Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
INFN

A fiber optic continuous strain sensing plant for CAOS in Perugia

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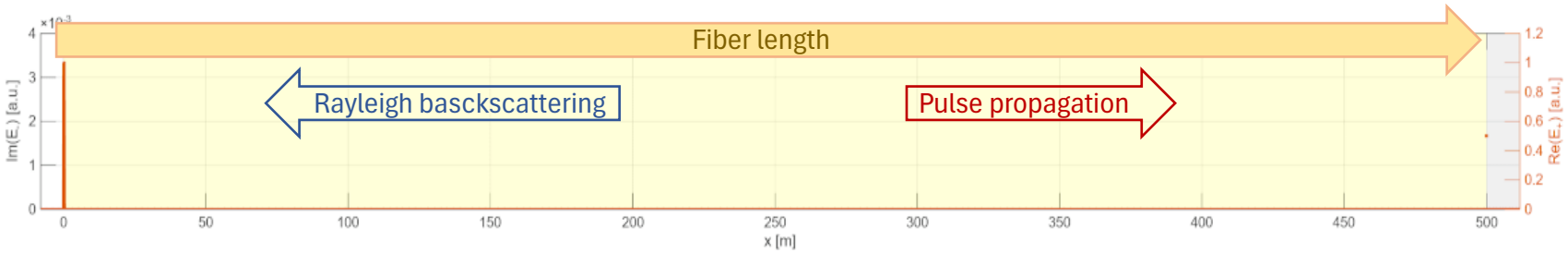
Summary

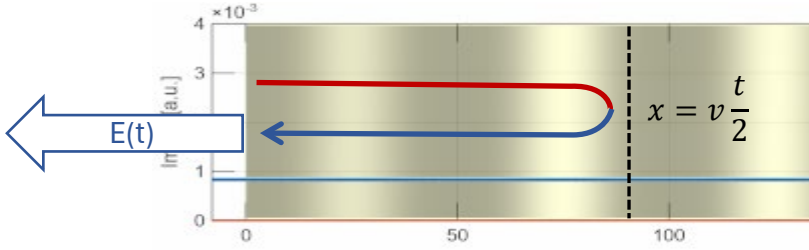
- Distributed acoustic sensing
- A plant designed for CAOS
- Implementation

Distributed Acoustic Sensing

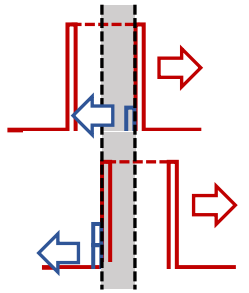
- When a **laser pulse** propagates in a single mode fiber, a **weak continuous reflection** is produced by Rayleigh scattering over imperfections of the medium.



- Light exiting the input end of the fiber at **time t** has traveled up to **position $x = v\,\frac{t}{2}$** and back.
  If a **longitudinal strain** is applied to the fiber that causes **a change in the optical path**, the **t-time output light** carries **twice the phase accumulated** by the pulse **between 0 and $x(t)$**.



- The pulse has a finite extension. The reflection from the front section is superimposed on that coming from the rear after half pulse-length propagation. As a result, the reflection at time t integrates contributions over **half the pulse length** in the fiber.
  This the **gauge length** of the interrogator, the integration length of the instrument.



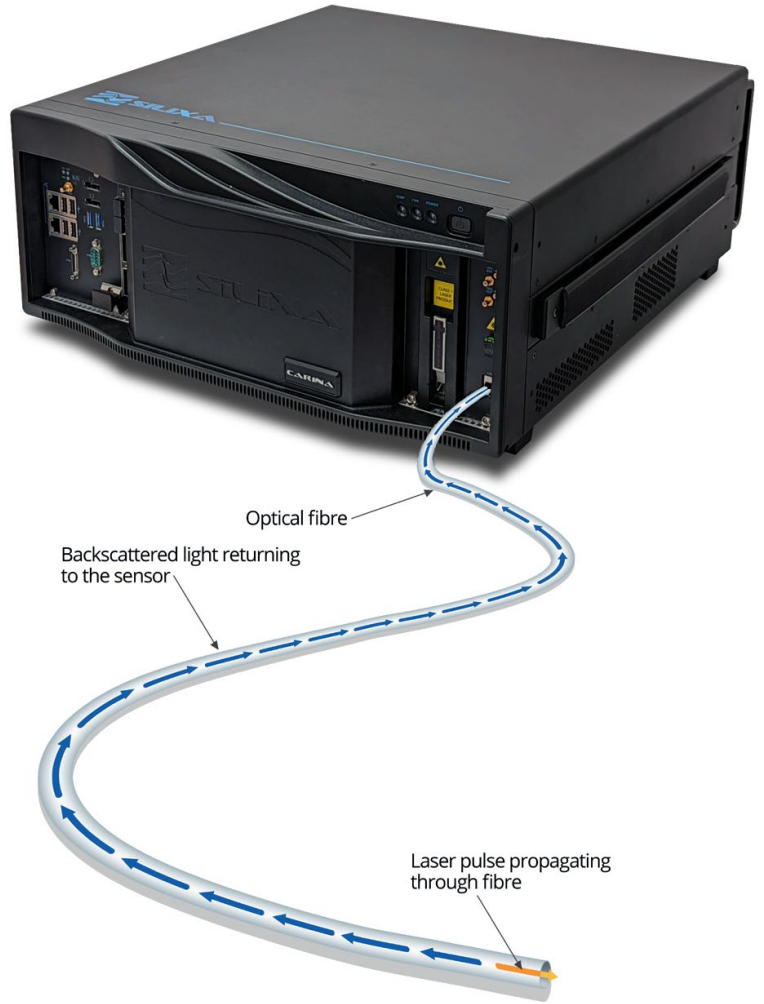
Gauge length

Silixa Carina

Gauge length (software selectable)	25 cm	2 m	10 m	30 m
Sensing range*	15 km	30 km	50 km	60 km
1 kHz amplitude spectral density**	90 pε per sqrt Hz	3 pε per sqrt Hz	300 fε per sqrt Hz	70 fε per sqrt Hz
10 Hz dynamic range**	130 dB			
Sample spacing	25 cm to 32 m (40,000 samples maximum)			
Spatial resolution†	1 gauge length			
Sampling frequency††	400 Hz to 100 kHz			
Acoustic sensitivity	<0.001 Hz to 50 kHz			

* Defined for single mode fibre.

** Median value for standard specification engineered ConstellationTM fiber, with interrogator settings optimised for a 700 m fiber length.



Fiber

After the experience of colleagues from
Istituto Nazionale di Geofisica e Vulcanologia (INGV)
and Università di Milano Bicocca
this cable has been chosen.

Property:

- single mode,
- no Teflon,
- good performance with DAS interrogators,
- reinforced, resistant to bending, duplex

LightMax®
THE FIBRE OPTIC BRAND

Dielectric Indoor - Outdoor Cable

Drop Fig8 | 2-4 Fibres | LSZH - BLACK
SM G.657.A2

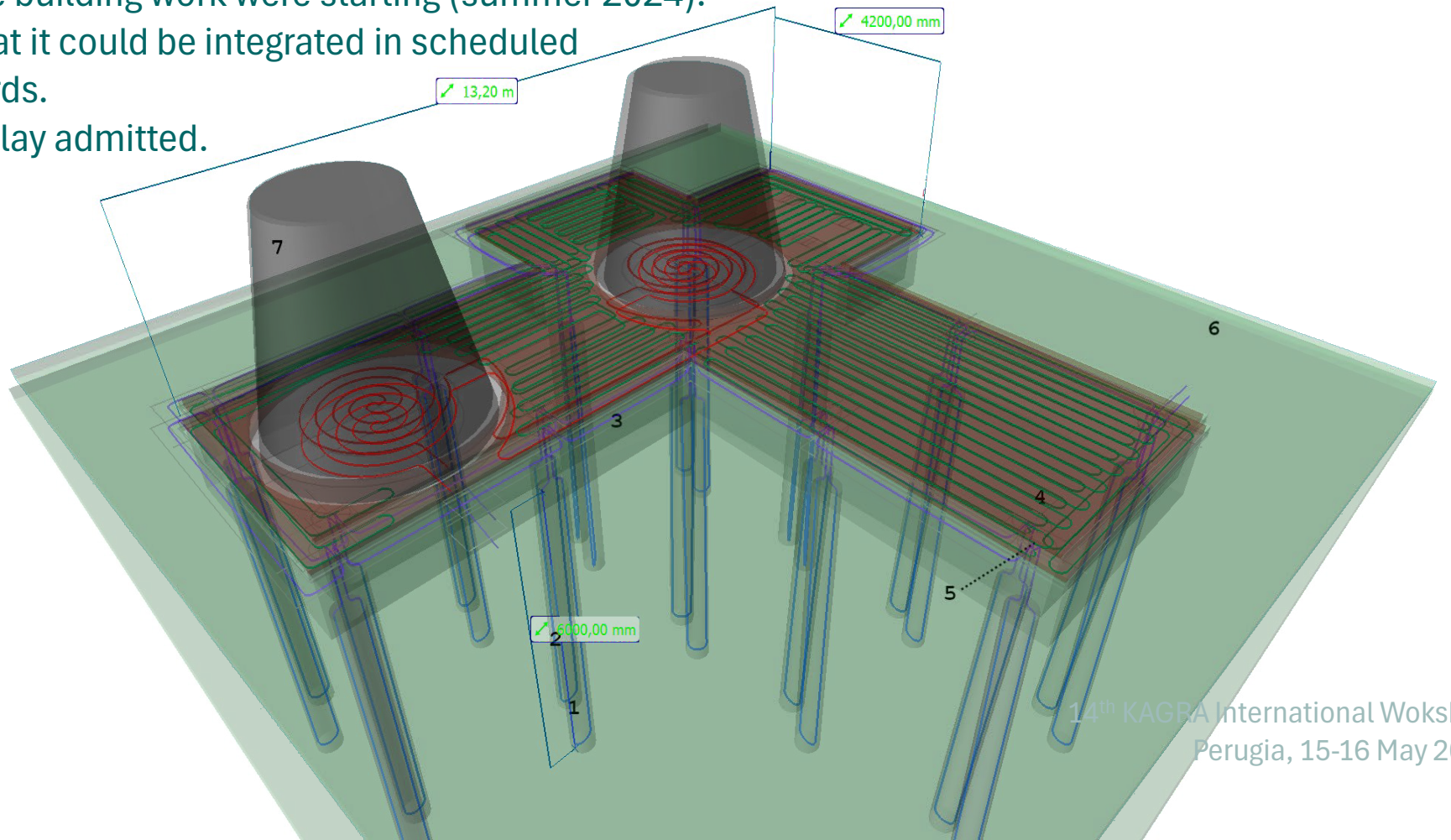
CABLE SPECIFICATIONS			
Cable type			Drop Fig8
Fibres count			2
Weight		kg/km	21.0
Nominal diameter	Drop portion	mm	2.0 ±0.1 x 5.3 ±0.2
	Overall		
Cable messenger		-	Yes - Steel wire
Outer sheath	Material	-	LSZH
	Colour	-	Black
Strength member	Material	-	FRP
	Diameter	mm	0.52
Temperature	Storage	°C	-40 ~ 60
	Operation		-40 ~ 60
Bend radius	Load	mm	40
	Unload		20
Crush resistance	Load	N/10 cm	1000
	Unload		500
Tensile	Load	N	300
	Unload		

A plant designed for CAOS

Fiber sensing was not integrated natively in CAOS design.
We started working at the plant as the building work were starting (summer 2024).
The plant had to be designed such that it could be integrated in scheduled building works or completed afterwards.
No design revision or construction delay admitted.

1. Foundation pillars (6 m)
2. Vertical fibers in the pillars
3. Reinforced concrete slab (110 cm)
4. Horizontal fibers
5. Floating floor tiles (above horizontal fibers)
6. External floor (with seismic joint)
7. Vacuum tower bases.

The vacuum towers lay on the circular coronas around the red fibers.



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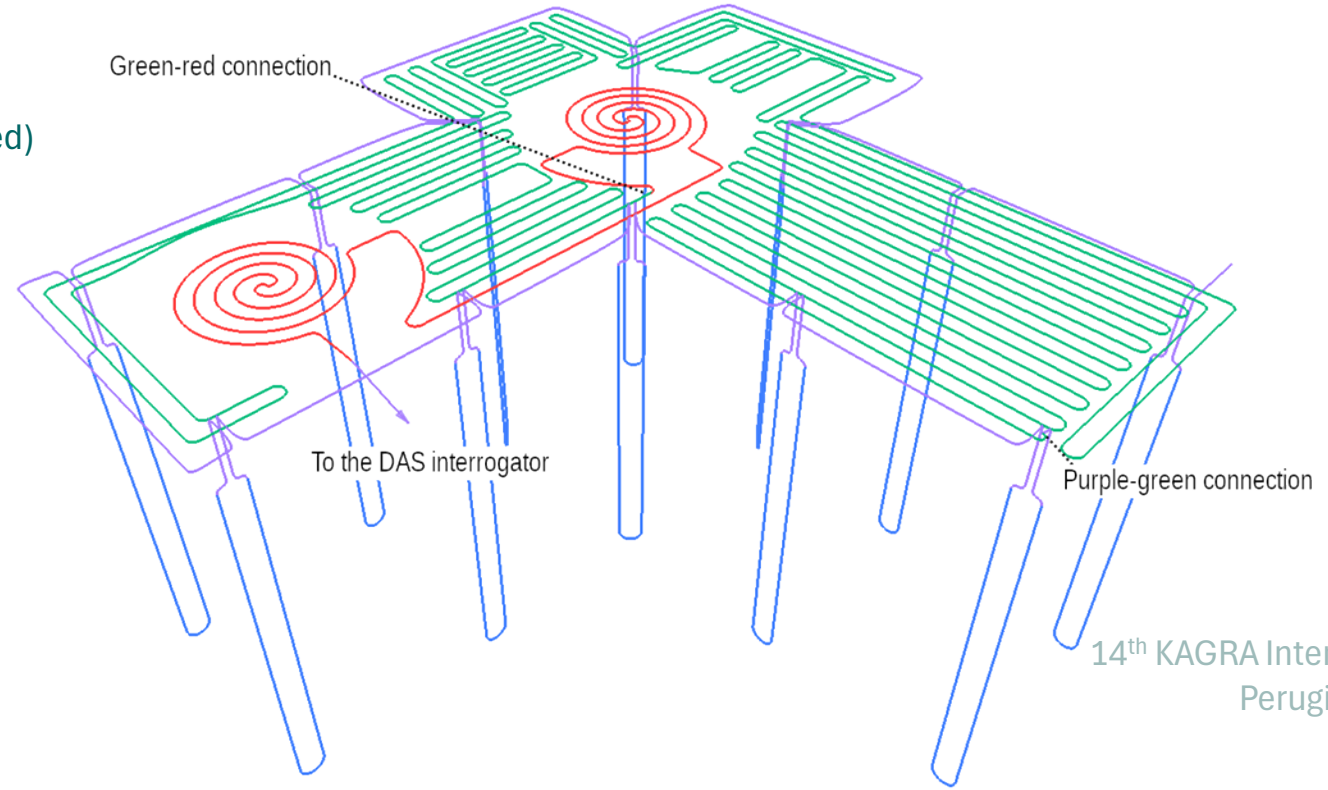
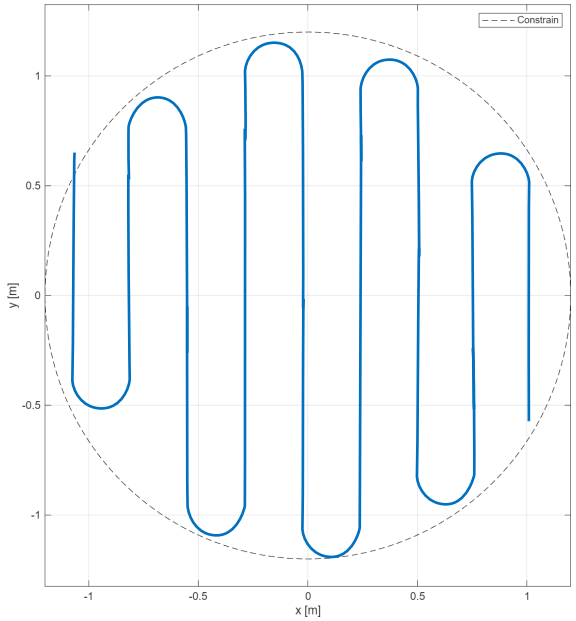
Blue: drowned vertical fibers
Purple: loose connections
Green: horizontal fibers under floating floor (still not deployed)
Red: horizontal fibers under the towers.



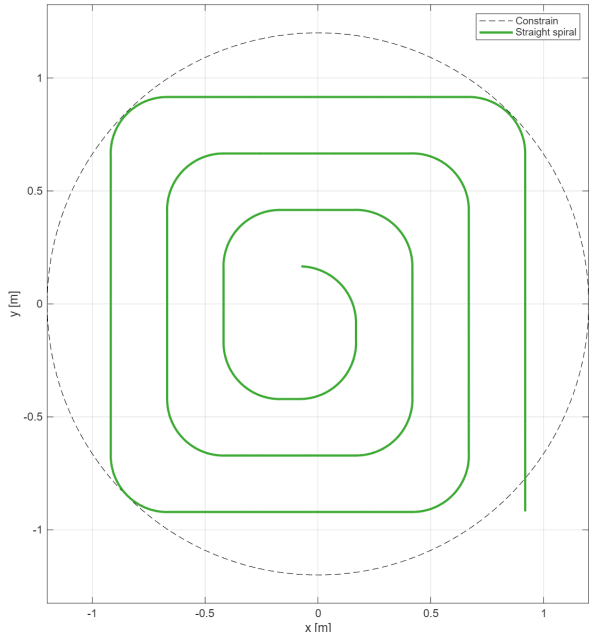
Small inaccessible areas under the vacuum towers

We have small available areas under the tower bases, with diameter $2.5\ \mathrm{m}$.
With construction requirement/constraints:

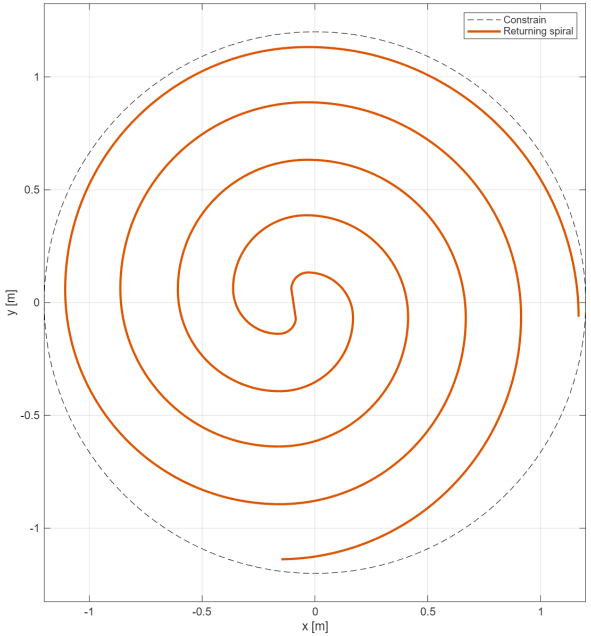
- signal readability,
- 2D sensitivity,
- one layer,
- maximum filling.



Sensitive in one direction only



Reduced filling



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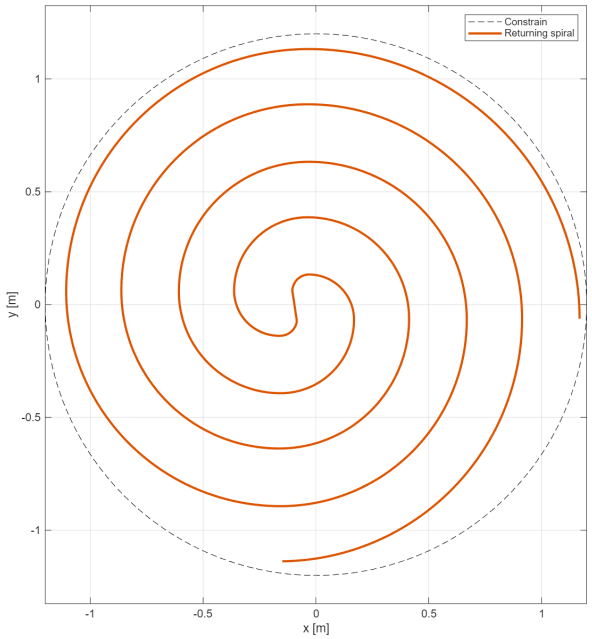
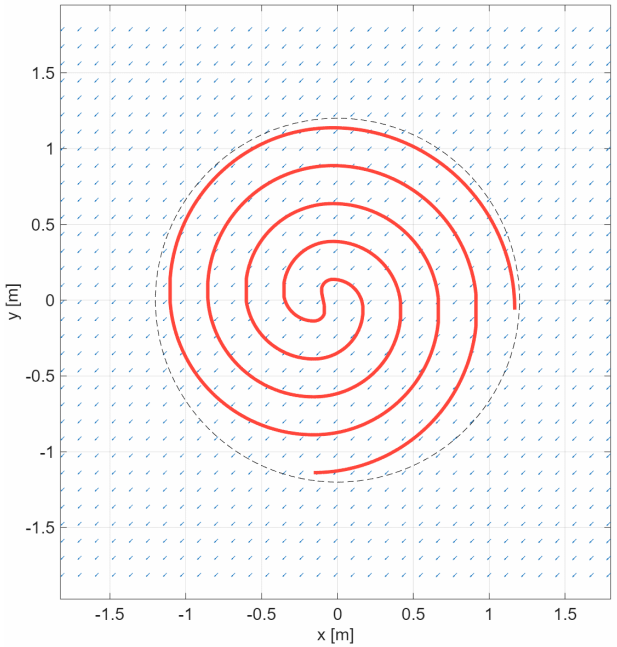
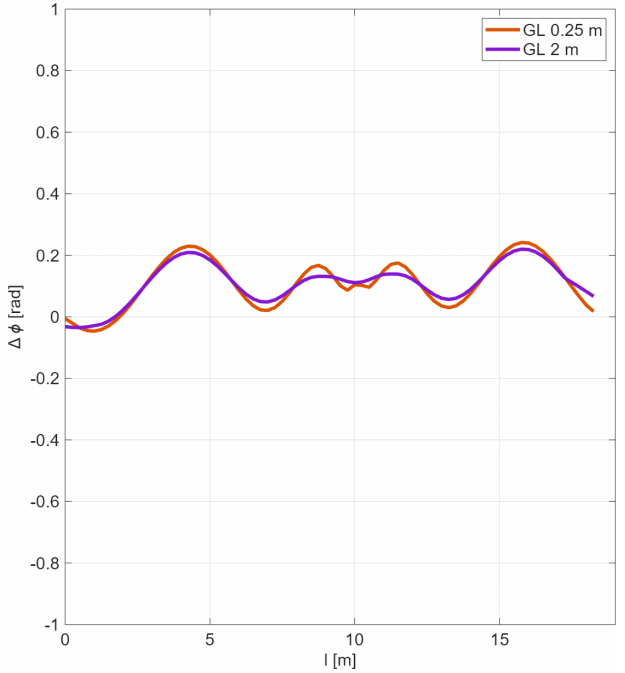
Spiral sensor

Is a spiral plant with $2.50\ \mathrm{m}$ diameter suitable for strain wave characterization?

- S/N ratio is increased with longer gauge lengths. Can this plant be interrogated with $GL > 0.25\ \mathrm{m}$?
- Can this plant discriminate strain directions?
- Can this plant distinguish longitudinal from transversal strain waves?







The accumulated phase due to fiber strain was simulated.

$GL\ 0.25\ \mathrm{m}$ and $GL\ 2\ \mathrm{m}$ are expected to give **comparable signals**.
$GL\ 2\ \mathrm{m}$ is weaker mainly in the center of the spiral ($l \approx 10\ m$).

This simulation:
f = 10 Hz
v = 4 km/s
s = 10^-8

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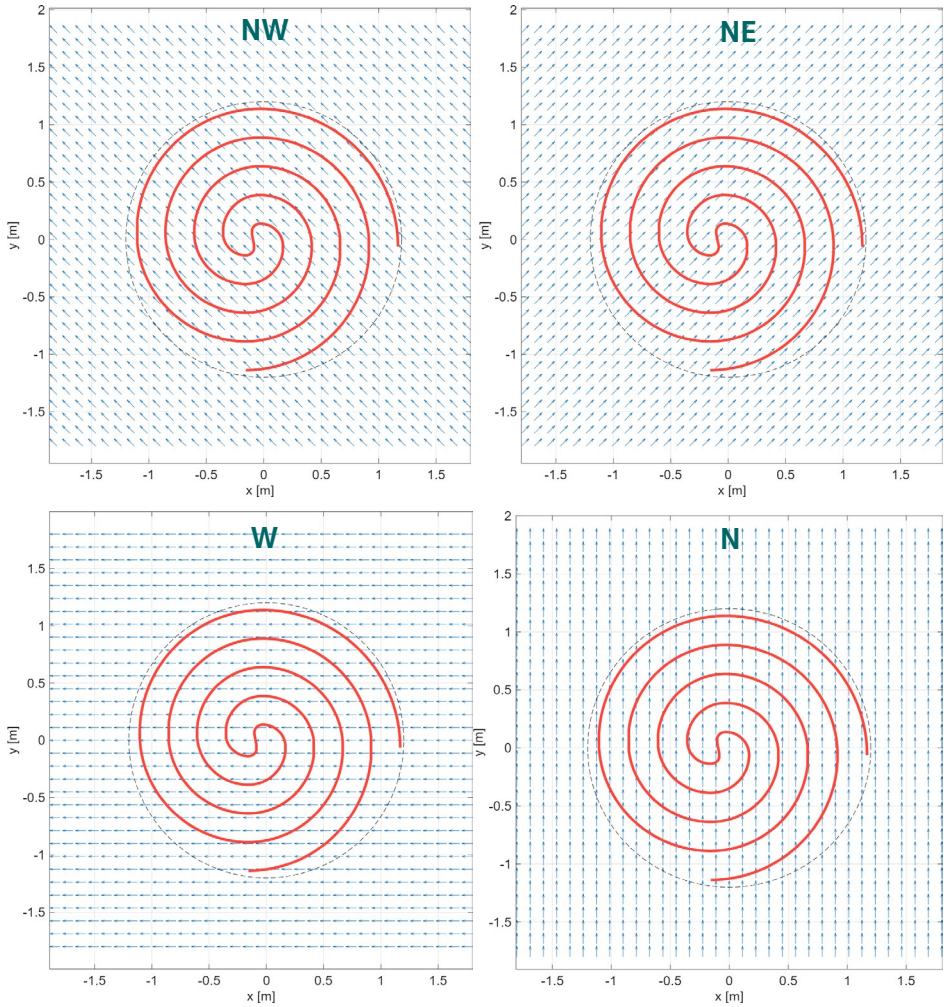
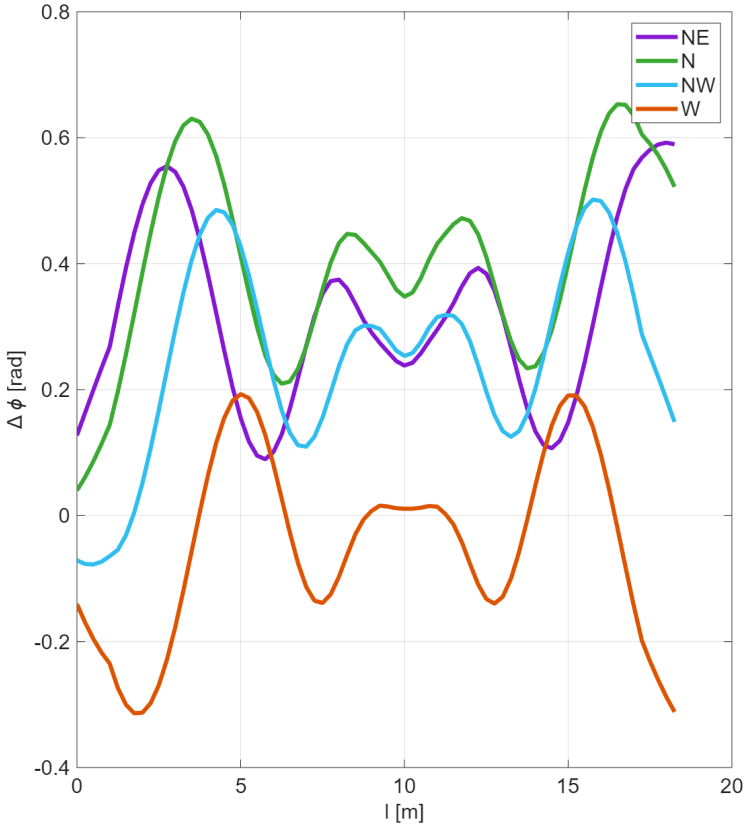
Spiral sensor

Can this plant discriminate strain directions?



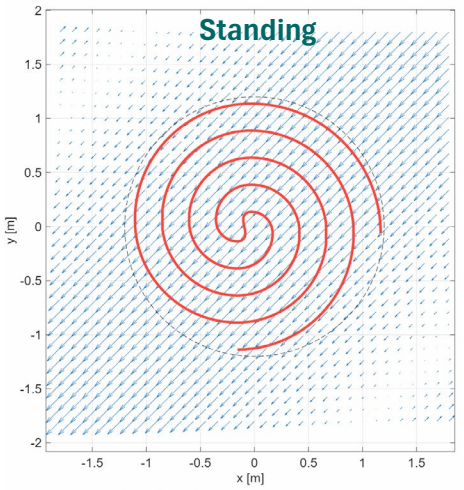


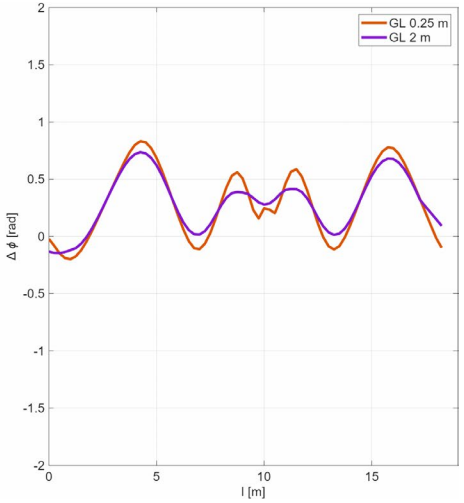
Different polarizations give **different phase plots** (evolving differently in time).

These simulations:
f = 10 Hz
v = 4 km/s
s = 10^-9
GL = 2 m

Spiral sensor

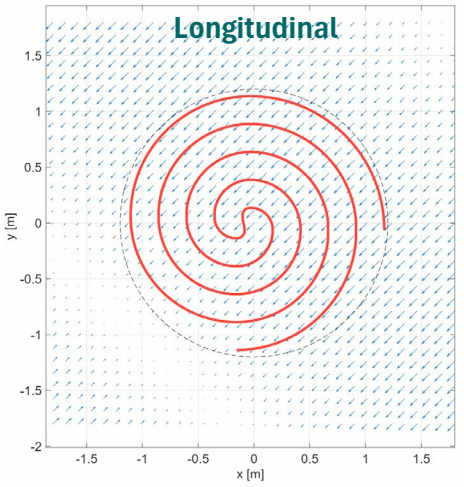
Can this plant distinguish longitudinal from transversal strain waves?

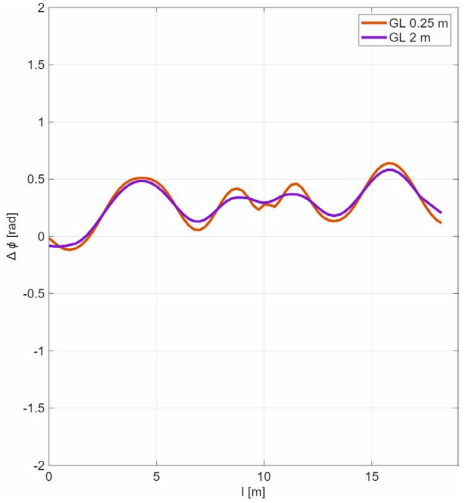


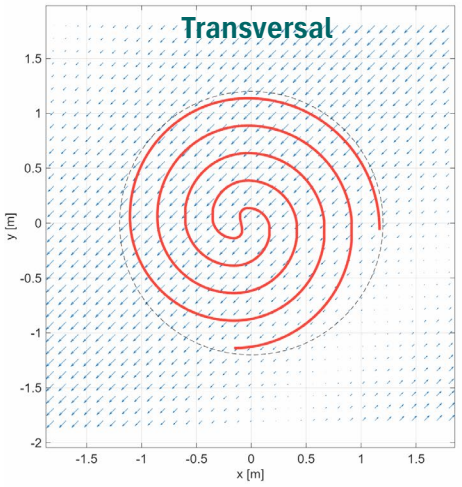


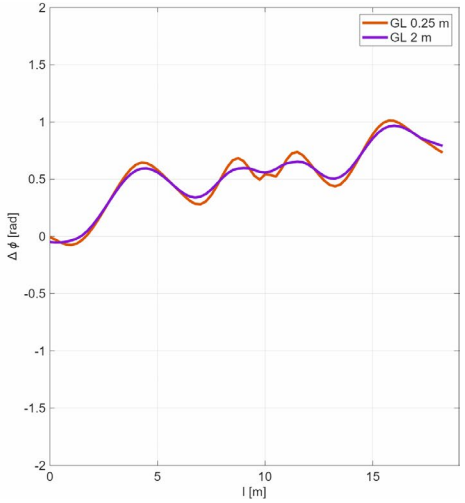
Longitudinal and standing waves can exhibit very small differences.
Transverse waves produce a characteristic rising phase.

These simulations:
f = 500 Hz
v = 4 km/s
s = 10^-9
same polarization



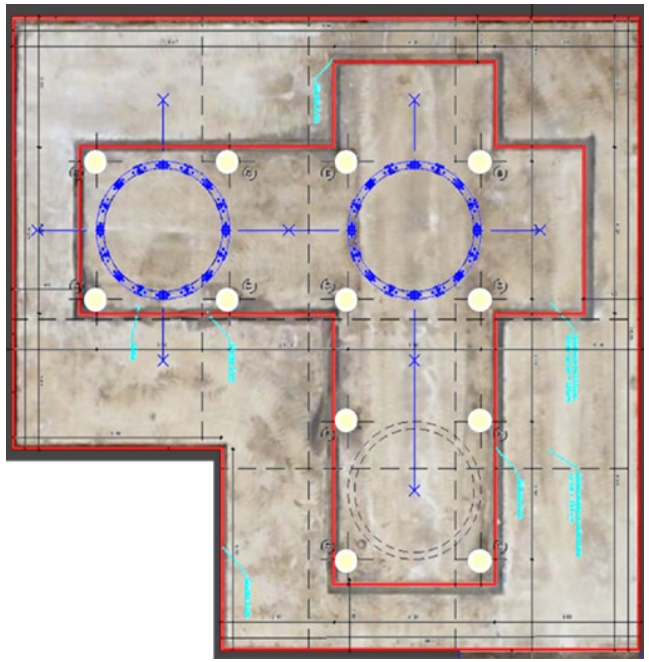






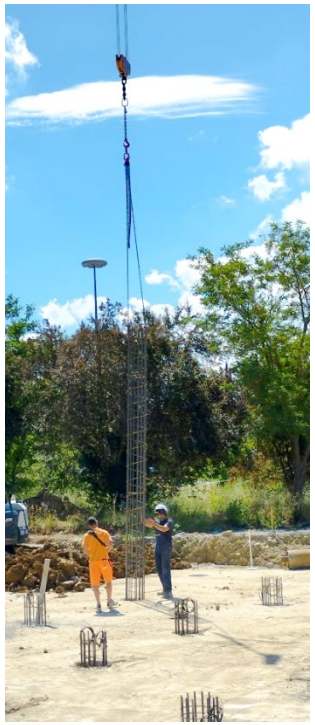
Implementation

Fiber installation in foundation pillars



Yellow. Foundation pillars of the experimental area.
Red. Isolating joint (ground cut).

Steel reinforcements are prepared with optical fiber (roundtrip, redundant).



Reinforcements are lowered into the drilled foundation holes.

Concrete is poured into holes.
The cement weight ensures adhesion to the fiber.

Six pillars equipped with duplex fiber cable.
Six with two duplex cables for further redundancy.

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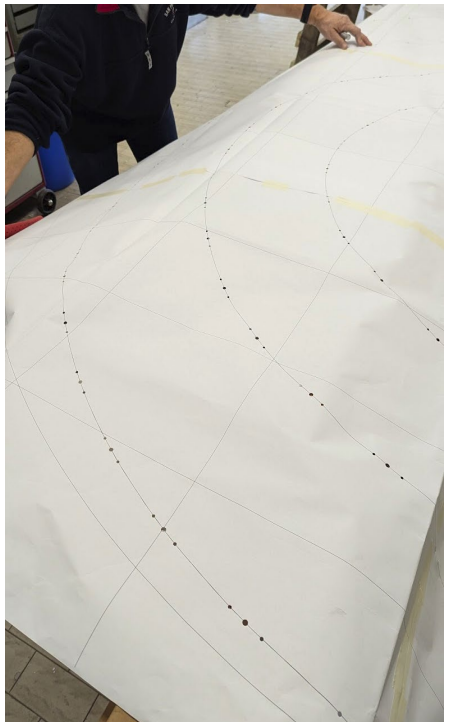
Implementation

Fiber installation below the towers

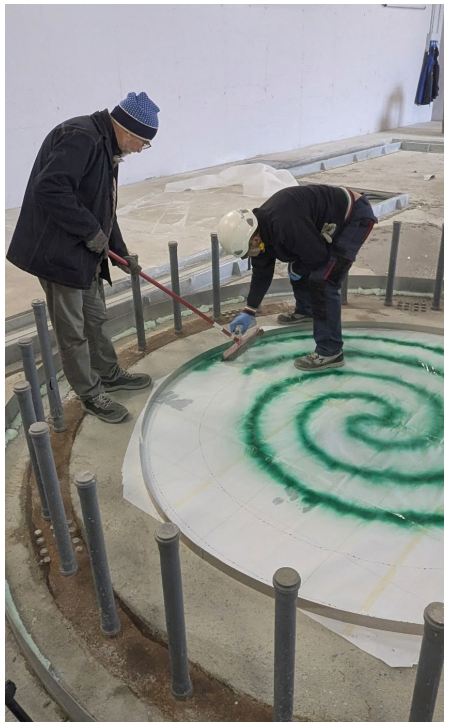
Confined areas must be equipped with fiber spirals, on top of the concrete layer.
Constrain: no groove cutting.

Pourable, **superior adhesion**, **non-shrinking**, **rigid** concrete:
MAPEGROUT COLABILE ZERO
+ MAPECURE SRA 0.25%
(normally used for structural repairs).

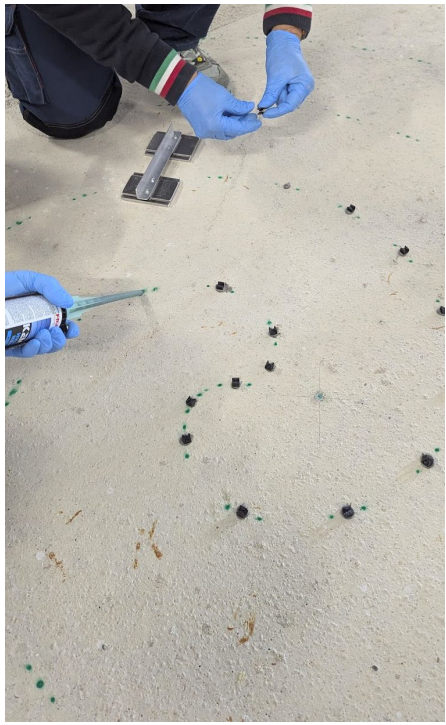
Accurate surface cleaning.



Drawing preparation.



Drawing transfer.



Placeholders.

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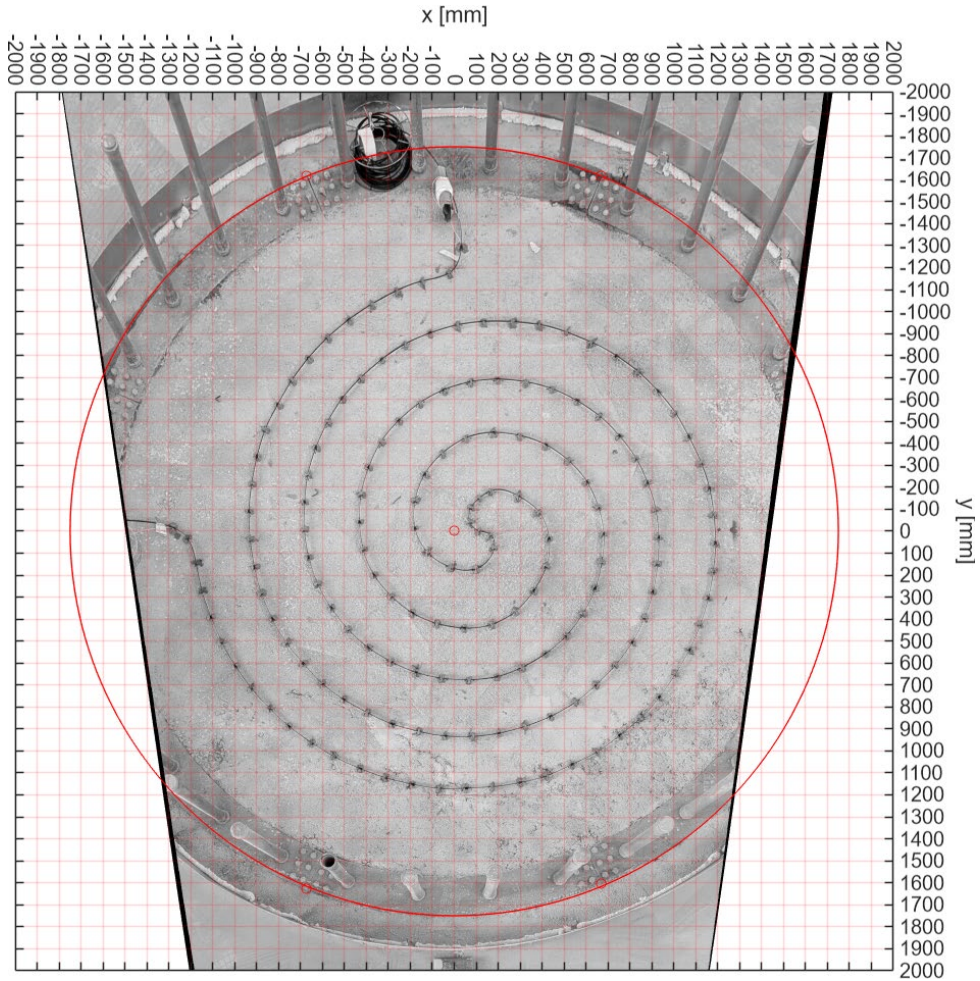
Implementation

Fiber installation below the towers (2)

Fiber in place.

Embedding fibers.



And don't forget retaining information!

Conclusions

- None, yet.

Perspectives

- This is a startup.
  Next part of the plant to be installed as soon as the laboratory is operational.
- Starting collaborations with
  Silixa
  INGV
  INFN-Roma1, GSSI, Newtonian noise experts