MEMS SENSORS FOR HIGH VOLTAGE LINES

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WHY IS THAT NECESSARY ?

National Electricity Grid → strategic infrastructure that must be reliable 24 hours/day and 7 days/week.

All the activity of the mankind society depends critically on this electricity grid.

Objectives of our work:

- better / more accurate monitoring of the grid while:
  - keeping the costs low
  - allowing redundancy of voltage and current measurement
- adaptive electric grids → react in an "intelligent" manner to the changing operating conditions.

Adaptability is not possible without having electric sensors (voltage and current) that are able to respond accurately and fast in order to allow the network monitor to take the correct decisions.

PRESENT SITUATION (VOLTAGE MEASUREMENT)

- Present day high voltage measurement systems are bulky and heavy

- Measurement accuracy is 0,1 % only in some special cases (electricity export)

- Usually, accuracy of 1 % - 2 % is commonly used

- The costs of such systems are high

- Their leakage could reach hundreds of Watts

- Their cost and size do not allow redundancy at a certain measurement point

REQUIREMENTS FOR THE MEASURING SYSTEM / DEVICE

- Voltage range: from 10 kV – 1500 kV
- Measurement accuracy: 0,2 % or better, preferably 0,05 %
- Frequency spectrum: at least 10x the basic frequency of the grid (50 Hz / 60 Hz)
- Duration in exploitation: minimum 5 years
- Measurement of the instantaneous voltage value
- Immune to vibrations produced by winds or earthquakes
- Immune to ambient temperature variations
- Preferable: redundancy assured
- Ease of maintenance
- etc.

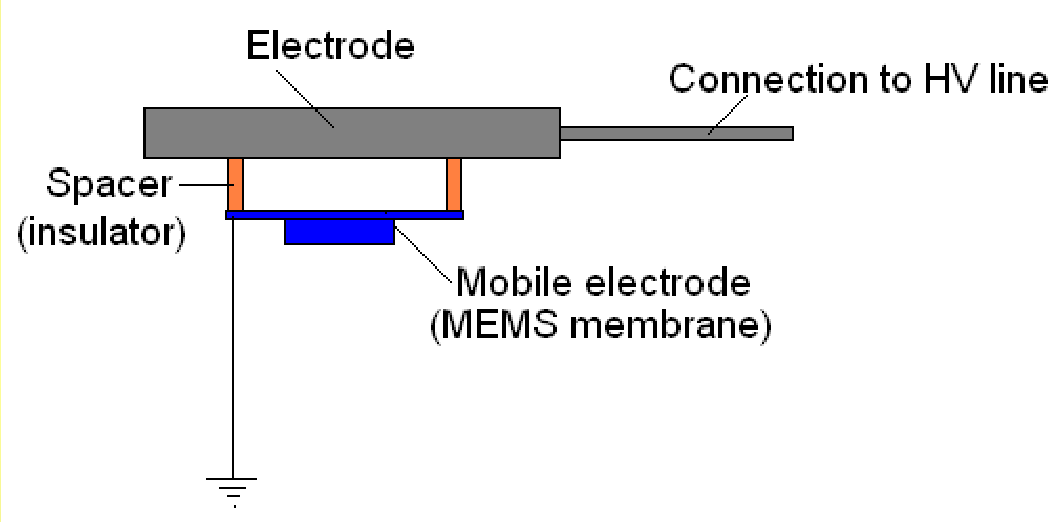
WORKING PRINCIPLE

- Deflection of MEMS membrane under the electrostatic field

- Optical reading of the membrane displacement

Deflection produced by the electric field

→ ANY voltage can be considered for measurement, provided that the field does not exceed the breakdown value

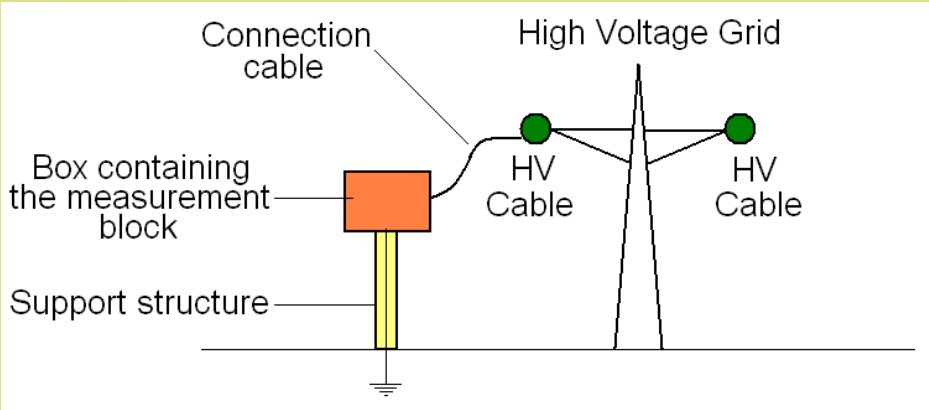


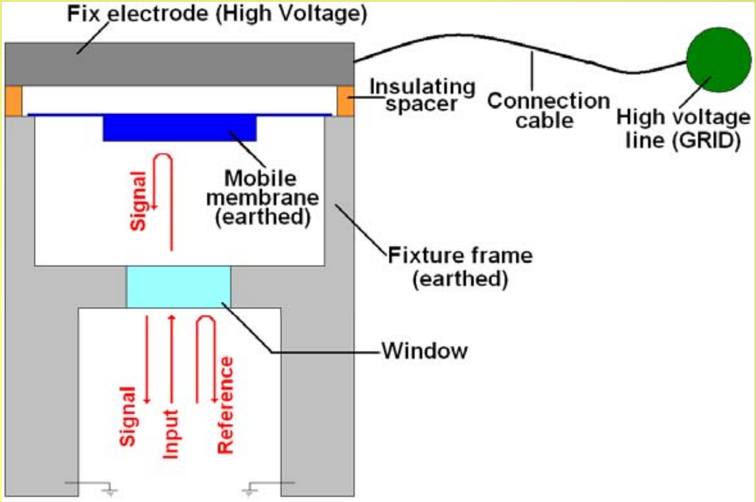
The maximum measured voltage depends on the spacer's thickness

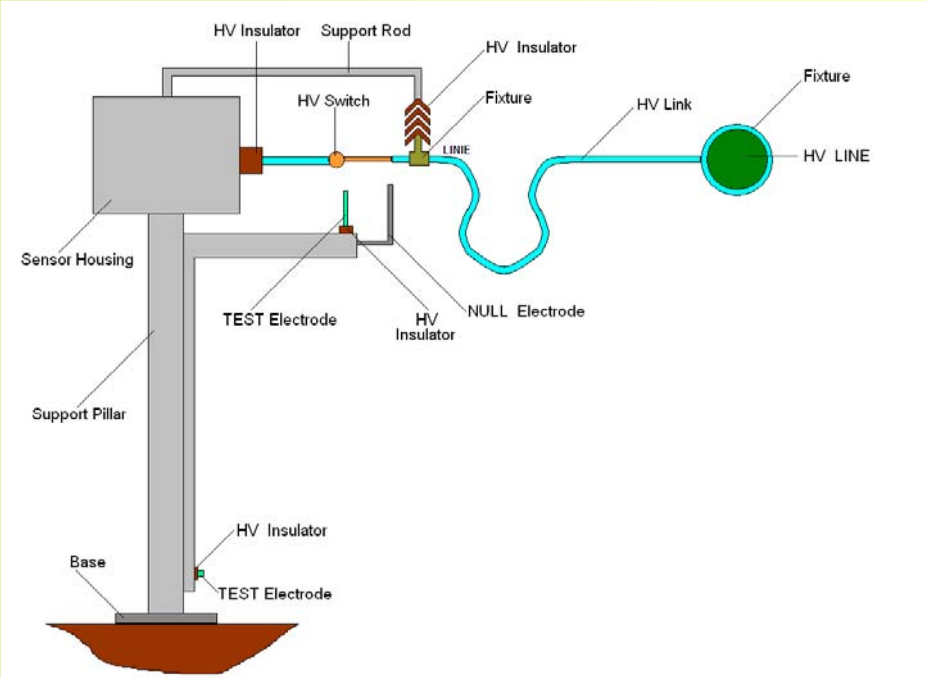
→ no other system change is necessary except for the spacer

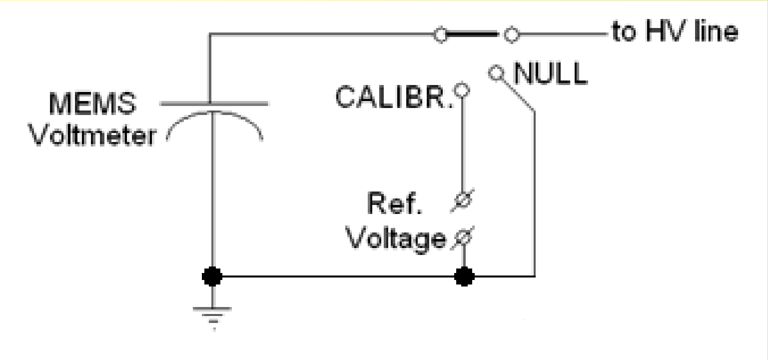
→ the MEMS device and reading optics remain the same !

WORKING PRINCIPLE - OVERALL SET-UP









- Working in low pressure insulating gas for decreasing damping / friction & variation of gas refractive index with temperature

WORKING PRINCIPLE

High electromagnetic noise

→ sensor mounted at a distance from the HV line in order to reduce the effect of current's magnetic field

→ optical reading necessary

→ immune to electromagnetic noise

→ sensitive enough

High sensitivity

→ we need an improved geometry of the membrane

→ larger deflection than "usual" membrane

Immune to vibrations and thermal cycling

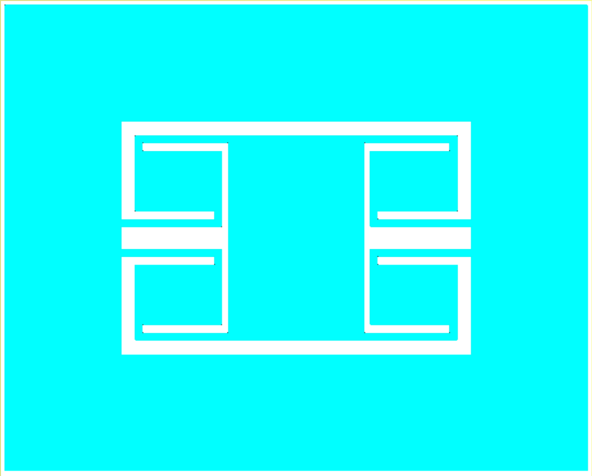
→ optical reading made in such a way so as to ensure immunity

MEMBRANE OPTIMIZATION

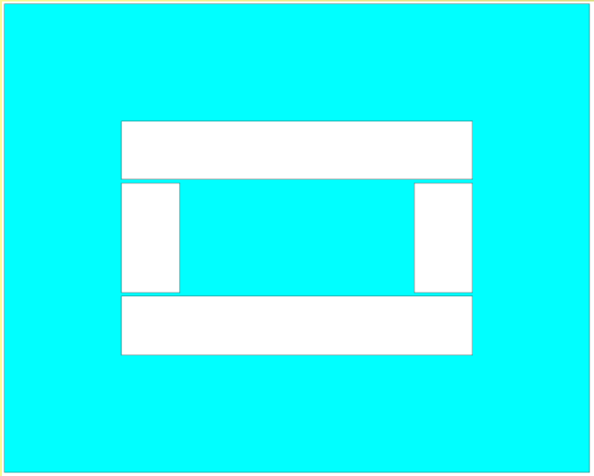
Requirements:

→ high sensitivity

→ the reflecting surface must remain planar



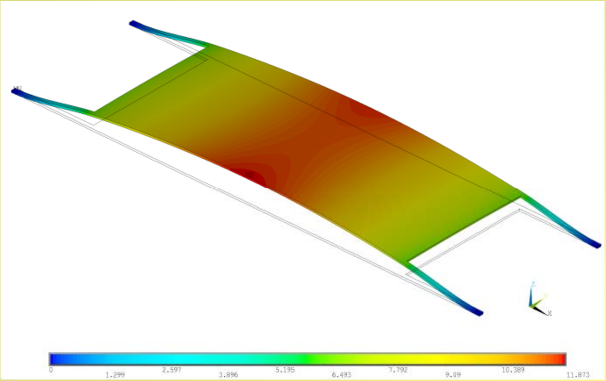
Optimized geometry of the membrane



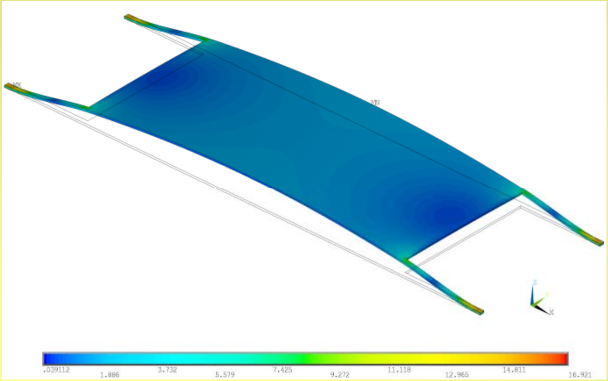
"Usual" geometry of the membrane

Electrostatic and mechanical simulations performed in ANSYS Multiphysics v. 12.1

MEMBRANE OPTIMIZATION



Displacement map
(Maximum value = 11,88 microns)



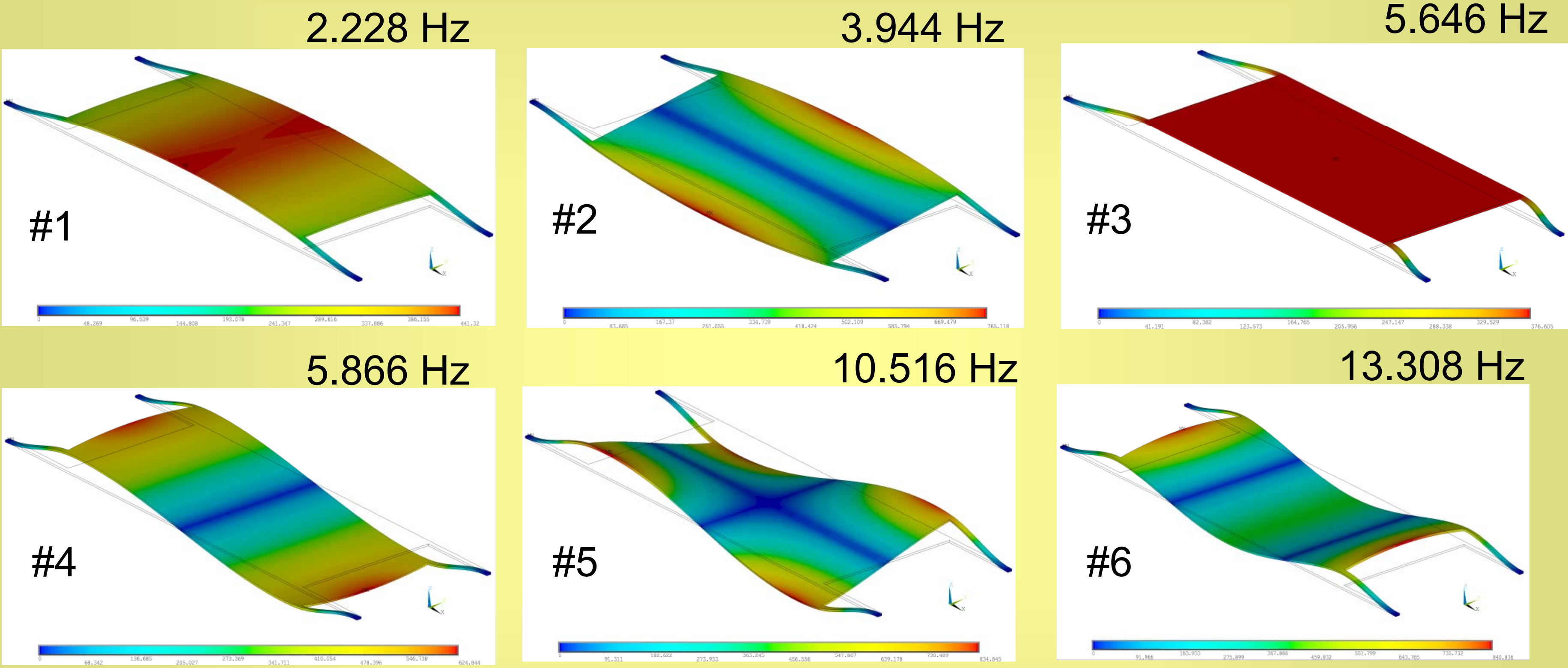
Von Mises stress map
(Maximum value = 16,92 MPa)

Surface curved → unsuitable for optical reading

Actuation:

- Voltage: 10 kV
- Distance between electrodes: 3000 microns

MEMBRANE OPTIMIZATION

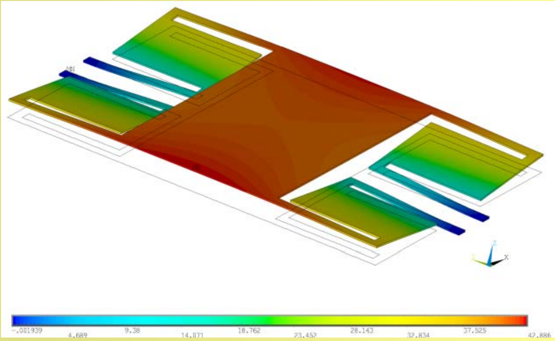


Modal analysis of the “usual” membrane

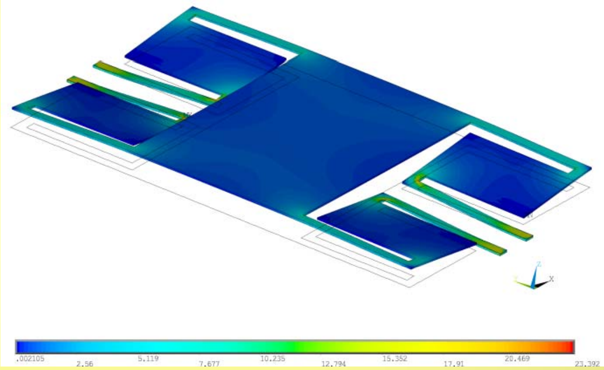
MEMBRANE OPTIMIZATION

Actuation:

- Voltage: 10 kV
- Distance between electrodes: 3000 microns



Displacement map
(Maximum value = 42,88 microns)

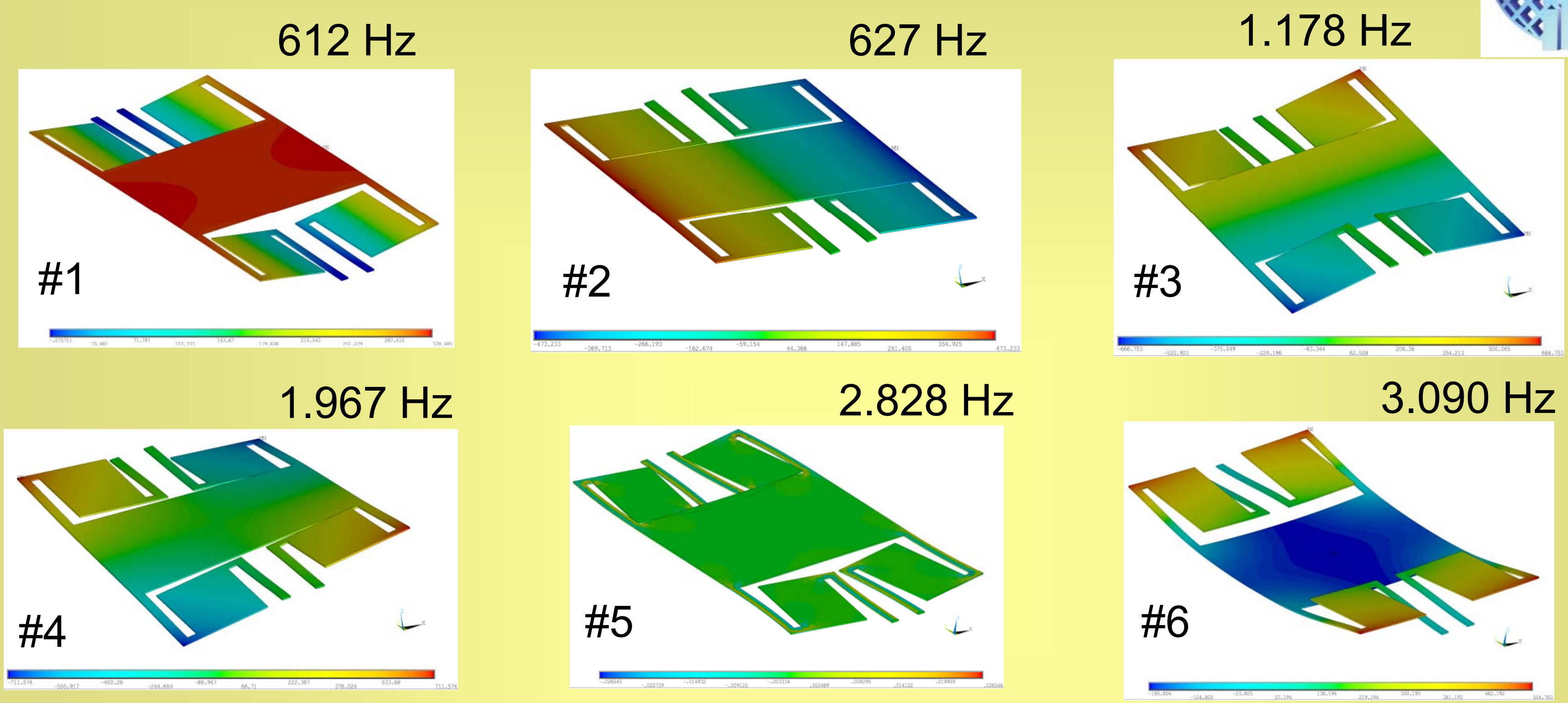


Von Mises stress map
(Maximum value = 28 MPa)

Surface planar → <u>suitable</u> for optical reading

Important → deflection more than 3x higher ➔ higher sensitivity !

MEMBRANE OPTIMIZATION



Modal analysis of the "usual" membrane

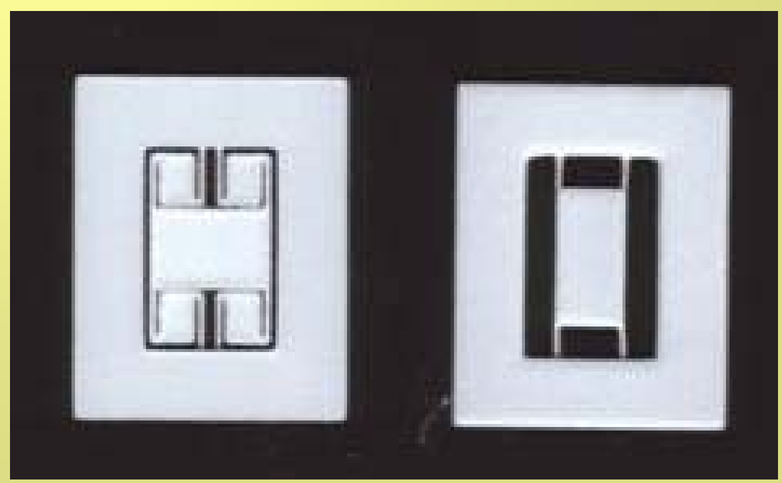
Important: →even at such large size, the optimized membrane has the first resonance at a frequency more than 10x the 60 Hz grid frequency in US and more than 12x the 50 Hz grid frequency in EU

→ no natural phenomenon (wind, earthquakes) has frequencies above 10 Hz

→ decreasing membrane size increases resonance frequency further

MEMBRANE OPTIMIZATION

	Optimized membrane	“Usual” membrane
Sensitivity	Higher (> 3x)	“Reference”
Optical readability	YES	DIFFICULT
First resonance	> 10x the 60 Hz grid with possibility to increase by reducing size	> 60x the 60 Hz grid



In order to rapidly test the concept and simulation results, the 3D Printed version (SLS) was made from nylon.

Experiments (mechanical) proved the increase in sensitivity.

OPTICAL READING

Optical reading must ensure

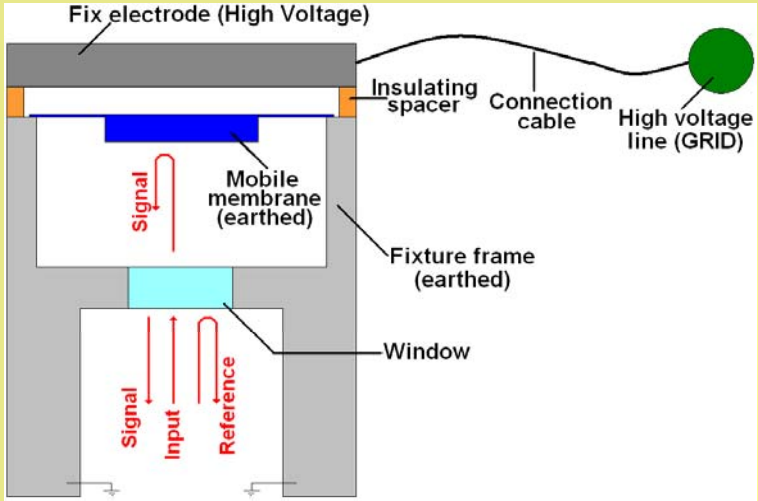
- → sensitivity
- → dynamic range
- → speed of response
- → immunity to electromagnetic noise
- → insensitivity to vibrations and temperature variations (prefered)
- → allow redundancy (prefered)

Two optical reading modes may be used

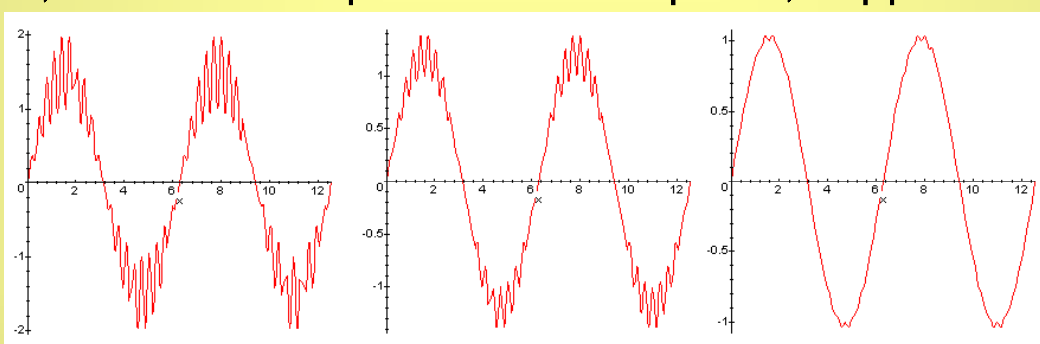
- → a modified version of the Fabry-Perot cavity
- → reflection at focus

OPTICAL READING

What happens if only one mobile electrode is used ?



Accelerations, due for example to an earthquake, suppress any useful signal.

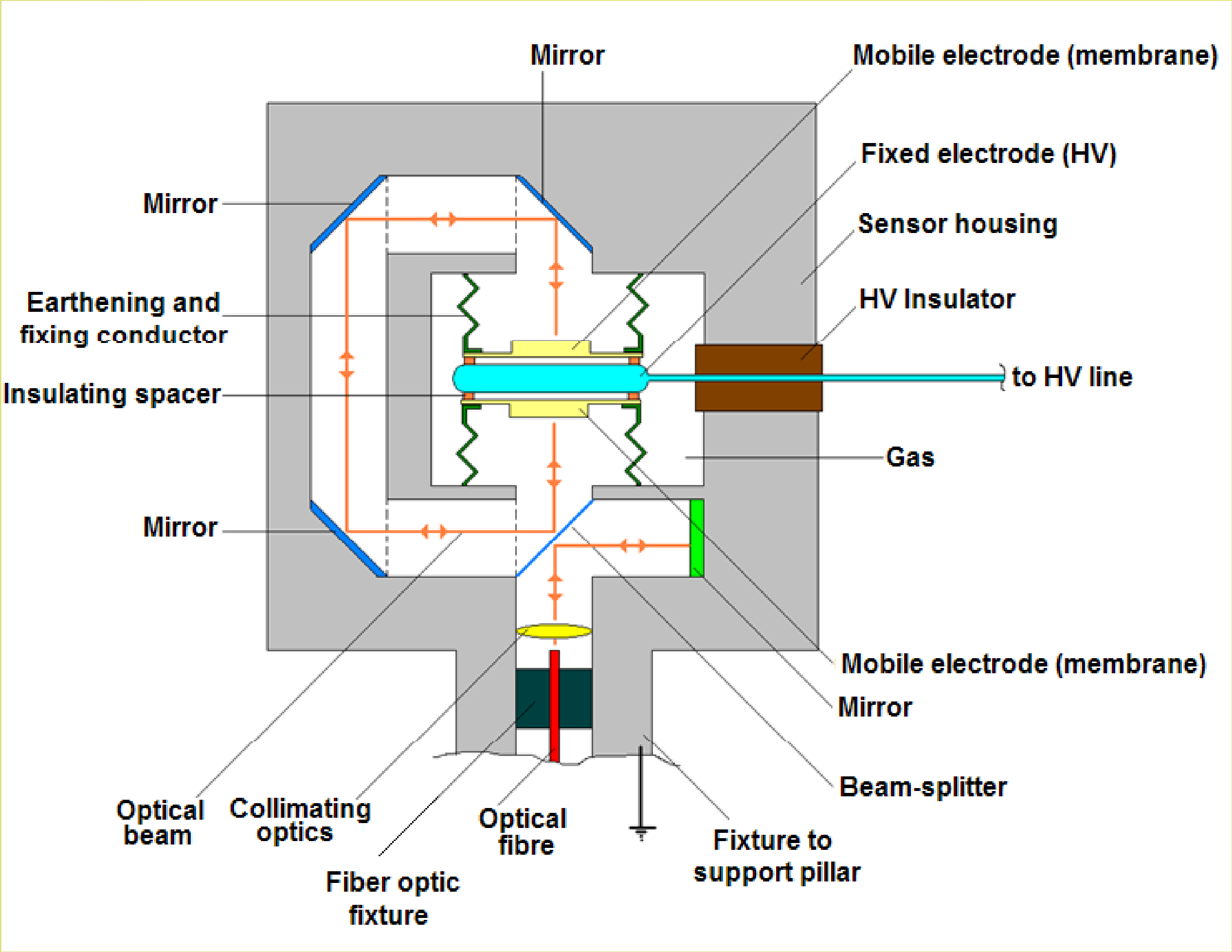


The oscillation behaviour for different values of the ratio of the oscillation amplitude due to the electric signal to the oscillation amplitude due to the seismic acceleration. Left: ratio equal to 1 (weak earthquake); Center: ratio equal to 0.4 (medium to strong earthquake); Right: ratio equal to 0.04 (very strong earthquake).

The horizontal axis shows the normalized time while the vertical axis depicts the relative amplitude of oscillation.

OPTICAL READING

Solution: two mobile electrodes



Modified Fabry-Perot cavity scheme

How it works

How many wavelengths are used and why

Sensitivity 2x that of the single membrane

Spurious accelerations canceled

OPTICAL READING

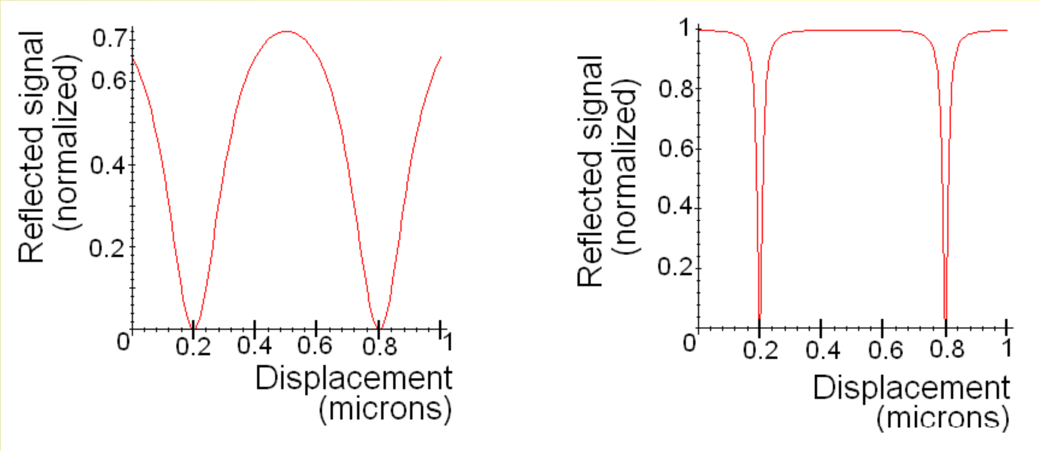
Sensitivity / accuracy depends on the finesse of the Fabry-Perot cavity.

Higher reflectivity of the surfaces imply higher finesse.

The displacement measurement resolution is of very few nanometers

→ for a total displacement of 42 microns it represents 0,01 % error

This is true in ideal conditions. In reality there is noise.



Fabry-Perot cavity reflectivity as a function of the mobile membrane displacement for two different reflectivity values of the cavity's surfaces.

Left: 30 % reflectivity;

Right: 90% reflectivity.

OPTICAL READING

Factors affecting accuracy:

- Noise → taking into account accelerations produced by winds and other small acceleration sources, the measurement accuracy goes to 0,1 % and better

→ an accuracy that is still useful

- Earthquakes → a 7 Richter degree earthquake produces an acceleration of 0,28g

→ accuracy becomes 6 % during the 40 seconds specific to an earthquake duration → acceptable on short timescales

→ the sensor works for 40 seconds as a low class device

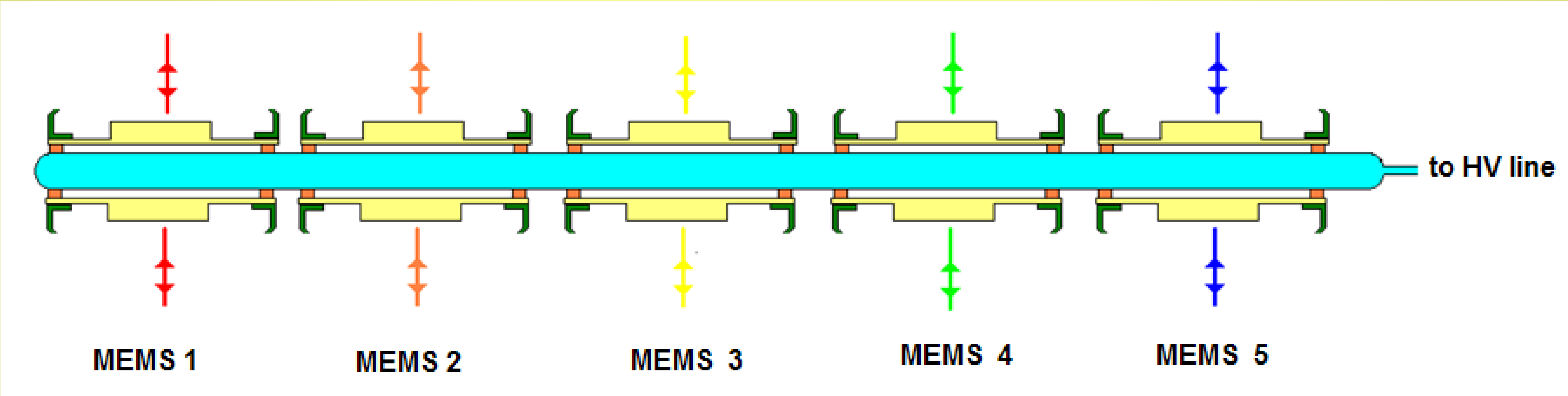
- Non-linearity of the Fabry-Perot curve

→ electronic linearization OR look-up tables (especially when several wavelengths are used)

→ a set of wavelengths is used in order to discriminate the correct value of the displacement (interferometry gives periodic signal for each wavelength)

OPTICAL READING

MEMS are delicate devices → redundancy is a must !



Each sensor may be read at a different set of wavelengths than the others in order to be able to determine which sensor is working and which is defective → easy maintenance.

Thus:

→ redundancy is achievable at low cost

→ sensor monitoring is easy

LOSSES SPECIFIC TO THE SENSOR

There are three main mechanism for losses:

a) the thermoelectronic emission current;

b) the displacement current;

c) the Fowler-Nordheim current.

Only the displacement current is the dominant loss mechanism.

For a 100 kV, 50 Hz grid, the value of the loss through displacement currents is 0.1 VA

Other losses are associated with the laser diode and optoelectronic sensor: 0,5 W

THE NET LOSS IS LESS THAN 1 W !

SENSOR PARAMETERS

	MEMS system	High voltage transformers
Voltage range	10 kV – 1500 kV For each range, only the insulating spacer must be changed	10 kV – 1500 kV For each voltage a different transformer has to be used
Accuracy	< 0,1 %	Normally 1 % - 2 %, in some cases 0,1 % - 0,2 %
Frequency spectrum	Depending on MEMS size, can be up to tens of kHz	Several kHz (less for those with inductors)
Size and weight	Overall sensing “box” of the order of 40 cm x 50 cm x 50 cm, 10 kg	1,5 m x 50 cm x 50 cm, hundreds of kg
Losses	< 1 W	~ hundreds of W at best
Redundancy	Easily achieved	Hard to achieve

THE MEMS VERSION HAS AN IMPORTANT POTENTIAL IN THE FIELD OF MEASUREMENTS ON HIGH VOLTAGE LINES

MAIN PROBLEM

The monocrystalline Silicon / Germanium / Silicon Carbide have to oscillate 100 times per second for a period of at least 5 years

→ how it will behave ?

→ defect dynamics ?

We have not found any data describing the behaviour under such load

Accelerated tests may offer a glimpse, but:

→ is the defect dynamics (generation, migration, etc.) the same at 100 Hz as well as to 10.000 Hz ?

For example: higher frequency may increase heat generation, which interferes with defect dynamics

Further theoretical and experimental study is needed.

THANK YOU !