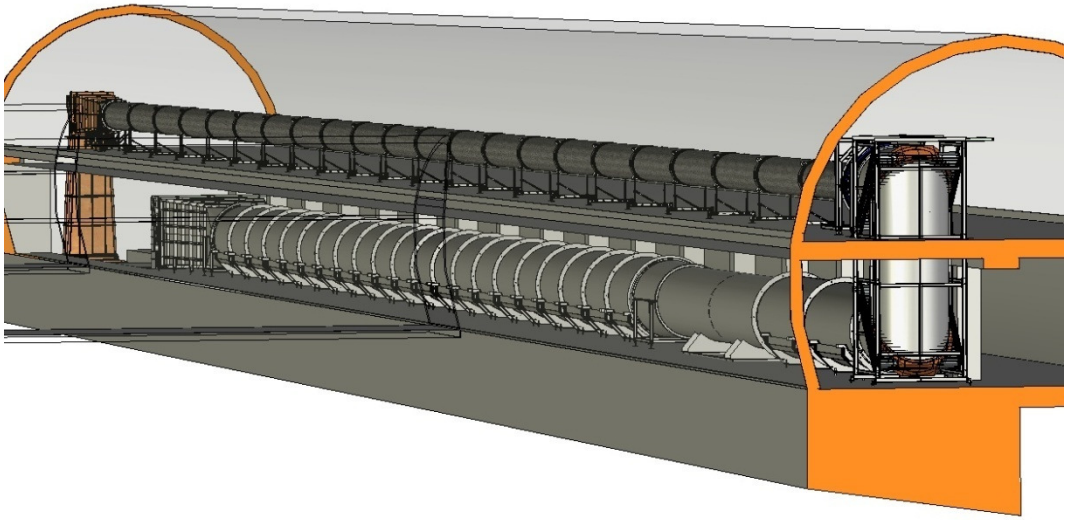
Large Pipe at CICLoPE: a new facility for detailed measurements of wall-bounded turbulence



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Co-authors: H. Nagib, H. Alfredsson, P. Monkewitz

..and the help of K. R. Sreenivasan, A. Smits, J. Fransson, A. Johansson, I. Marusic, P. Proli, F. Persiani, …

General background

FUNDAMENTAL RESEARCH

- Well known governing equations
- Controversies and uncertainties over fundamental issues
  - Large scale structures and energy transfer
  - Anisotropy
  - (non) universality of the Karman constant
  - Scaling of spectra/correlations/higher order statistics
  - ……..

- NEED OF HIGH REYNOLDS NUMBER FLOWS
- NEED TO RESOLVE ALL TURBULENCE SCALES
- NEED OF A WELL CONVERGED STATISTICS

Available tools

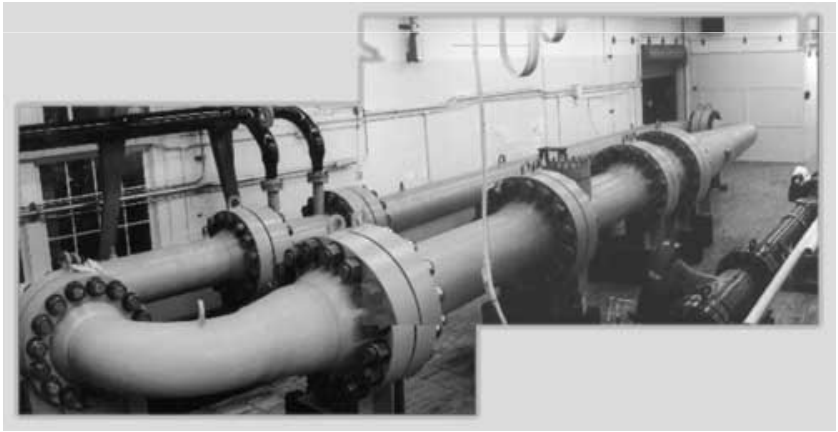
	Reynolds number	Resolution	Statistics
DNS	X	√	√
Atmospheric experiments	√	√	X
Laboratory experiment	√	?	√

How to increase Re ?

"SuperPipe" in Princeton

- $D \approx 13$ cm
- $L/D = 200$
- High pressure (about 200 atm)
  $Re \approx 5000 - 38 \times 10^6$
- Very small viscous length scales

$$\mathrm{Re} = \frac{UL\rho}{\mu}$$



- NEED OF HIGH REYNOLDS NUMBER APPARATUS √
- NEED OF A WELL CONVERGED STATISTICS √
- NEED TO RESOLVE ALL TURBULENCE SCALES X

What is a minimum Reynolds ?

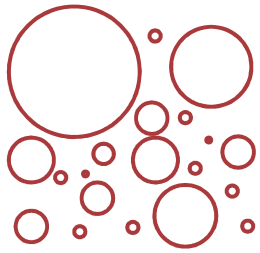
$$\frac{u}{u_\tau} = \frac{1}{\kappa} \ln\ y^+ + B$$

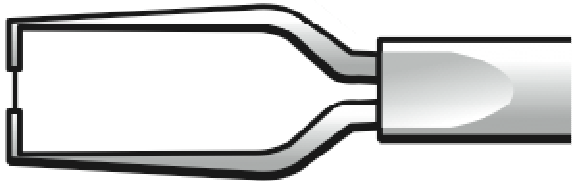
- Overlap region in the log law: $200 < y^+ < 0.15R^+$ (data from MTL and NDF)
- 1 decade of y^+ ($y^+ = 2000$, -> $R^+ = 13300$
- Reynolds number range ($Re_{max}=3\ Re_{min}$)

$$13300 < R^+ < 40000$$

(data from superpipe -> increase R^+)

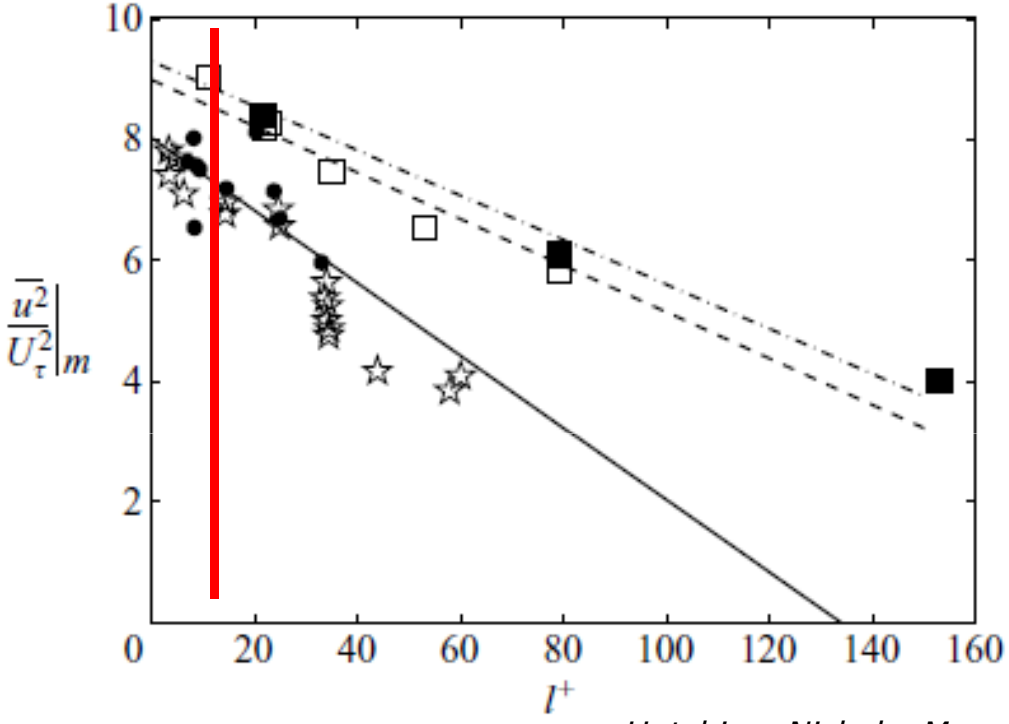
Small scale resolution





- Mini hot-wires (standard configuration)
- Minimum diameter of the wire = 0.6 μm
- Hot-wire L/D > 200 for probe interference
- Wire length > 120 μm
- $l^+ < 10$ to avoid spatial averaging

$l^* > 12$ μm



Hutchins, Nickels, Marusic and Chong JFM (2009)

- l+=10 seems to be enough to resolve the inner peak

Why a "large" facility?

- Relevant Reynolds number (pipe)
  - $Re = u_\tau R / \nu$
- Relevant length scale - viscous length scale
  - $l^* = \nu / u_\tau$

$$l^* = R / R^+ = R / Re$$

i.e. independent of fluid, pressure etc.

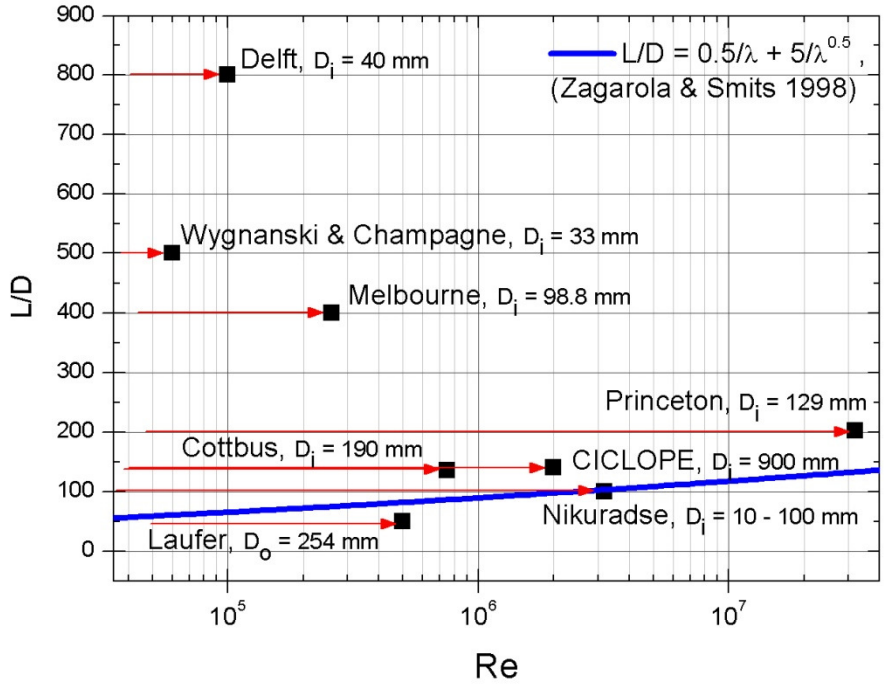
- ***Keeping the minimum l* and high Re we must increase R***

$l^* > 12\ \mu m$ and $R^+ < 40000$ → $R=0.48$ m

Why a "long" facility?

- ***To allow a fully natural developed turbulent flow:***

$L/D > 100$ ⇒ $L = 100$ m



The pipe (specifications)

- Diameter accuracy (same as NDF and MTL: $\Delta U < 0.2\%$)

$$\frac{\Delta U_\infty}{U_\infty} = \frac{\Delta S}{S} = 2\,\frac{\Delta D}{D}$$

$$\Delta D \leqslant \frac{\Delta U_\infty}{U_\infty}\frac{D}{2} = 0.9mm$$

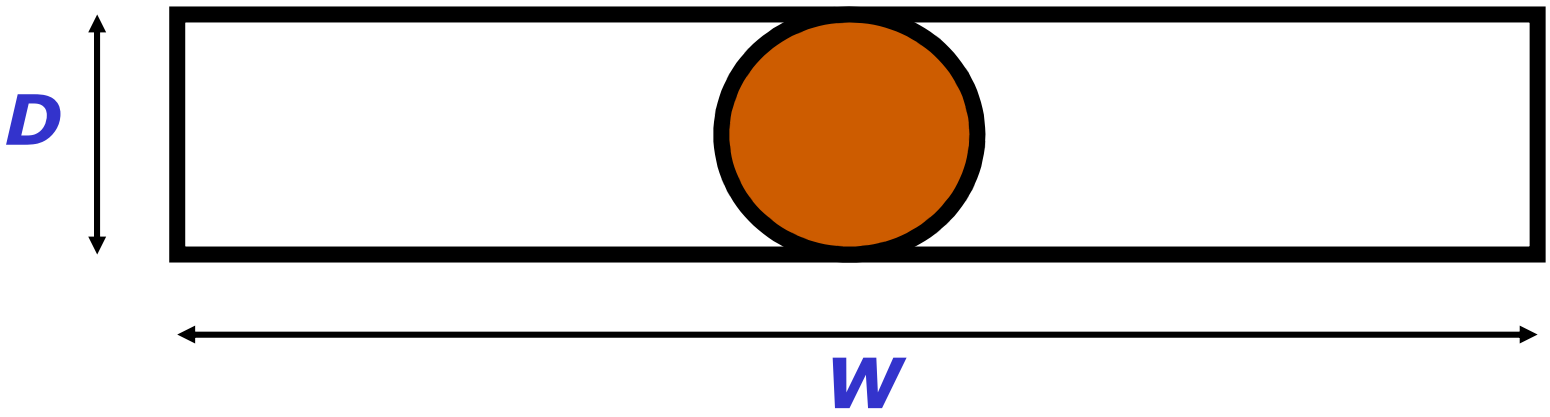
- For Hydro-dynamically smooth surface: (from Zagarola and Smits: *sand equivalent roughness* $k_{s+}<3$)

  $k_s < 3\ l^*$ (where $l^* = 12\ \mu m$)

  For honed surfaces $k_s \sim 3\ k_{rms}$ (rms roughness k_{rms})

$k_{rms} = 12\ \mu m$

Why a pipe ?



- Aspect ratio $W/D > 8$
- $A_{channel} / A_{pipe} \approx 10$

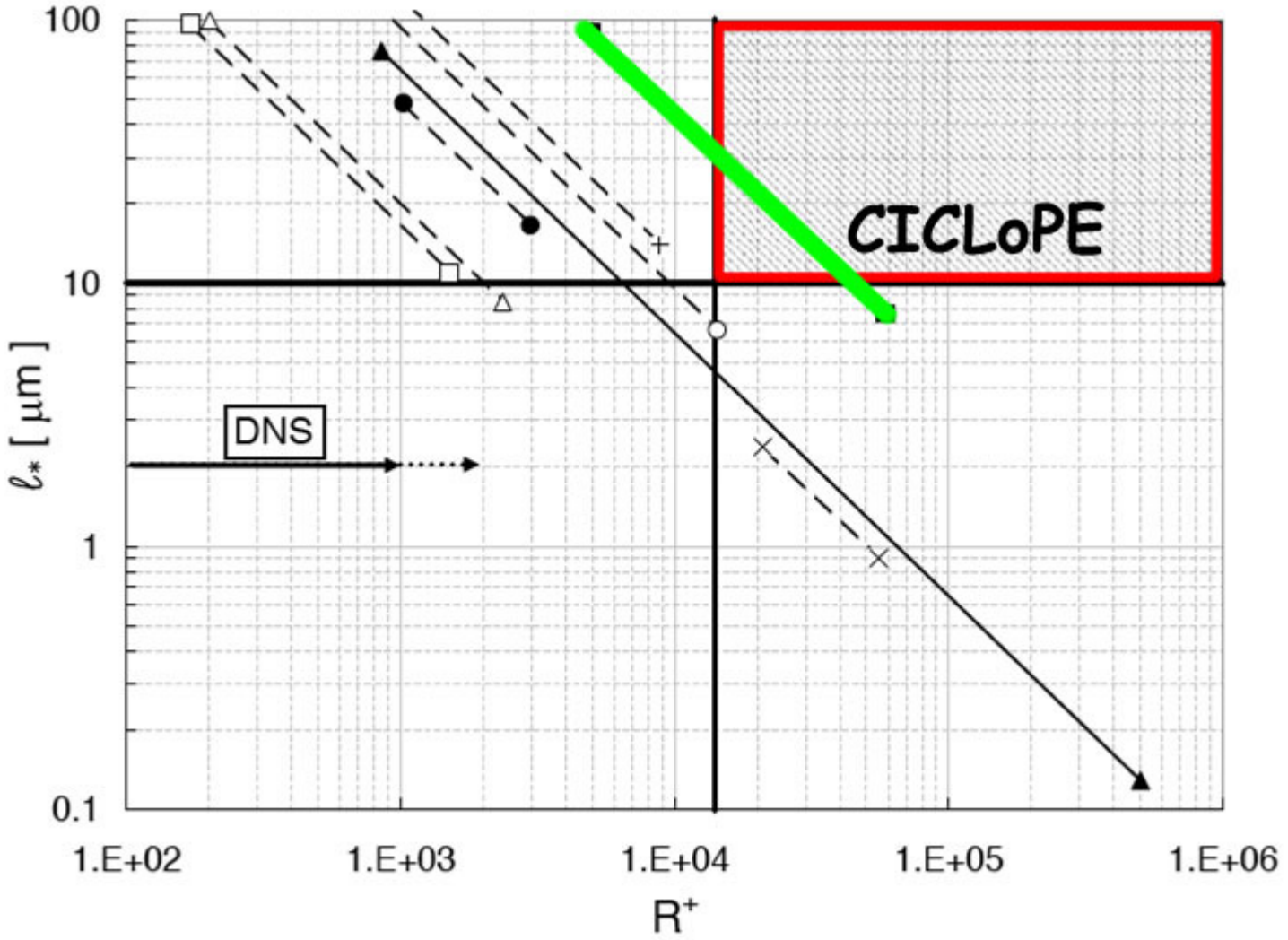
- In the channel there is a need of an independent measure of the WSS

The new experiment

- From the *1st* and *2nd Workshop on Wall-Bounded Turbulent Flows,* Princeton 2003 and Trieste 2004
  http://www.princeton.edu/~asmits/workshop/index_trieste.html

  - Pipe flow
  - Closed circuit
  - Atmospheric pressure
  - Diameter 90 cm
  - Total length: at least 100 m
  - $R^+ = 40000$
  - Velocity ≈ 60 m s^{-1}
  - Moveable test-section

A new experiment



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Why CICLoPE?

"Large" pipe facility requires:

- Total length and characteristic dimensions
- Precision requirements need very low environment contamination
  - Electrical noise
  - Background disturbances
- Highly sophisticated instrumentation

Not easy to install in a single existing laboratory
… absolute necessity of a cooperation between Universities

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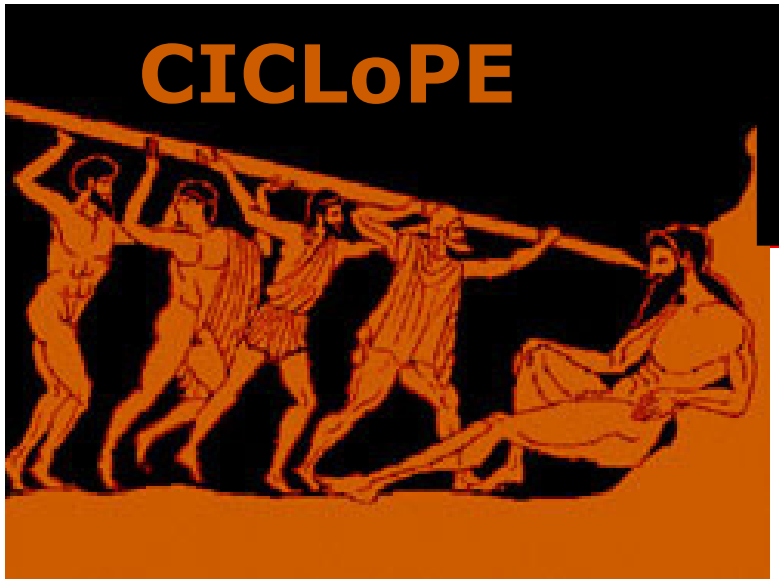

Large scale international collaboration

CICLoPE

Center for **I**nternational **C**ooperation in **Lo**ng **P**ipe **E**xperiments

Partners

- Bologna U. (I)
- KTH Stockholm (S)
- IIT Chicago (US)
- ICTP Trieste (I)
- EPFL Lausanne (CH)

EU Interested Institutions

- Roma U. (I)
- Cambridge U. (UK)
- Imperial College (UK)
- Politecnico di Milano (I)
- CERN Geneva (CH)
- Max Planck (D)
- Illmenau Univ. (D)
- Ecole Polyt. Lyon (F)

Non -EU Interested Institutions

- CalTech (US)
- Princeton U. (US)
- New Hampshire U. (US)
- U. Melbourne (AU)
- Shinshu U. (JP)
- Nagoya U. (JP)

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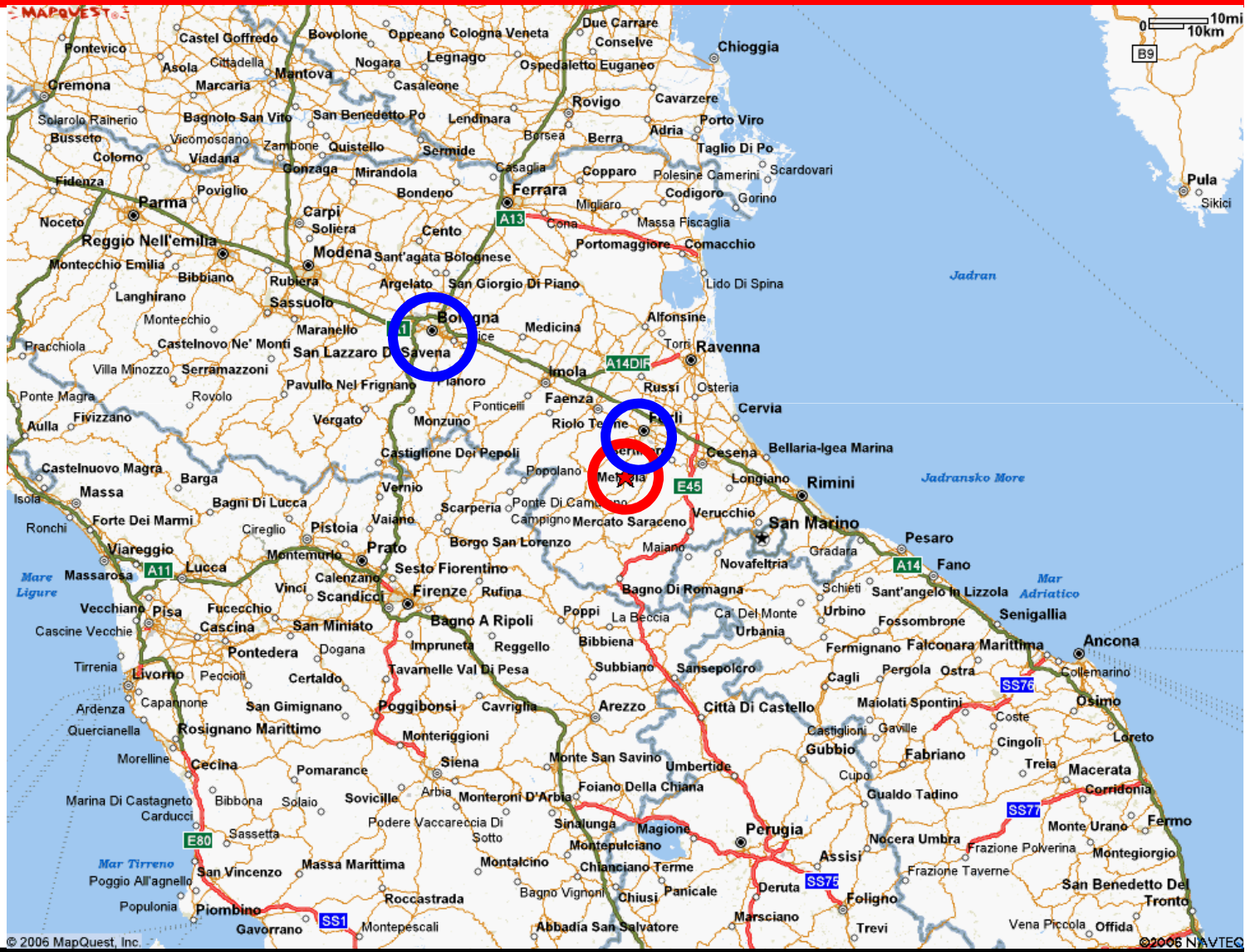
The site

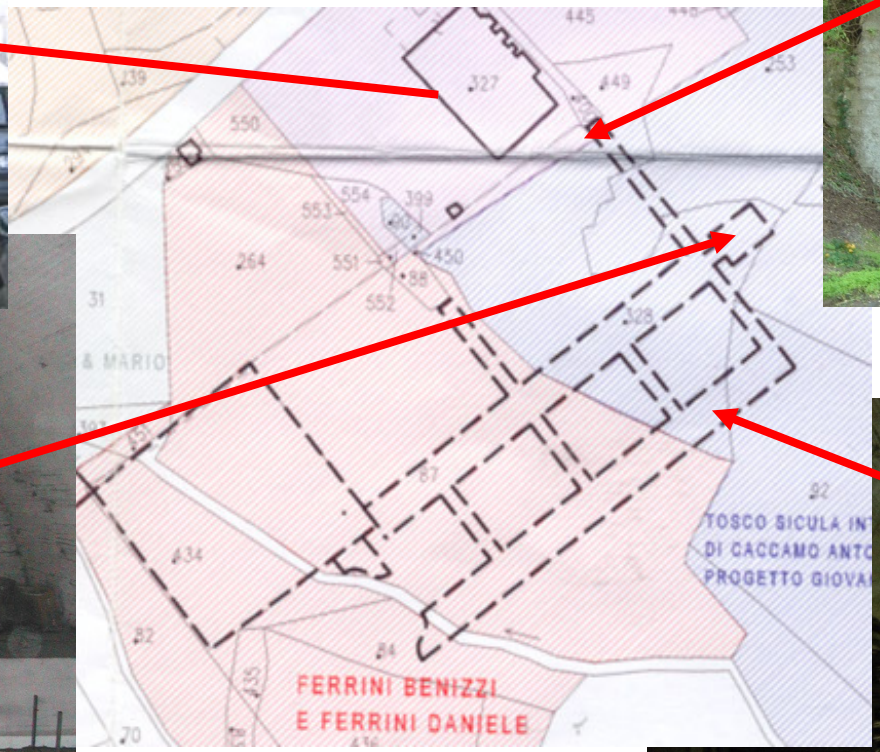
- Predappio



The Industry Caproni

- Tunnels of the "Industria Aeronautica Caproni"
- Built in Predappio to increase the airplane production during the war

The tunnels



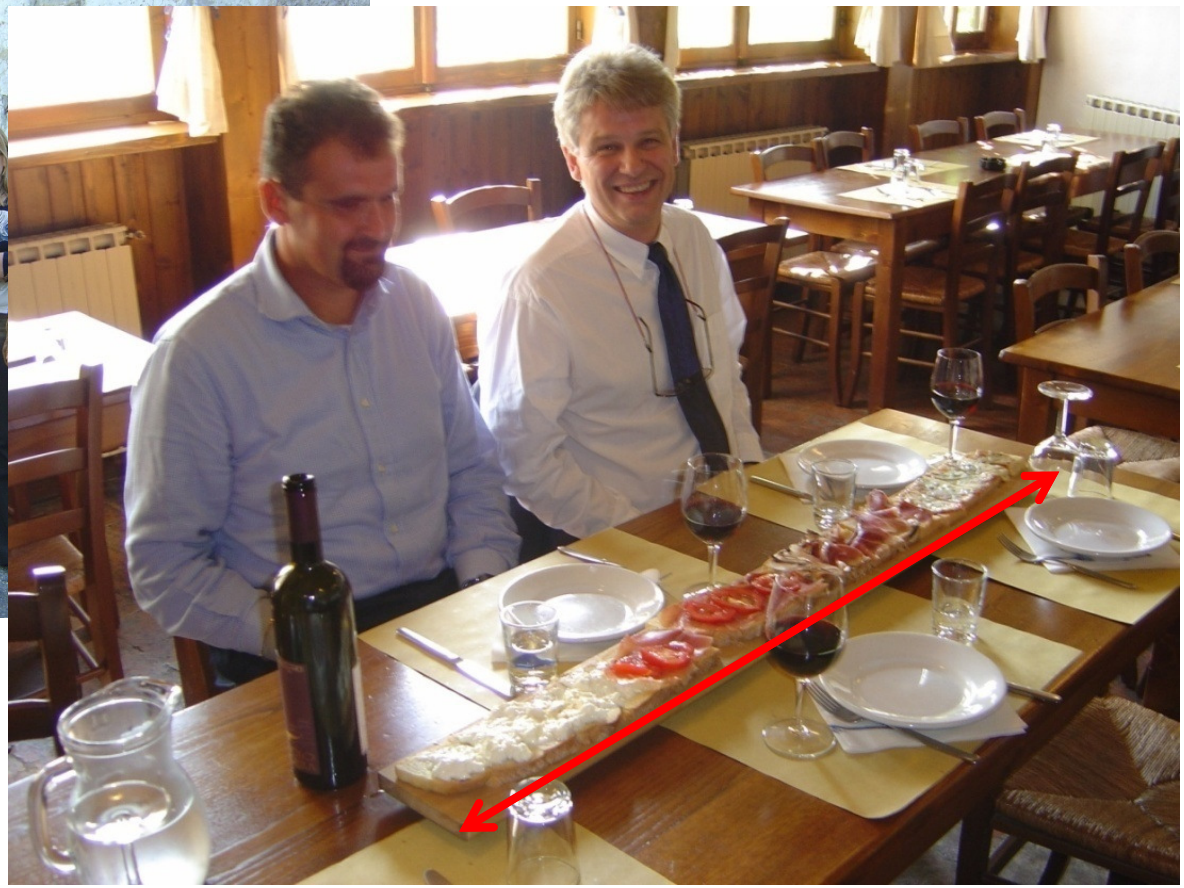
Tunnel characteristics

- Located 60 m underground
- No vibrations
- Closed environment with stable conditions
- Geological test and radar measurements

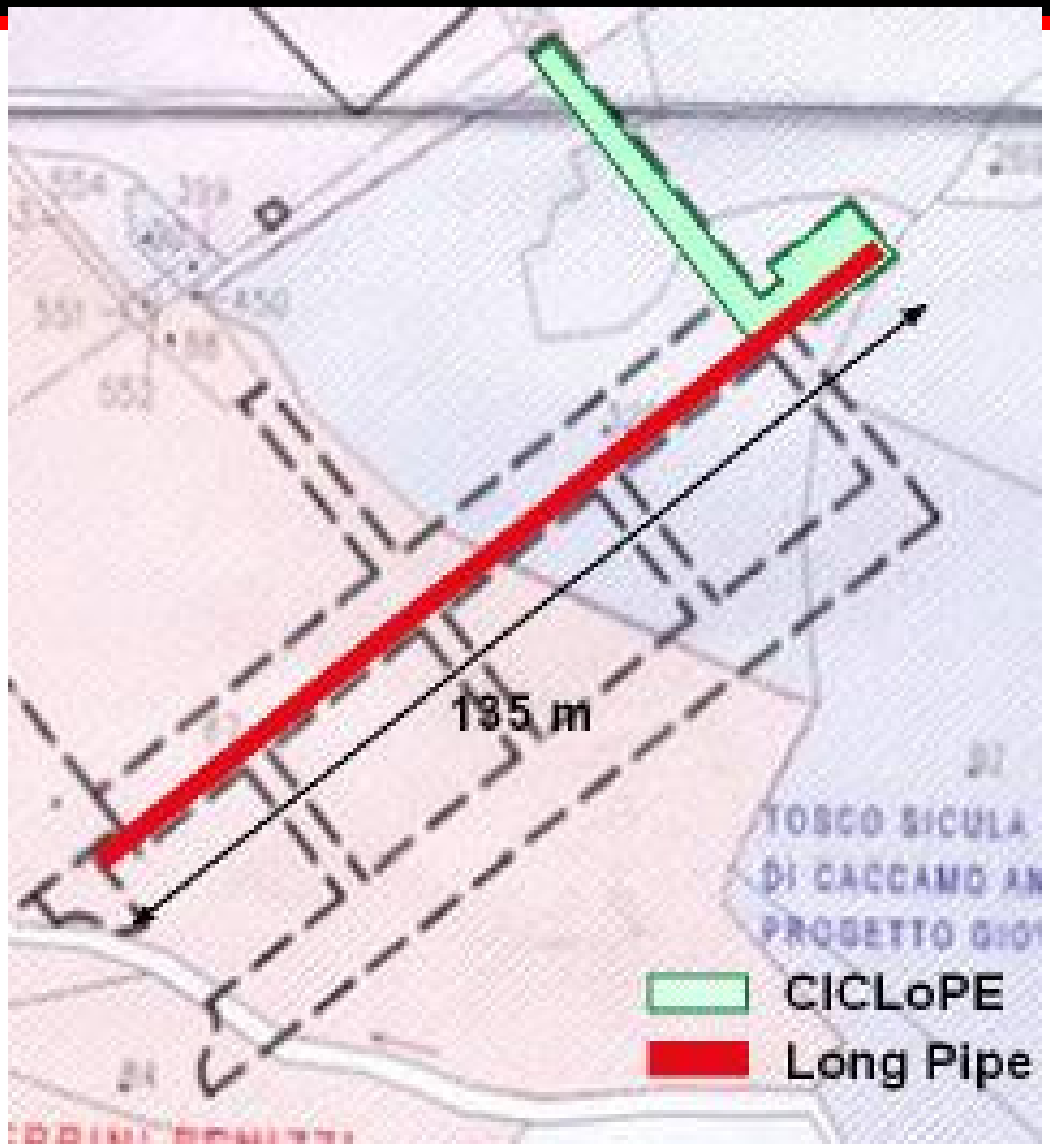
  - Structure of the ground
  - Very good condition
  - Concrete up to 2.3 m thick

- Low RFI and AC perturbation

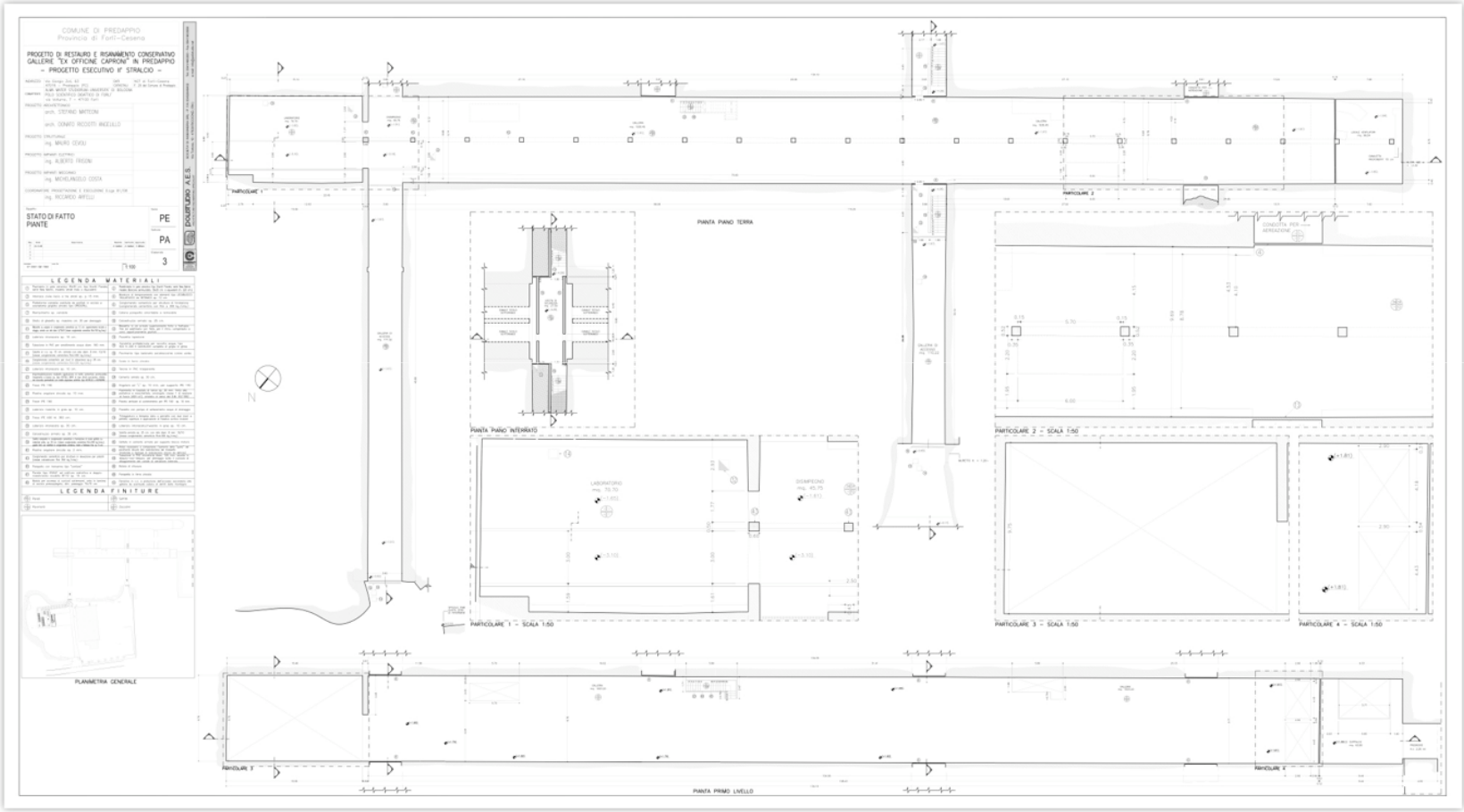
Not only the tunnels……



The laboratory



Tunnels renovation



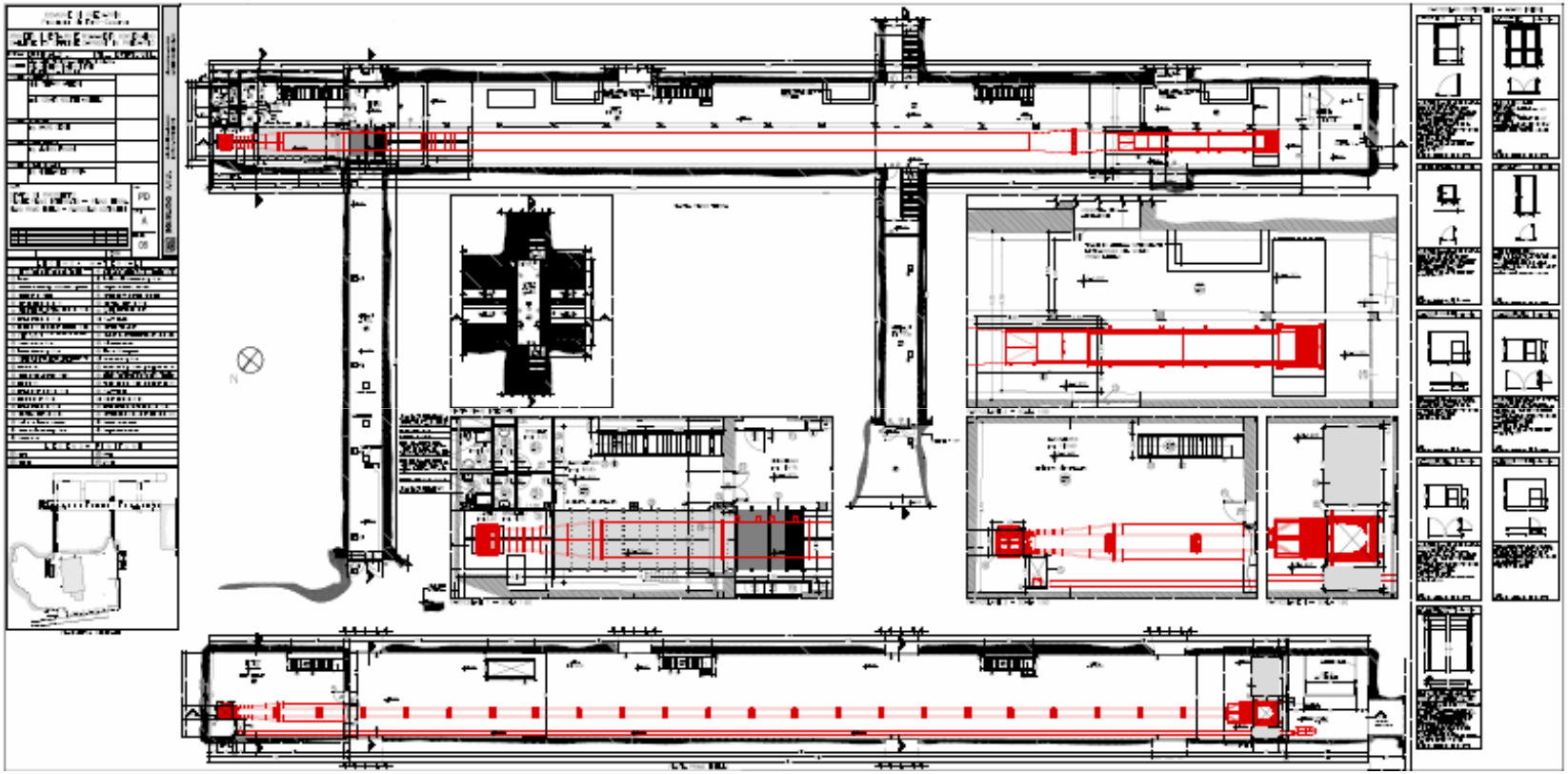
Before after

Current state of the tunnel

Current state of the tunnel

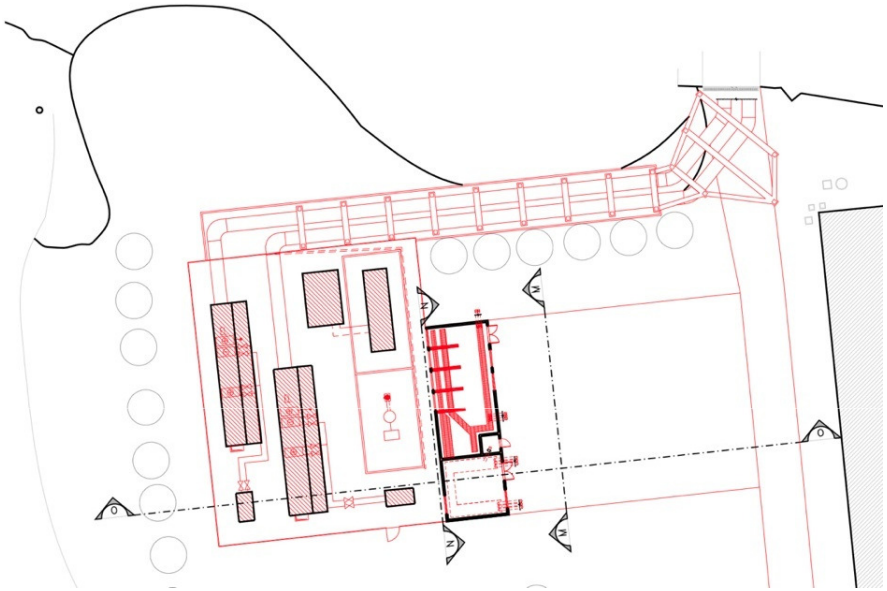
Current state of the tunnel

The final set-up of the laboratory



- Start in september 2010
- End before spring 2011

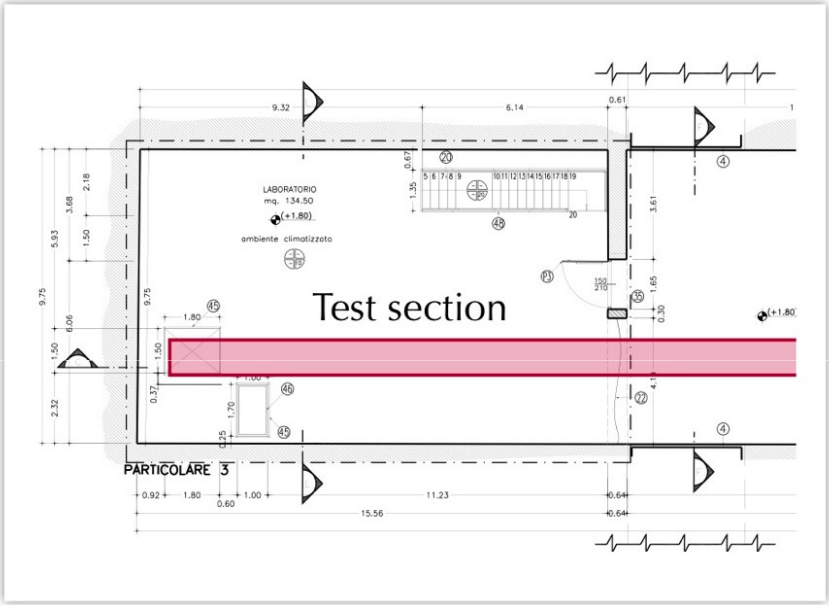
Installation of all systems

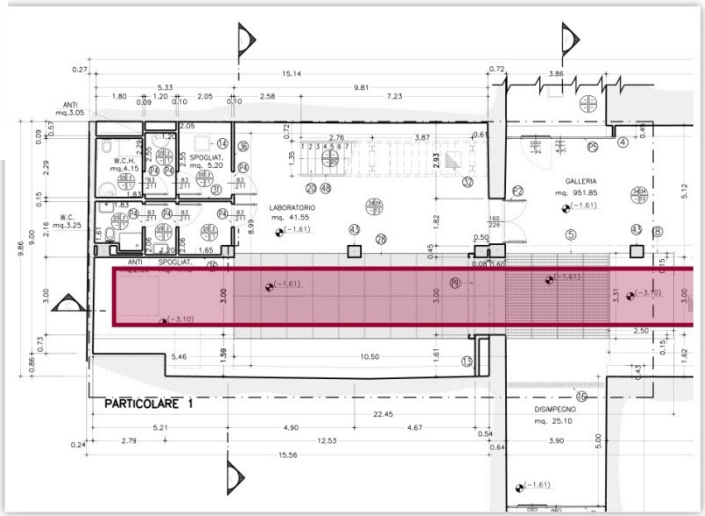


- Electricity distribution
- Light
- Ventilation
- Cooling system for the fan

The future laboratory

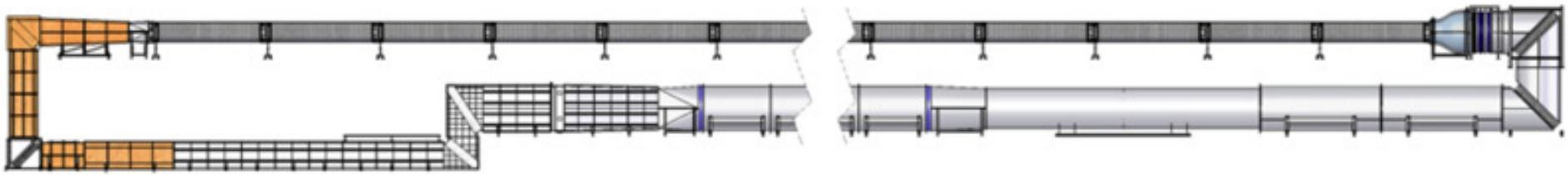
Upper floor





Lower floor

The “Large Pipe”

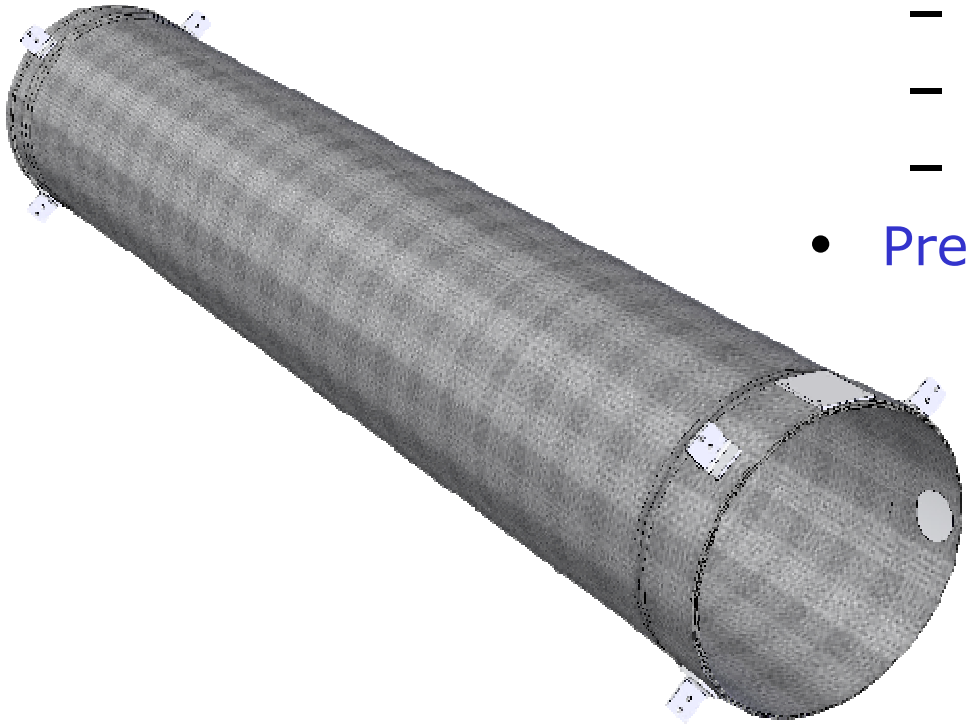


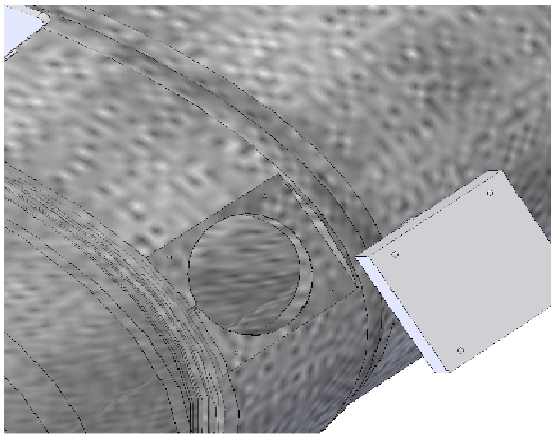
- Characteristics
- Length: 120 m
- Diameter: 0.9 m
- L/D: 125

- Flow conditions
- Velocity: 70 m/s
- Power: 340 kW

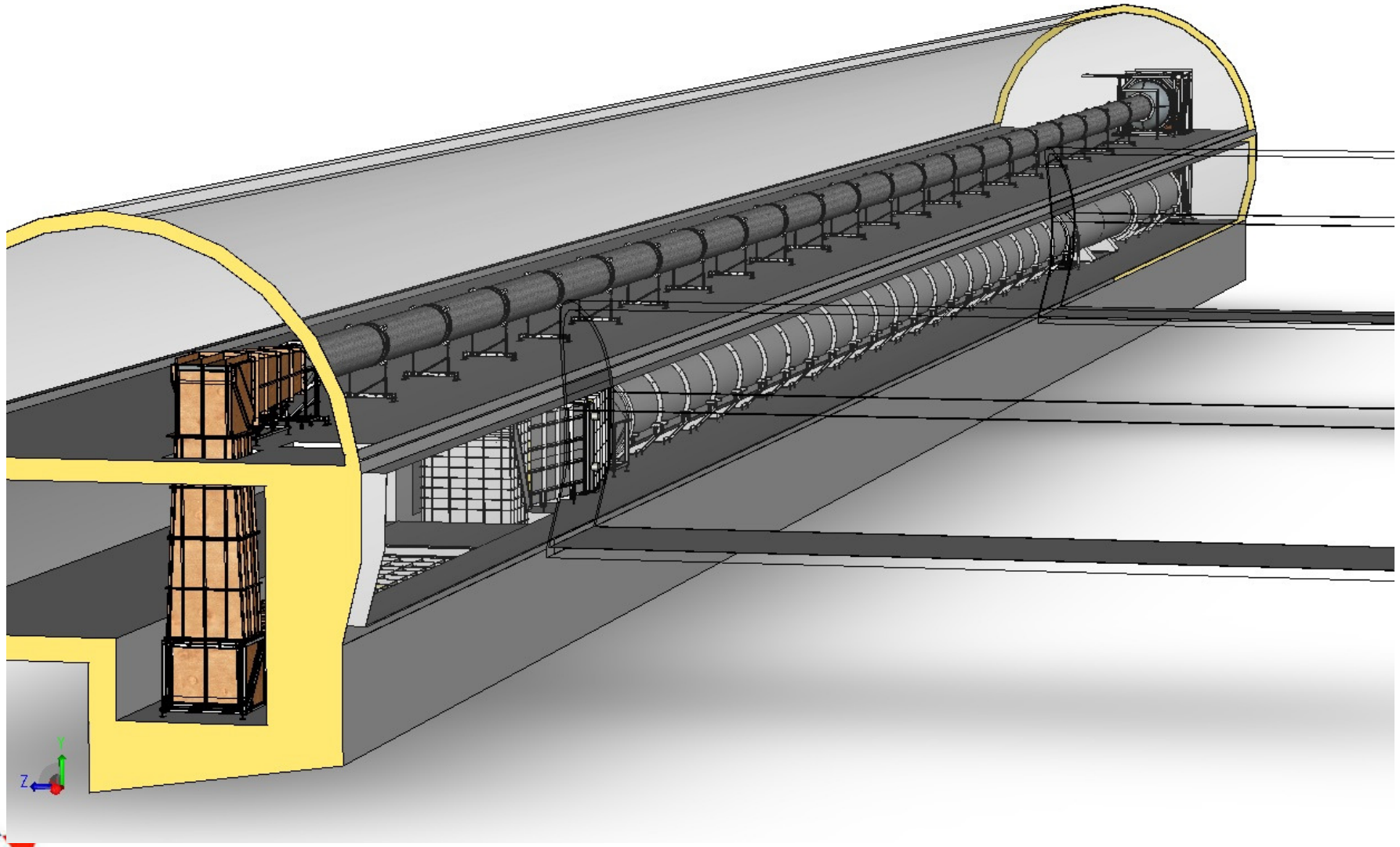
The pipe elements

- Pipe elements
  - Carbon fiber
  - 5 m modules
  - 3 mm thick
  - Possibility to insert devices
  - Roughness < 2.5 μm
- Presence of removable test section

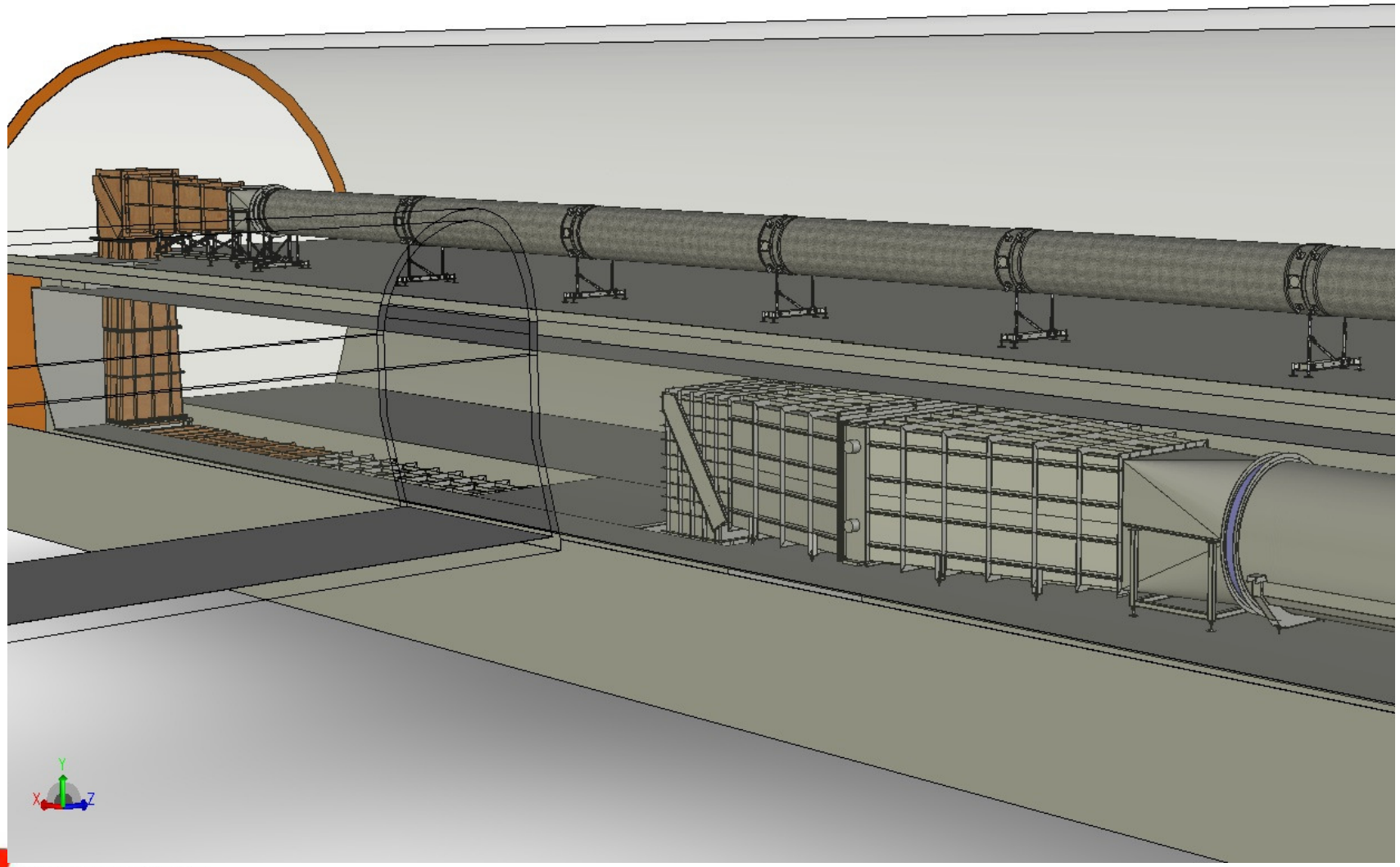




The apparatus



The apparatus



Flow quality

- $\Delta Um(t) \sim$ RPM regulation $\leq 0.001\%$
- $\Delta Um(x) \leq 0.2\%$ (Diameter variations $\leq \pm 0.5$ mm)
- $\Delta T(t) \leq \pm 0.1°C$
- $dT/dx(70\ m/s) = 0.025\ °C/m$ (3°C/120 m)
- Sound pressure level < 87 dB at 70 m/s
  - (1/10th of lowest p_{rms} in the pipe)

Flow conditions

	U_m [m/s]	Re_D	R+	l* [μm]
DNS	1.4	84’000	2200	222
	11	0.66 M	13’000	34.5
	38	2.3 M	40’000	11.1
	70	4.2 M	71’000	6.3

User requirements

- Flexible setup for future experiments
- Measurement accesses along the whole pipe
- Exchangeable test section
- Possibility to mount custom elements at 2 or 3 positions along the pipe

Unique features and new opportunities

- Unique features
  - High Reynolds number
  - Large separation between large and small scales
  - High flow quality
  - Resolution of all scales

- New opportunities
  - Accurate measurement of small scale quantities
    - Correlation between large and small scales
    - Energy transfer between scales
  - Detailed flow structure measurement

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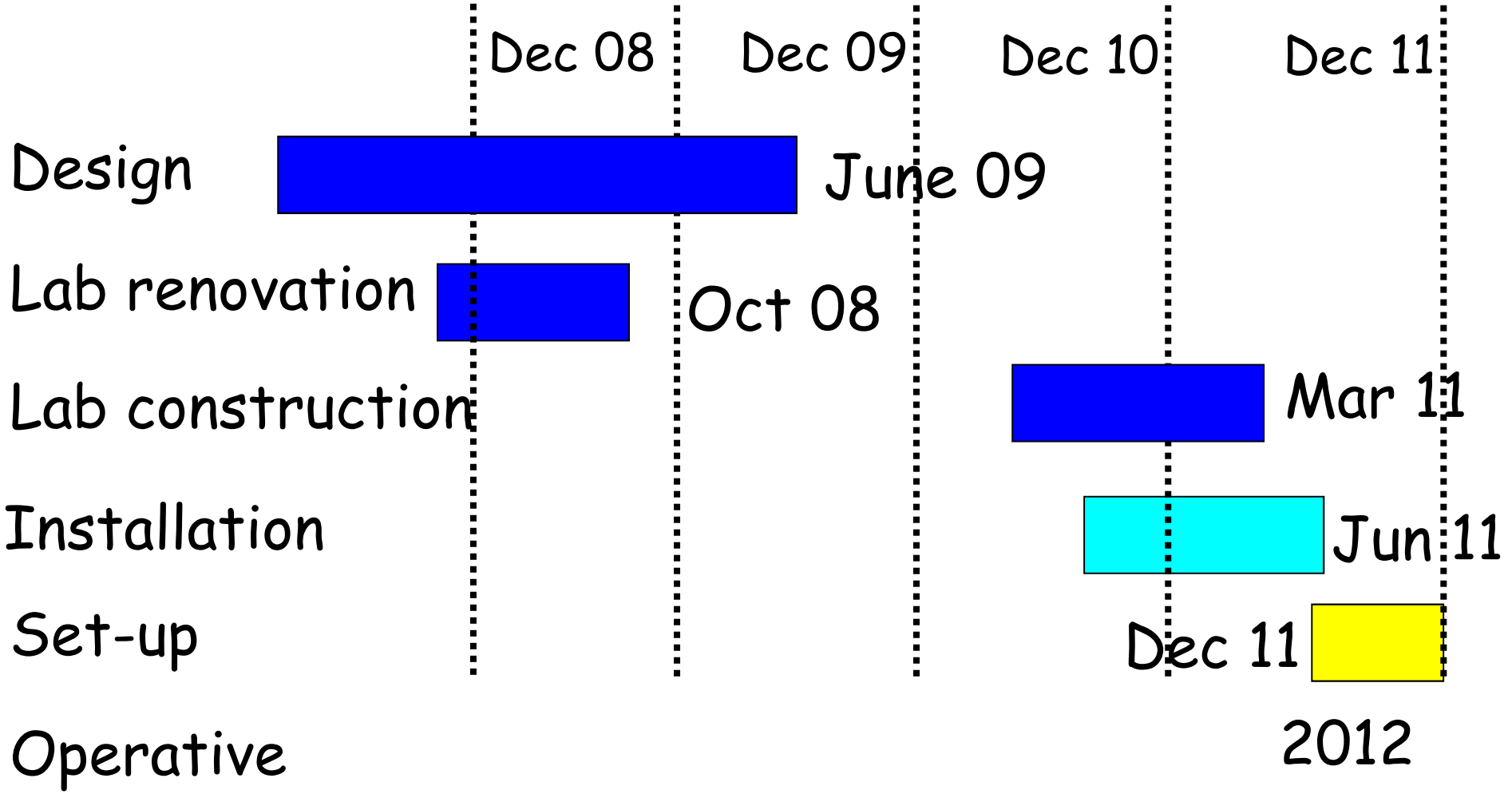
Schedule


Dec 08
Dec 09
Dec 10
Dec 11
Design
June 09
Lab renovation
Oct 08
Lab construction
Mar 11
Installation
Jun 11
Set-up
Dec 11
Operative
2012

THANK YOU FOR YOUR ATTENTION !!!!

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