NiPS Laboratory
Noise in Physical Systems

Summer School: "Energy Harvesting at micro and nanoscale"

July 26, 2012 – Erice (TP), Sicily, Italy

Advances on nonlinear MEMS harvesters

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Outline

- ***Introduction and motivations***
- *Sources available for Energy harvesting … wind, sun,* ***vibrations****, …*
- *Linear versus* ***bistable approach***
- *Bistable:* ***Magnetic*** *versus* ***Nonmagnetic*** *approach*
- *MEMS technologies: mechanically bistable*
- ***Magnetic****: One "working" magnet versus two "working" magnets*
- ***Magnetic****: 1-D versus 2-D*
- ***Magnetic****: Bi-stable versus Tri-stable*
- ***Magnetic****: magnetically coupled cantilever array versus single bistable*

Introduction and motivations

- ***Several situations can be considered where one would need a source of electrical energy …***
- ***… while in the "middle of nowhere" you may want to make a phone call and your mobile phone battery is dead !***

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Introduction and motivations

- ***Several situations can be considered where one would need a source of electrical energy …***
- *Out of other many different possibilities … often **vibrations** are present and can represent a powerful source of energy that can be therefore exploited for several uses*

milocca.wordpress.com

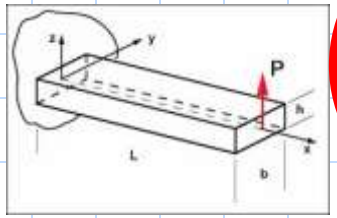
Introduction and motivations

- ***Several situations can be considered where one would need a source of electrical energy …***
- *Out of other many different possibilities … often **vibrations** are present and can represent a powerful source of energy that can be therefore exploited for several uses*
- *This applies also to "modern" systems !*

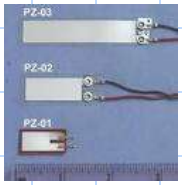
Introduction and motivations

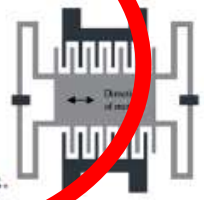
Vibrational source

Coupling mechanical structure

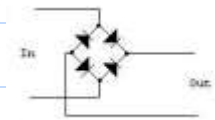


Mechanical-to-electrical conversion





Output energy



Accelerations:
- Magnitude
- Power Spectrum

- Linear
- **Nonlinear**

- **Piezoelectric**
- Electrostatic
- Electromagnetic

- "direct" use of power
- "store" power

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- *MEMS technologies: mechanically bistable*
- ***Magnetic****: One "working" magnet versus two "working" magnets*
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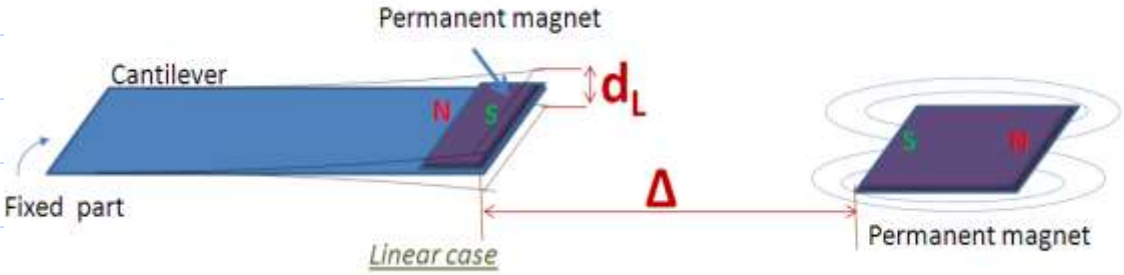
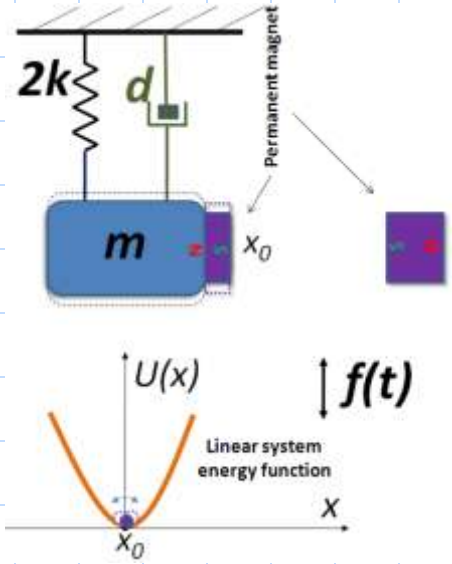
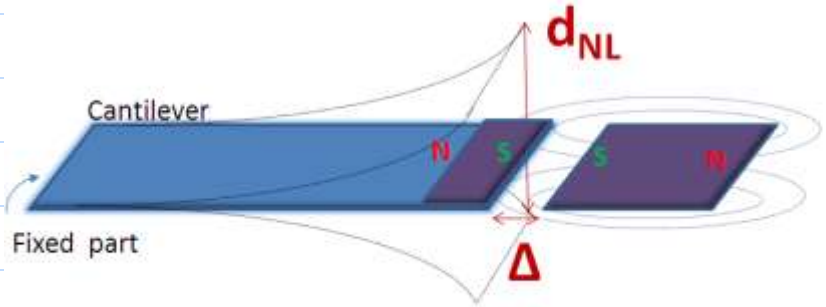
Linear versus Bistable approach

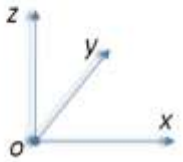
- ***Linear "resonant" cantilever***

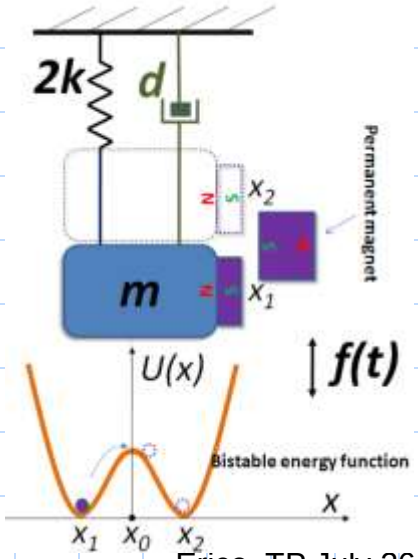




- ***Bistable cantilever***

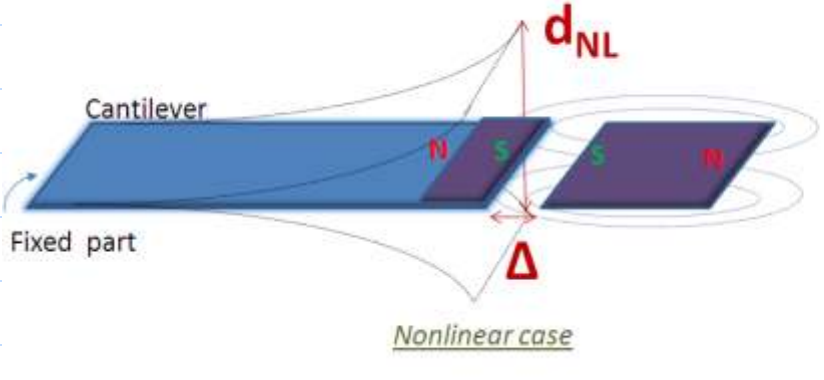


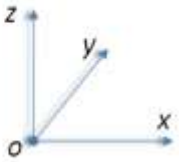


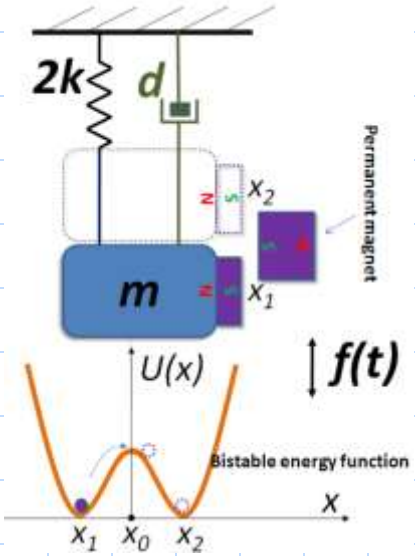


Linear versus Bistable approach

- ***Bistable cantilever***







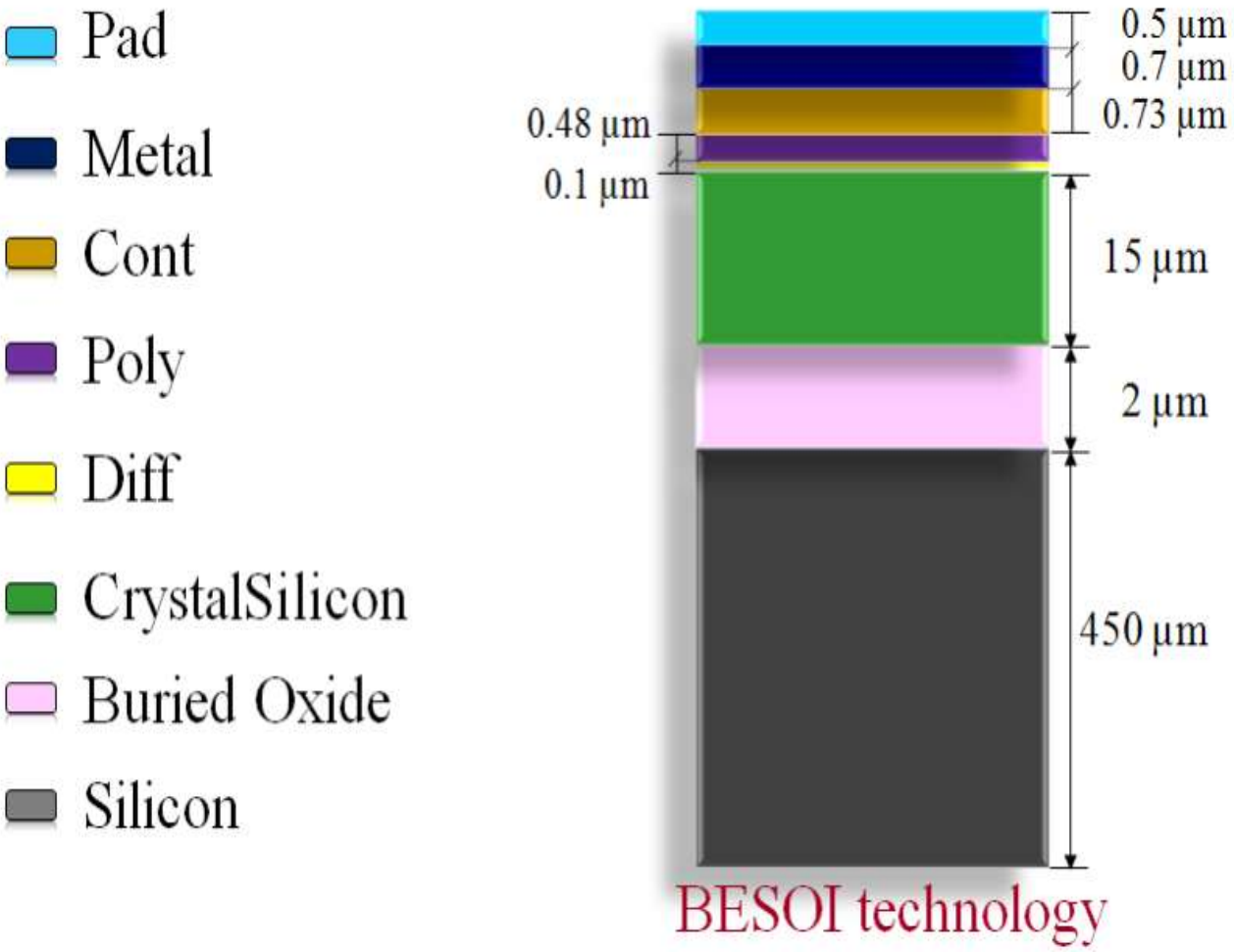
$$m\ddot{x} + d\dot{x} + \Psi = f(t) \qquad \Psi \triangleq \frac{\partial U(x)}{\partial x} = U'(x)$$

$$U(x) = kx^2 + (ax^2 + b\Delta^2)^{-\frac{3}{2}} + c\Delta^2$$

$$\Psi = U(x)' = \frac{\partial}{\partial x}\left[kx^2 + (ax^2 + b\Delta^2)^{-\frac{3}{2}} + c\Delta^2\right] = -3ax(ax^2 + b\Delta^2)^{-\frac{5}{2}} + 2kx$$

Linear versus Bistable approach

- ***Bistable cantilever***
- ***BE-SOI technology***



- SOI wafer: 15 µm c-Si layer, 450 µm carrier substrate, 2 µm buried oxide;
- Front and back side DRIE etching technique.

- Fabrication: Centre Nationale Microeletronica (CNM), Barcelona, Spain

Linear versus Bistable approach

- ***Bistable cantilever***
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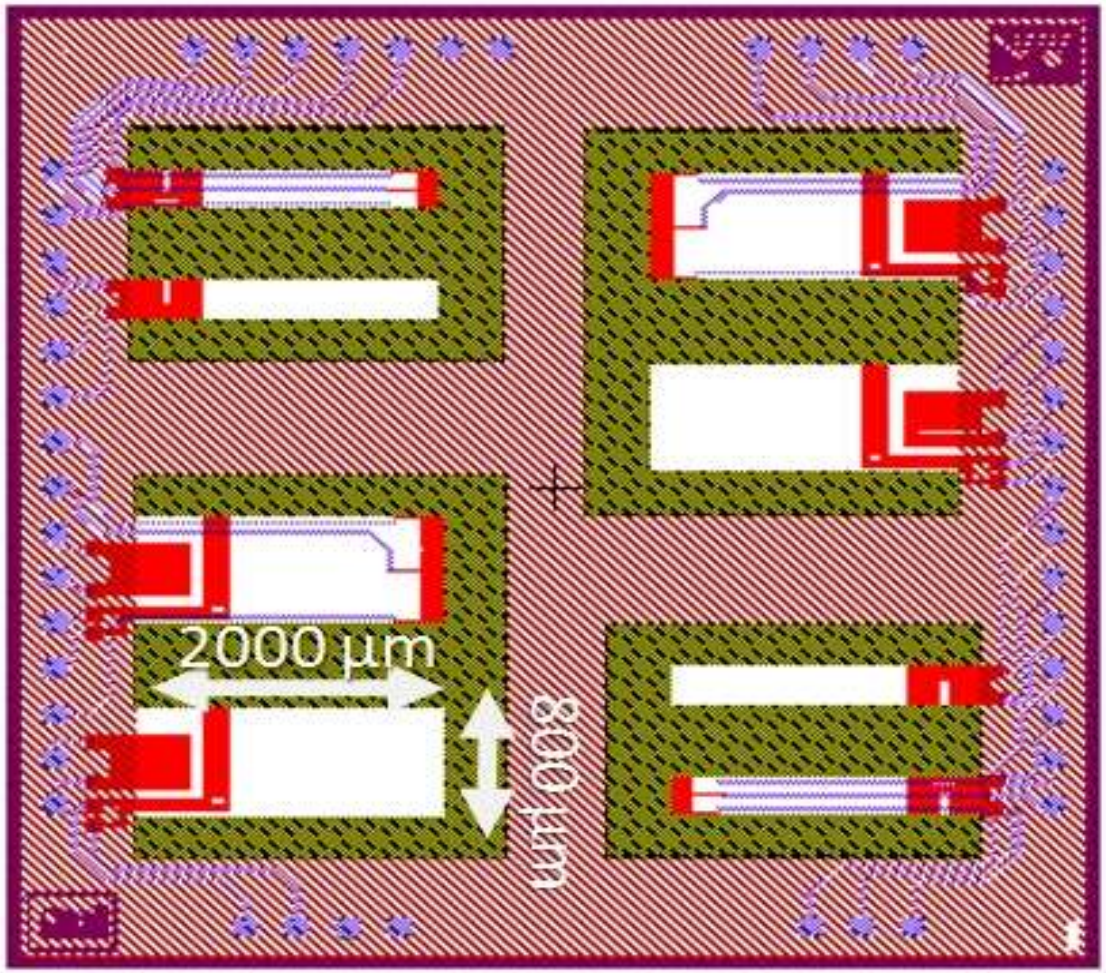
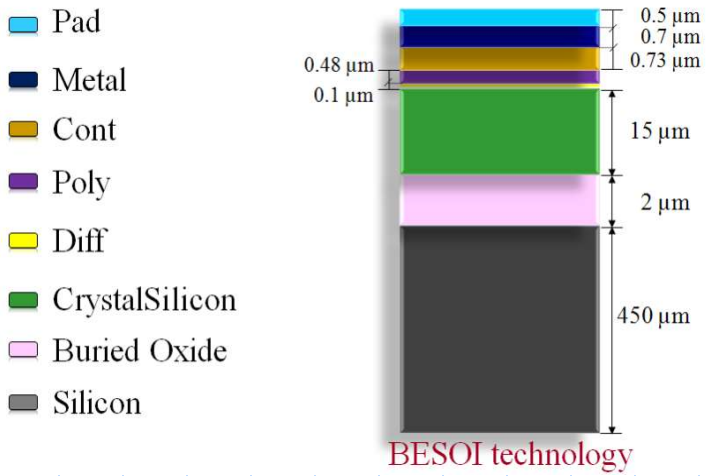
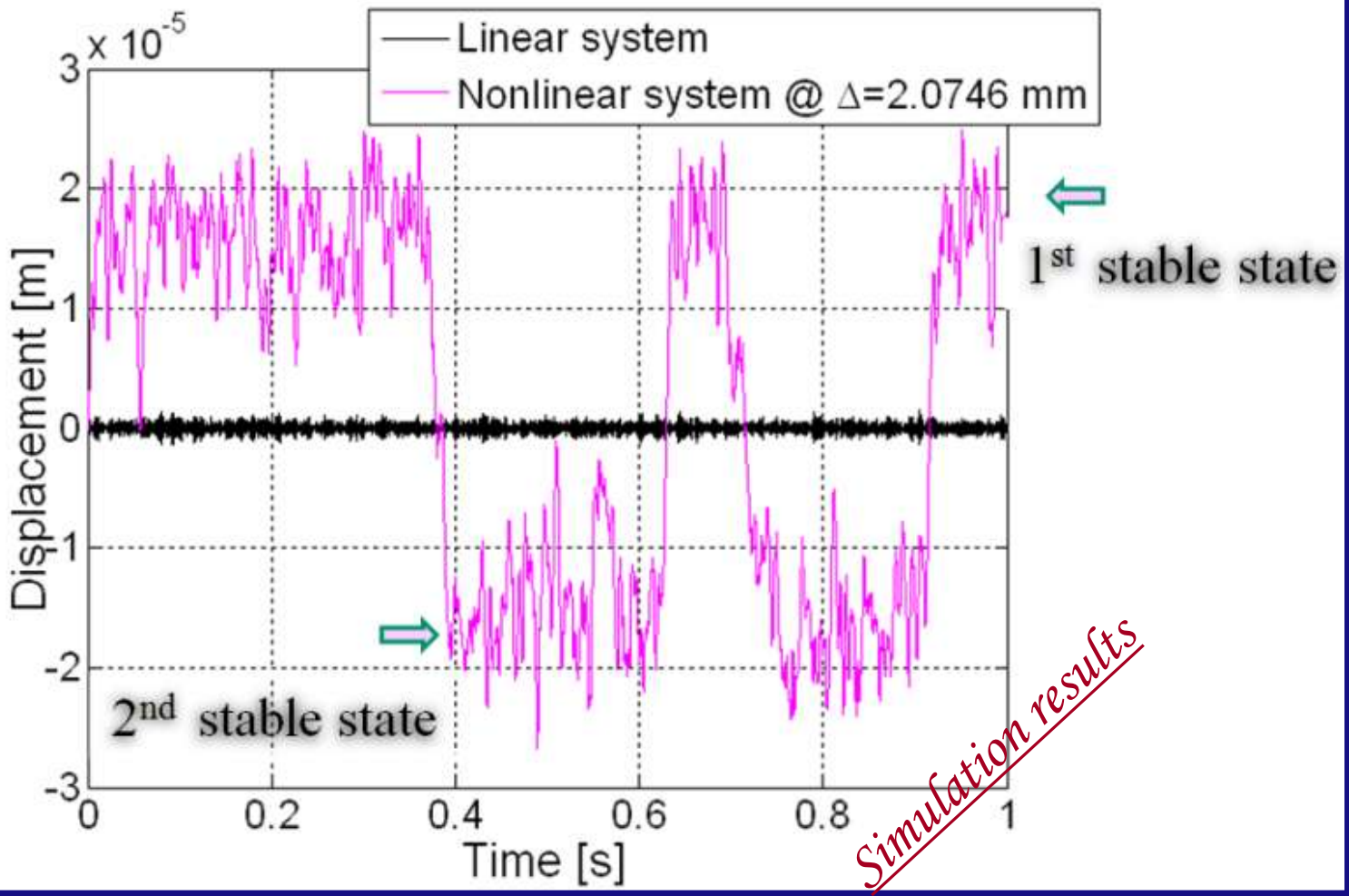




Linear versus Bistable approach

- ***Bistable cantilever***
- ***BE-SOI technology***

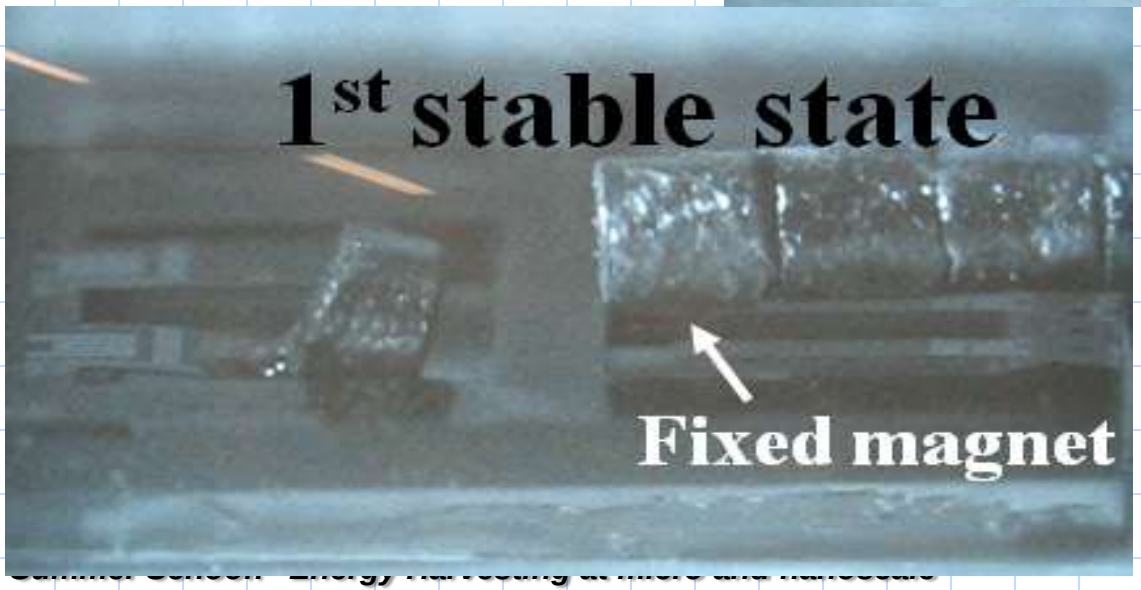
@ σ= 50 mN



Linear versus Bistable approach

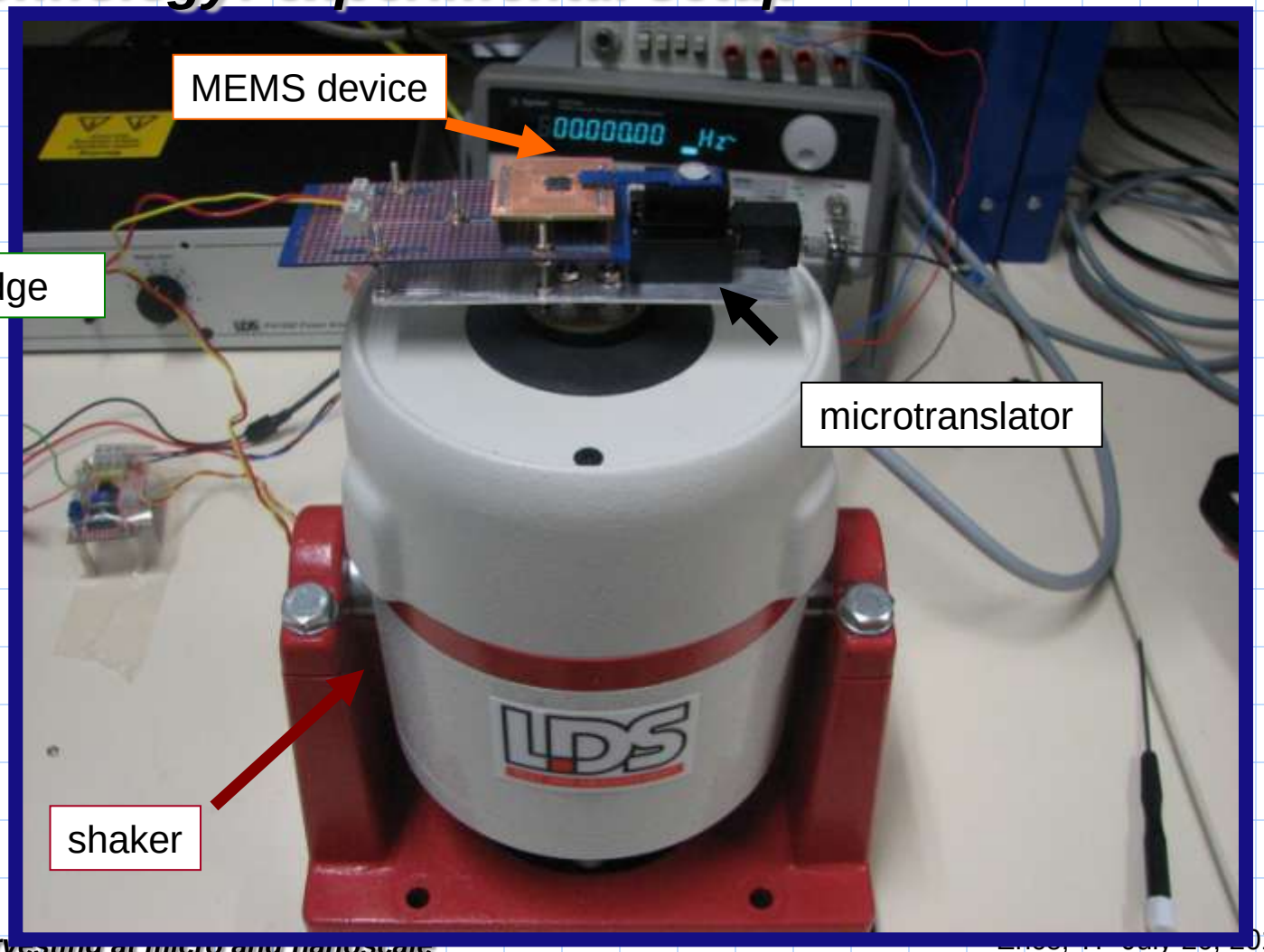
- ***Bistable cantilever***
- ***BE-SOI technology***

Permanent magnet deposited:
- Nd Fe B material
- Cylindrical shape
- Radius and height of 500µm



Linear versus Bistable approach

- ***Bistable cantilever***
- ***BE-SOI technology: experimental setup***



Linear versus Bistable approach

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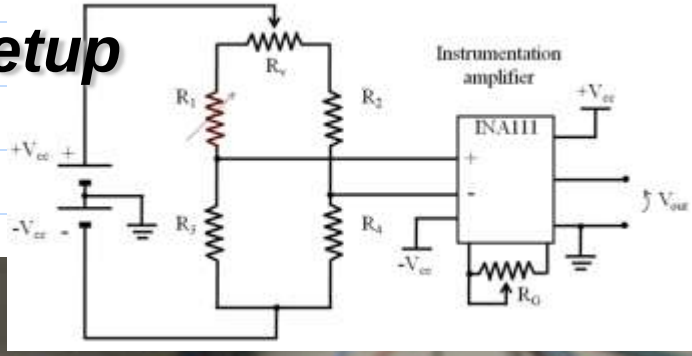
Conditioning circuit



MEMS device

Permanent magnets stack

Output strain gauge

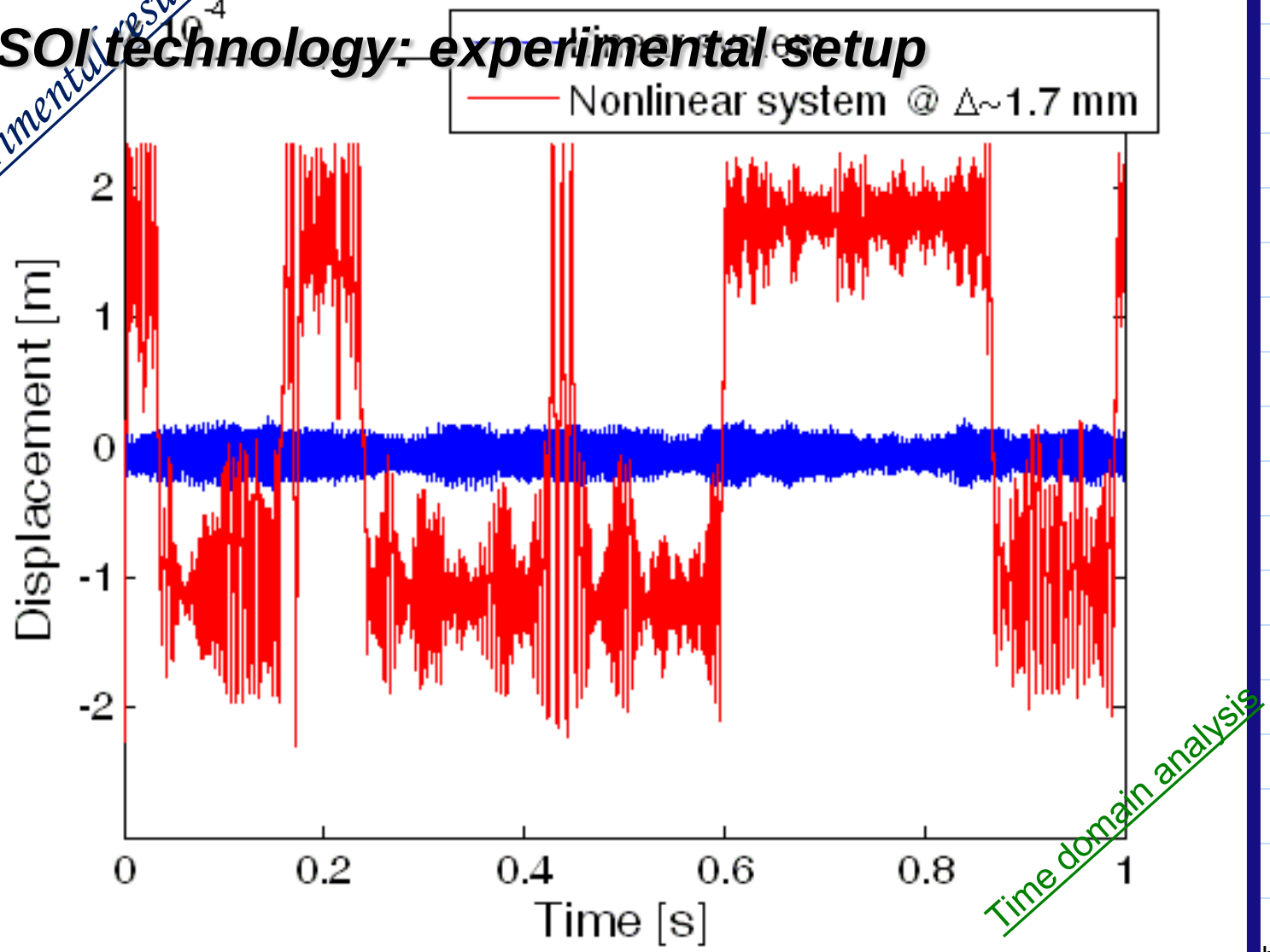
Linear versus Bistable approach

- ***Bistable cantilever***
- ***BE-SOI technology: experimental setup***

Experimental results

σ=20 μN

@ 0.88 g



Time domain analysis

Linear versus Bistable approach

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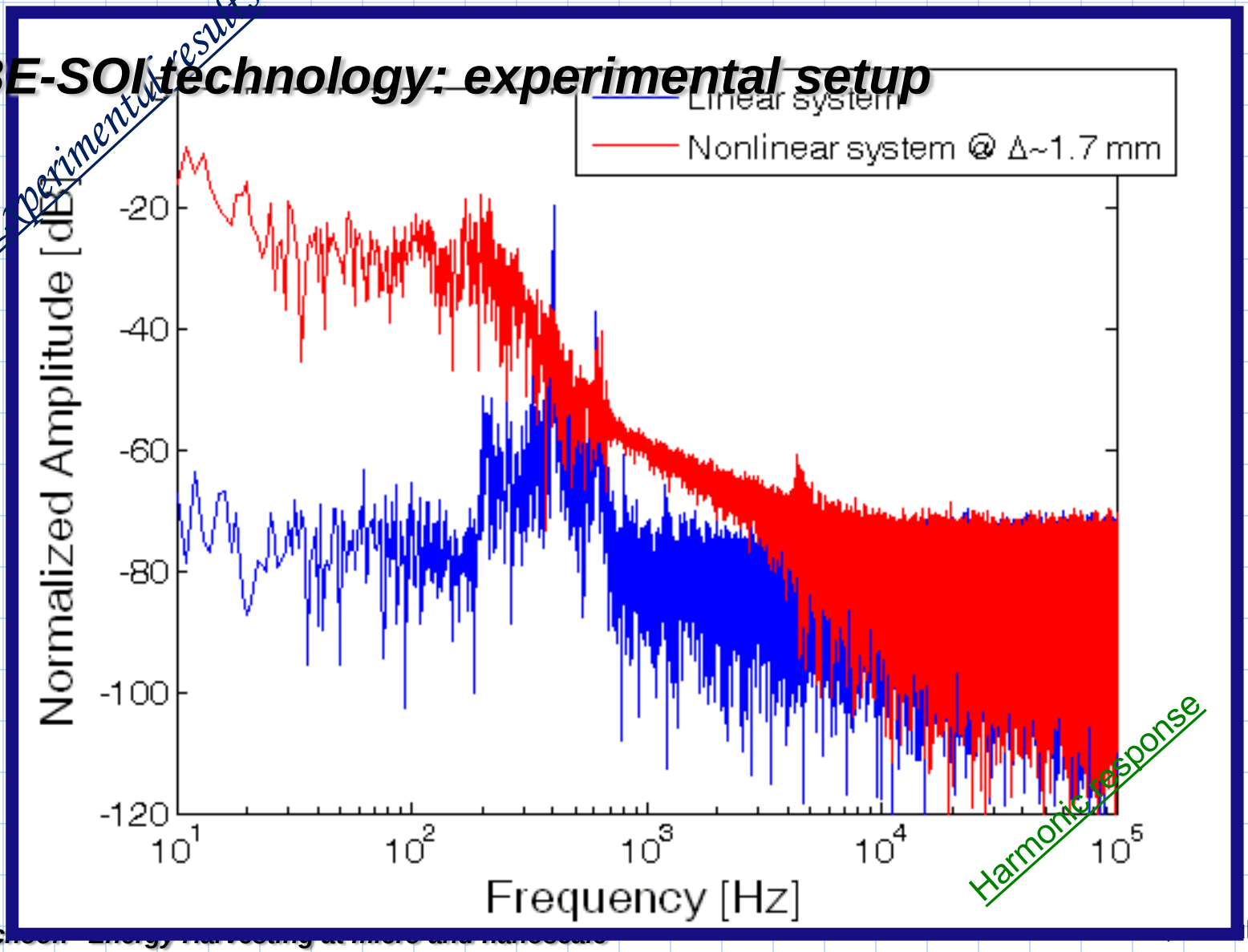

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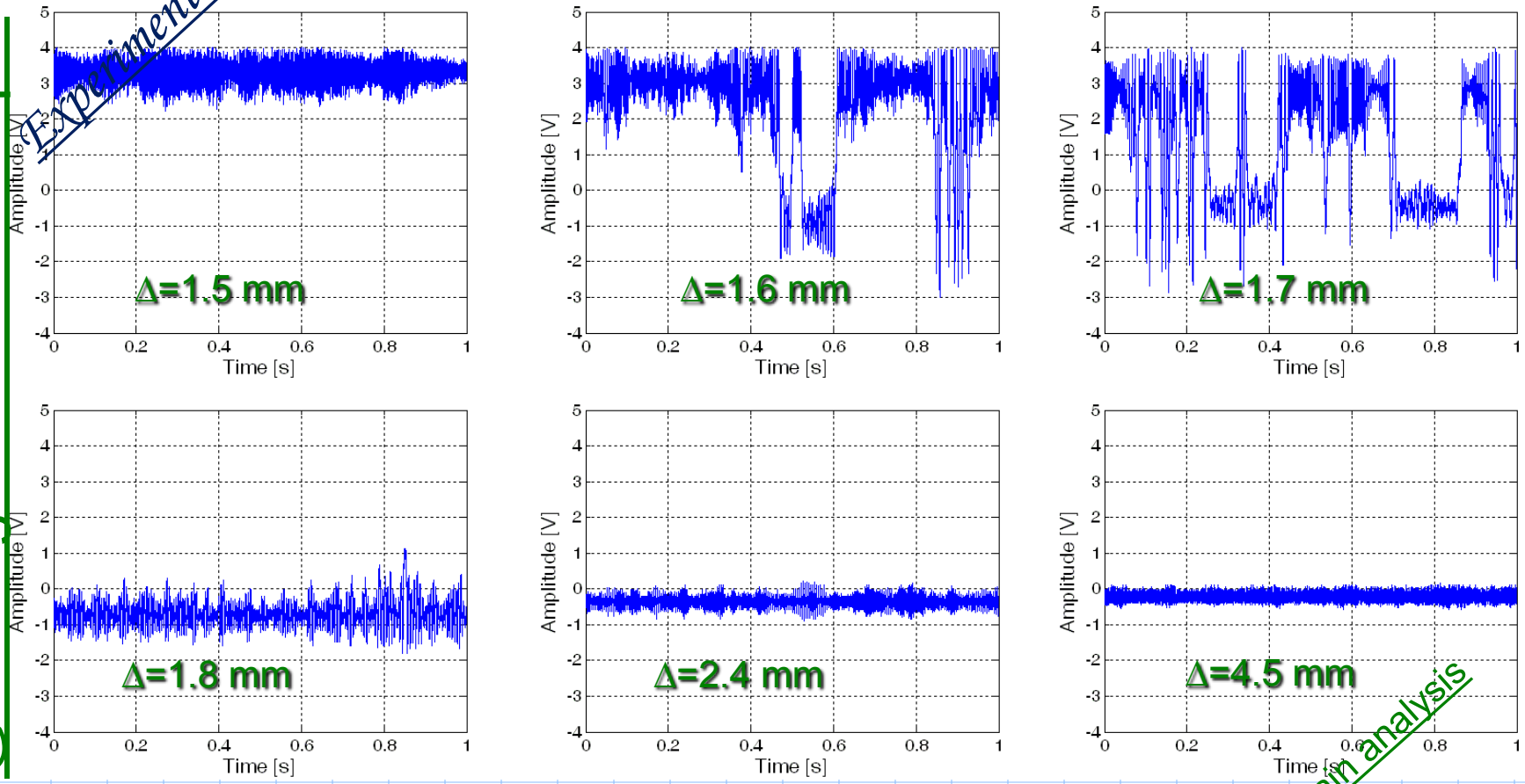

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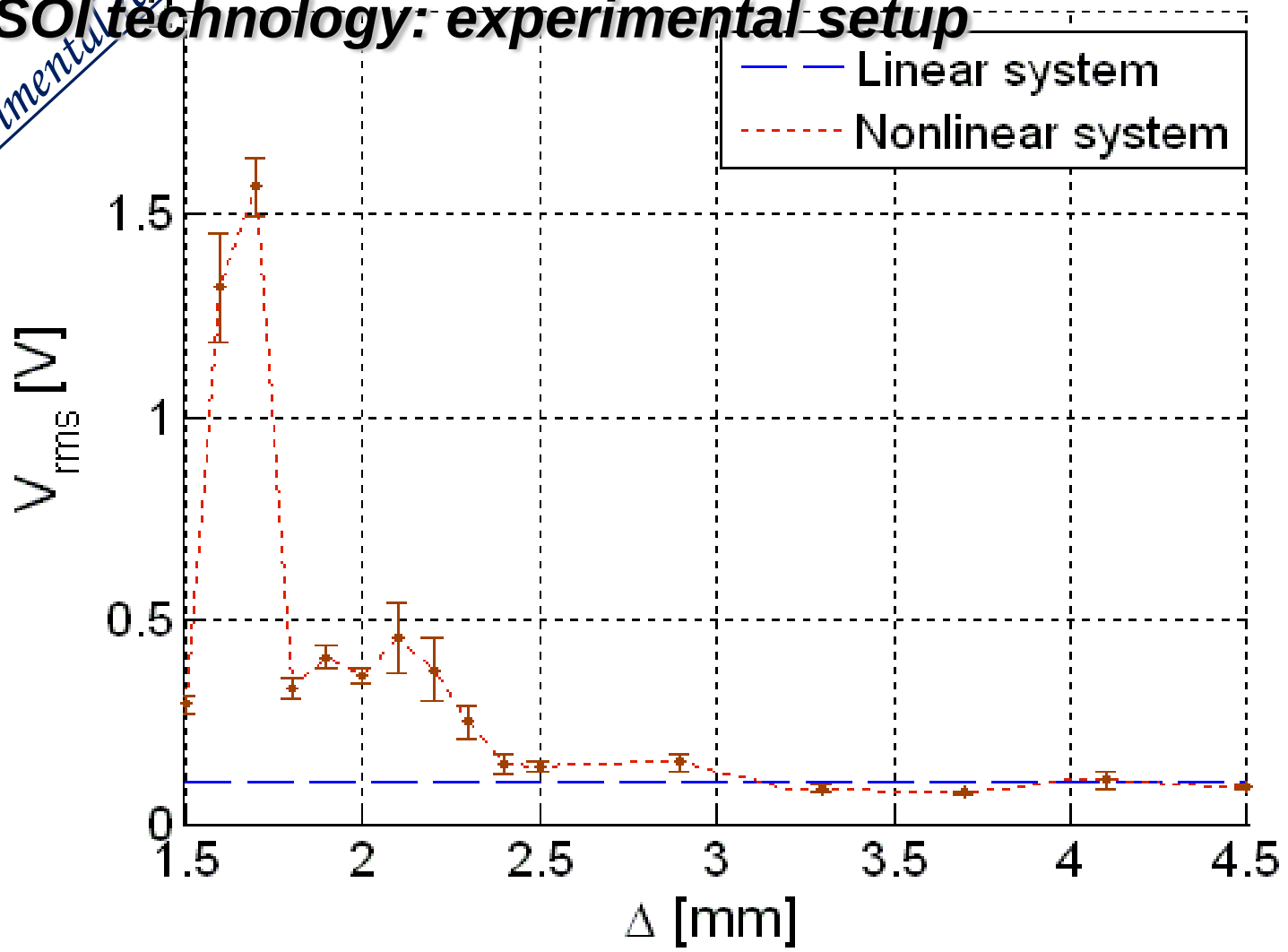

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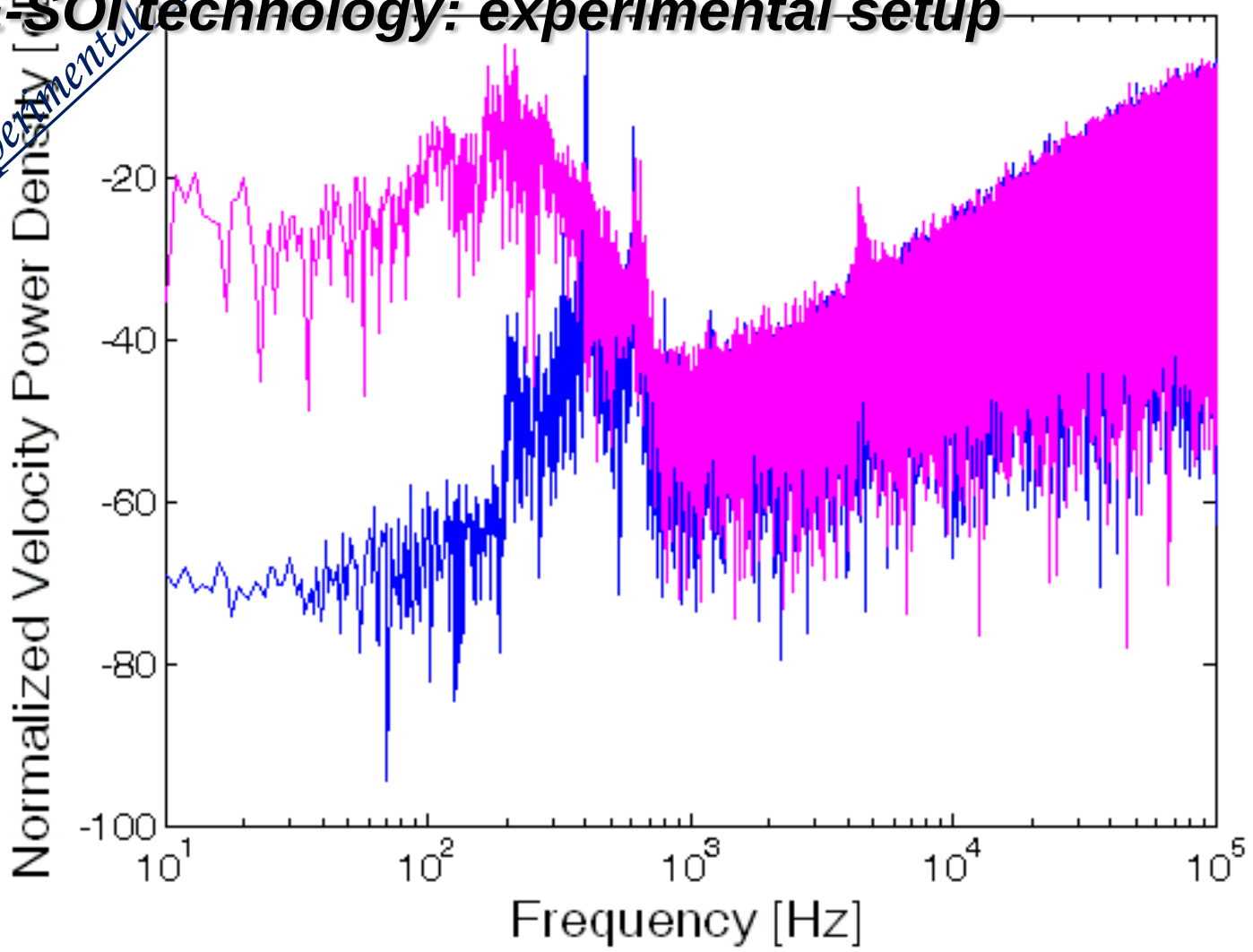

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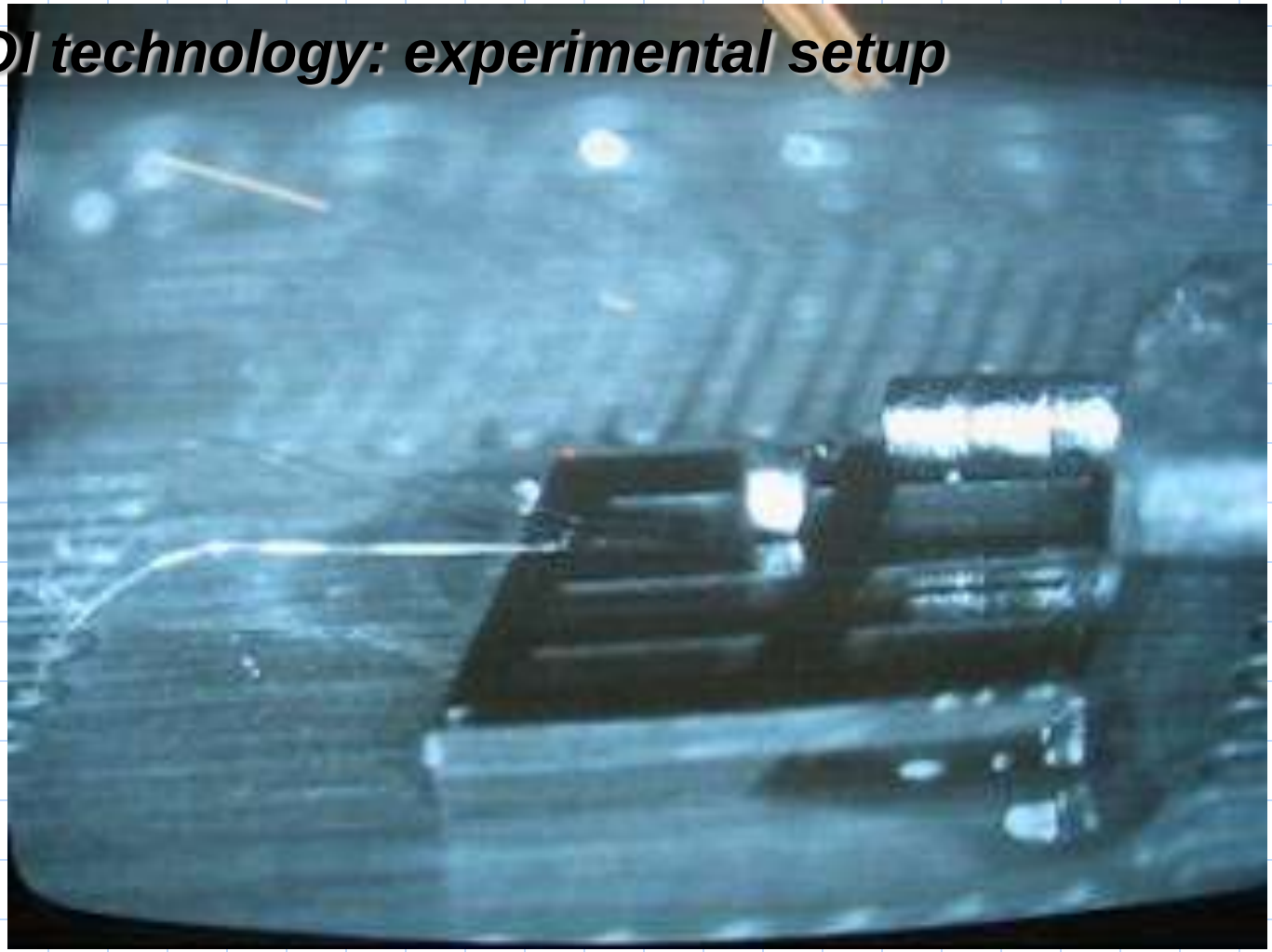

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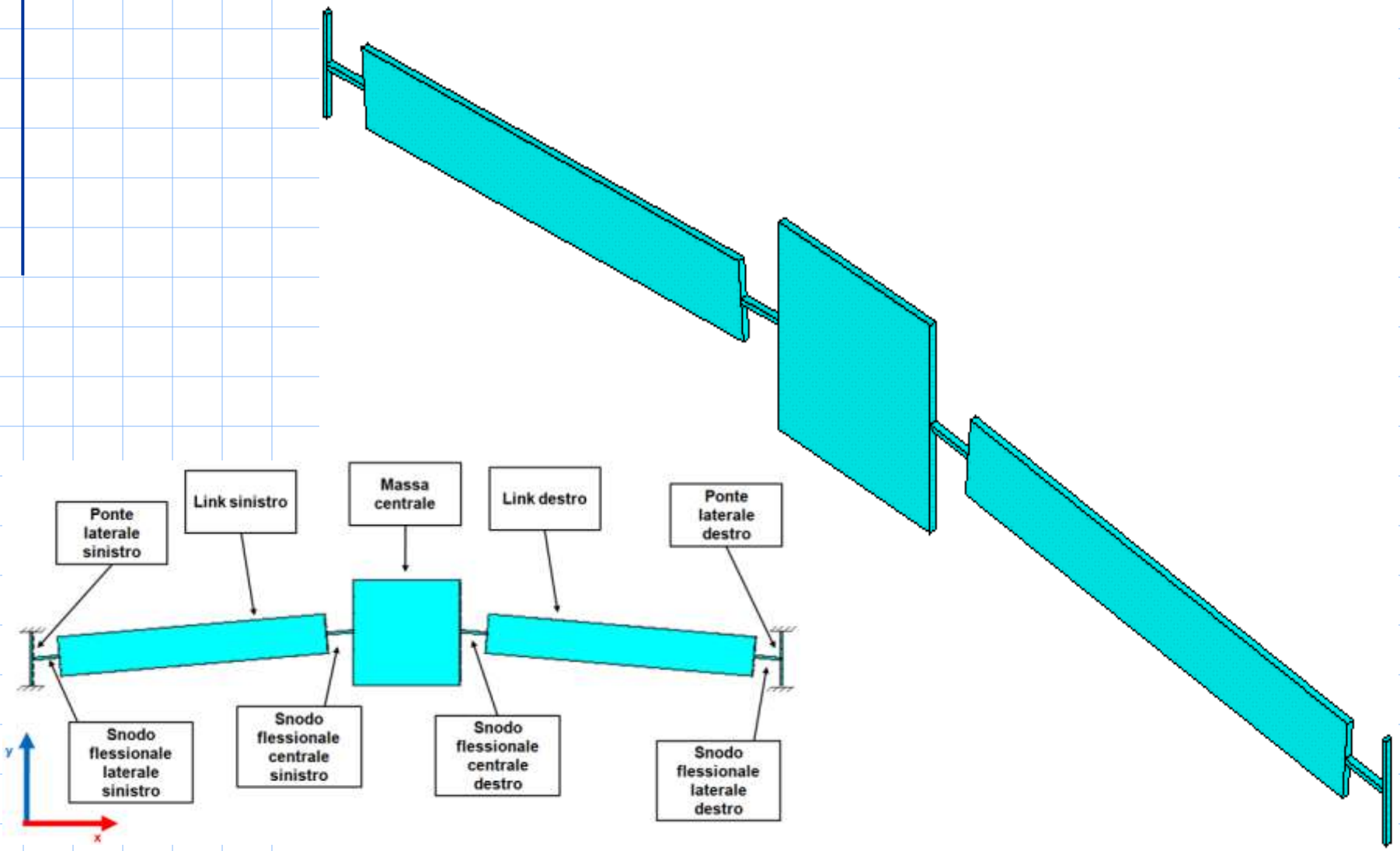
Magnetic versus Nonmagnetic

- ***The basic device structure***



Magnetic versus Nonmagnetic

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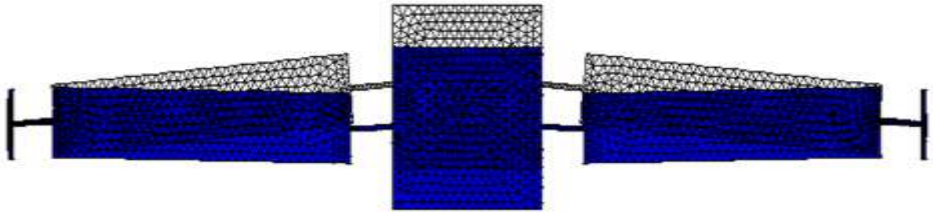
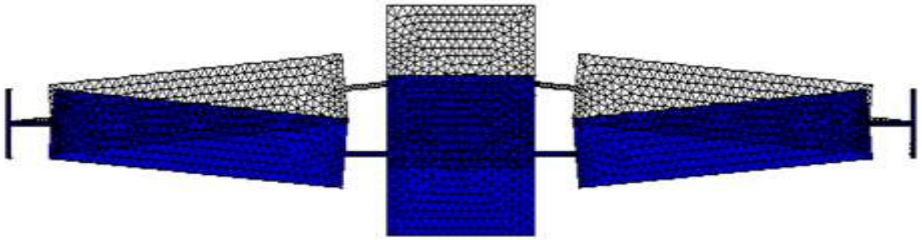


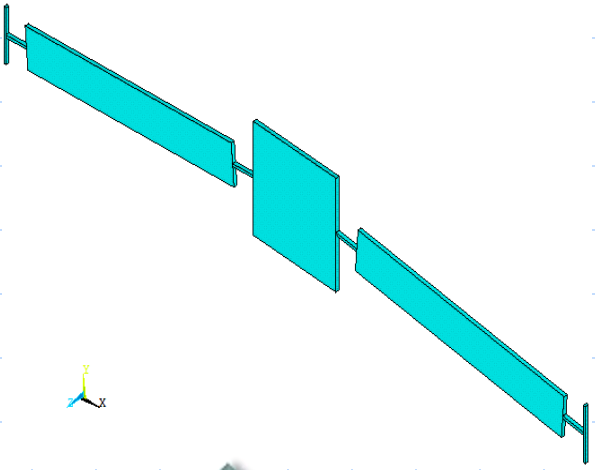
Unstable equilibrium position

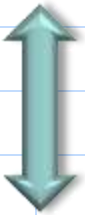


2nd Stable equilibrium position

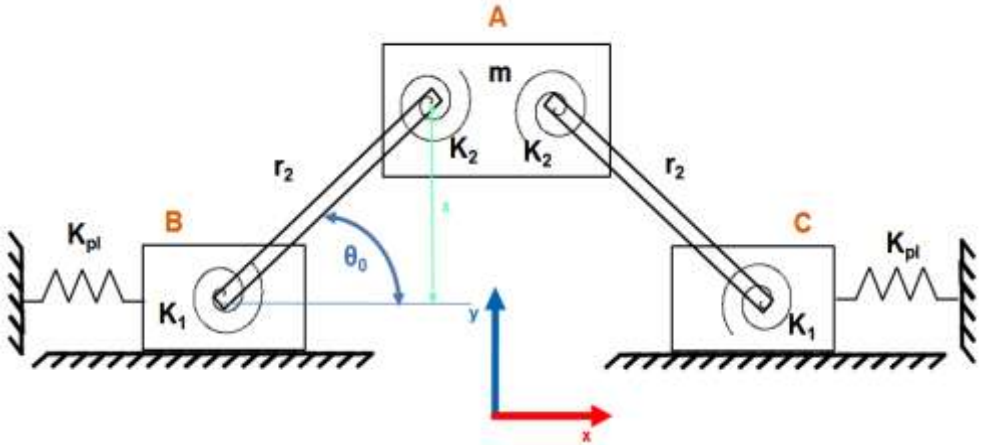
Magnetic versus Nonmagnetic

- ***Analytical modeling***





Pseudo-Rigid-Body Model



$$m\ddot{x} + d\dot{x} + \psi(x) = f(t)$$

$$\psi(x) = -\frac{dU(x)}{dx}$$

$$U(x) = K_1 \psi_1^2 + K_2 \psi_2^2 + K_{pl} \psi_{pl}^2$$

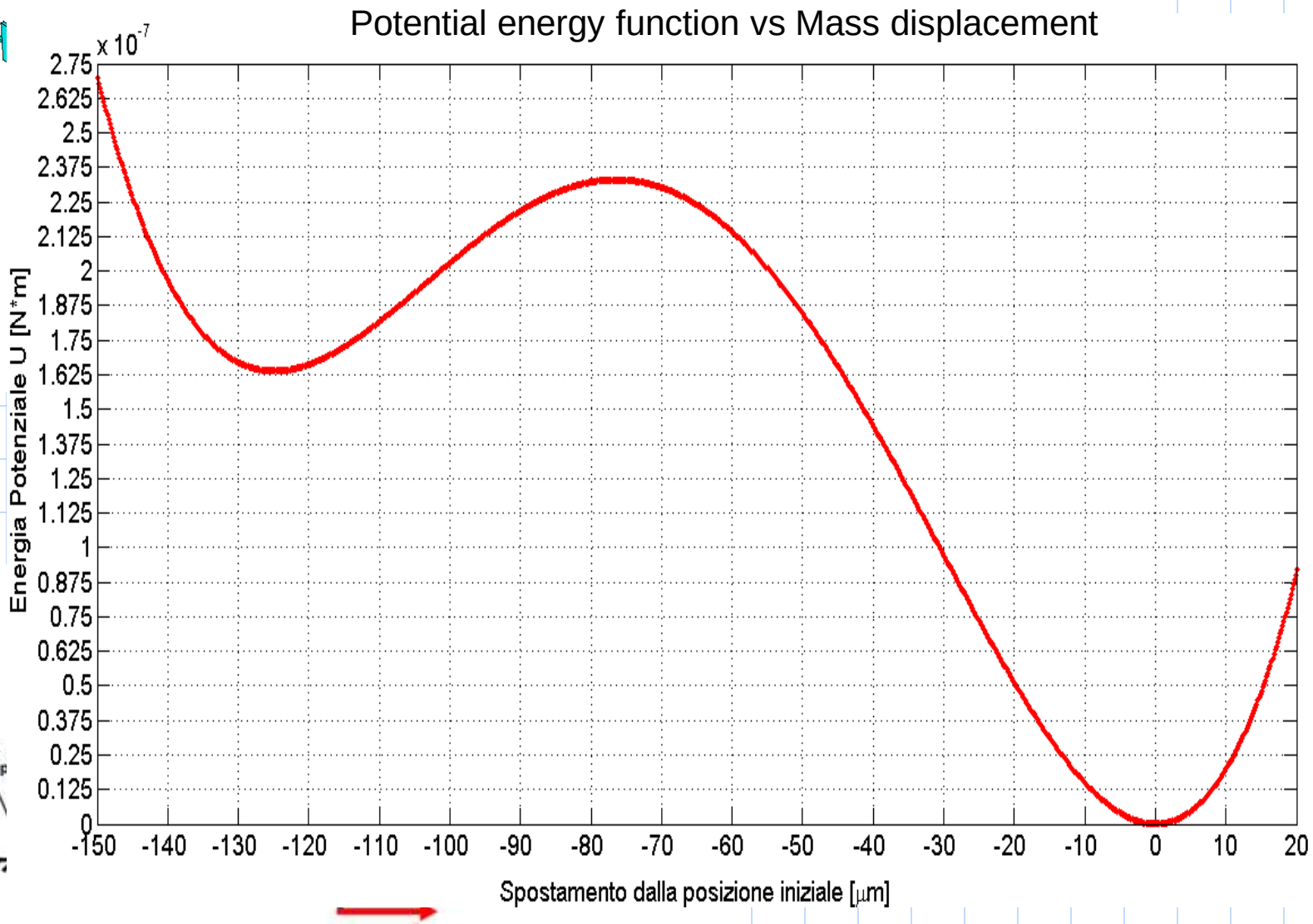
$$\psi_{1-2} = \arcsin\left(\frac{x}{r_2}\right) - \theta_0$$

$$\psi_{pl} = r_2 \cos\left(\arcsin\left(\frac{x}{r_2}\right)\right) - r_2 \cos(\theta_0)$$

$$K_{1-2} = \frac{EI_{1-2}}{r_{1-2}} \qquad K_{pl} = 192\frac{EI_{pl}}{r_{pl}^3}$$

Magnetic versus Nonmagnetic

Analytical modeling



$f(t)$

$K_{pl}\psi_{pl}^{2}$

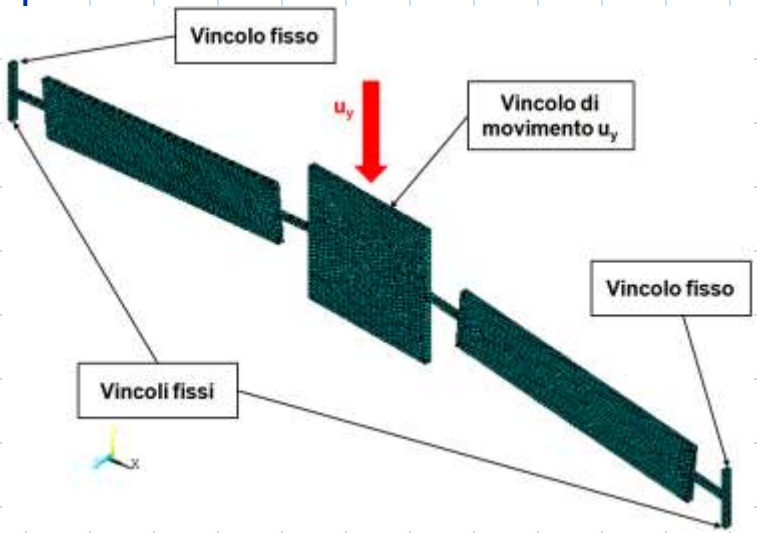
θ_0

$-r_2\cos(\theta_0)$

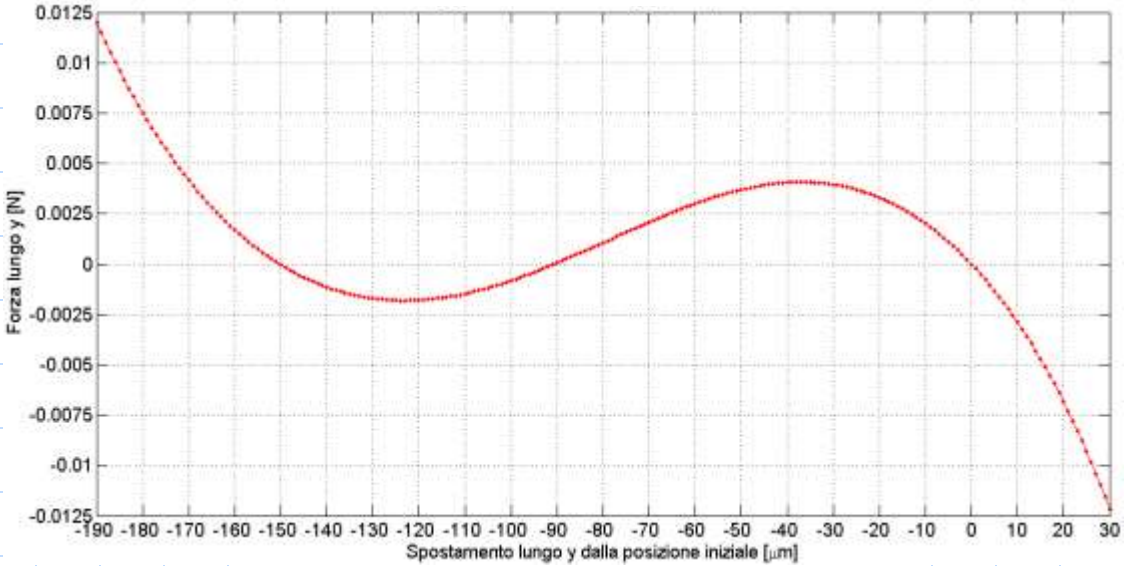
$192\frac{EI_{pl}}{r_{pl}^3}$

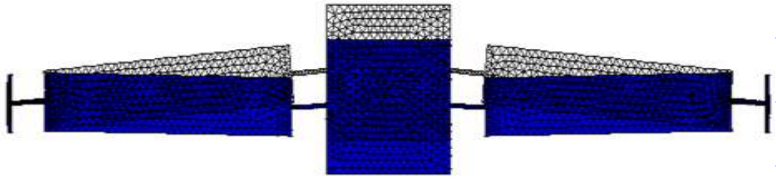
Magnetic versus Nonmagnetic

- ***FEM (Ansys) modeling***

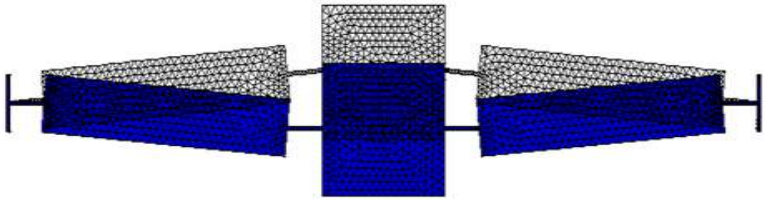


Force vs Displacement



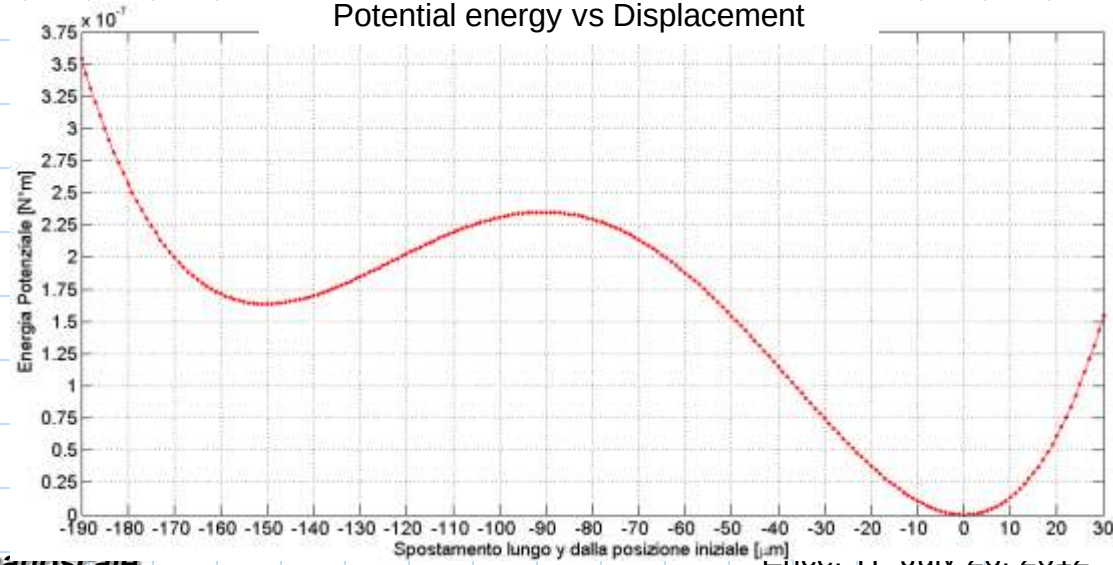


Unstable equilibrium position



2nd Stable equilibrium position

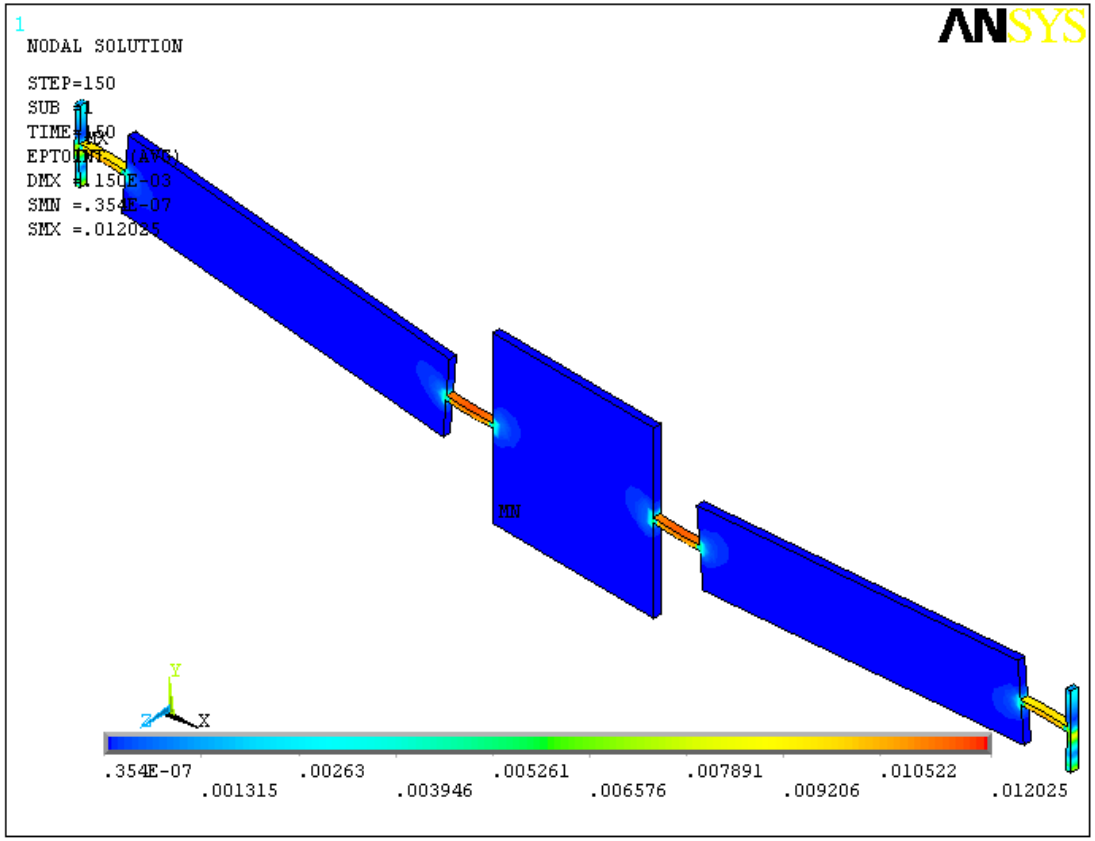
Potential energy vs Displacement

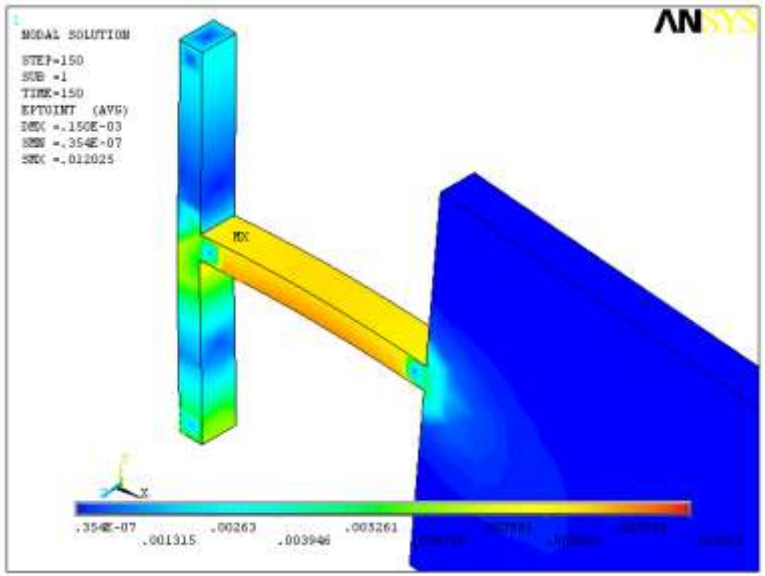


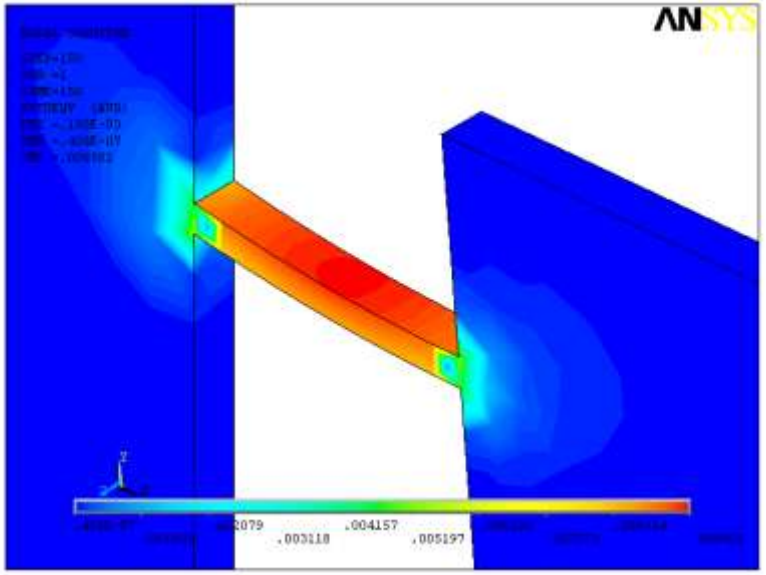
Magnetic versus Nonmagnetic

FEM (Ansys) modeling

The collection of electrical energy will take place in the areas where the largest deformations occour

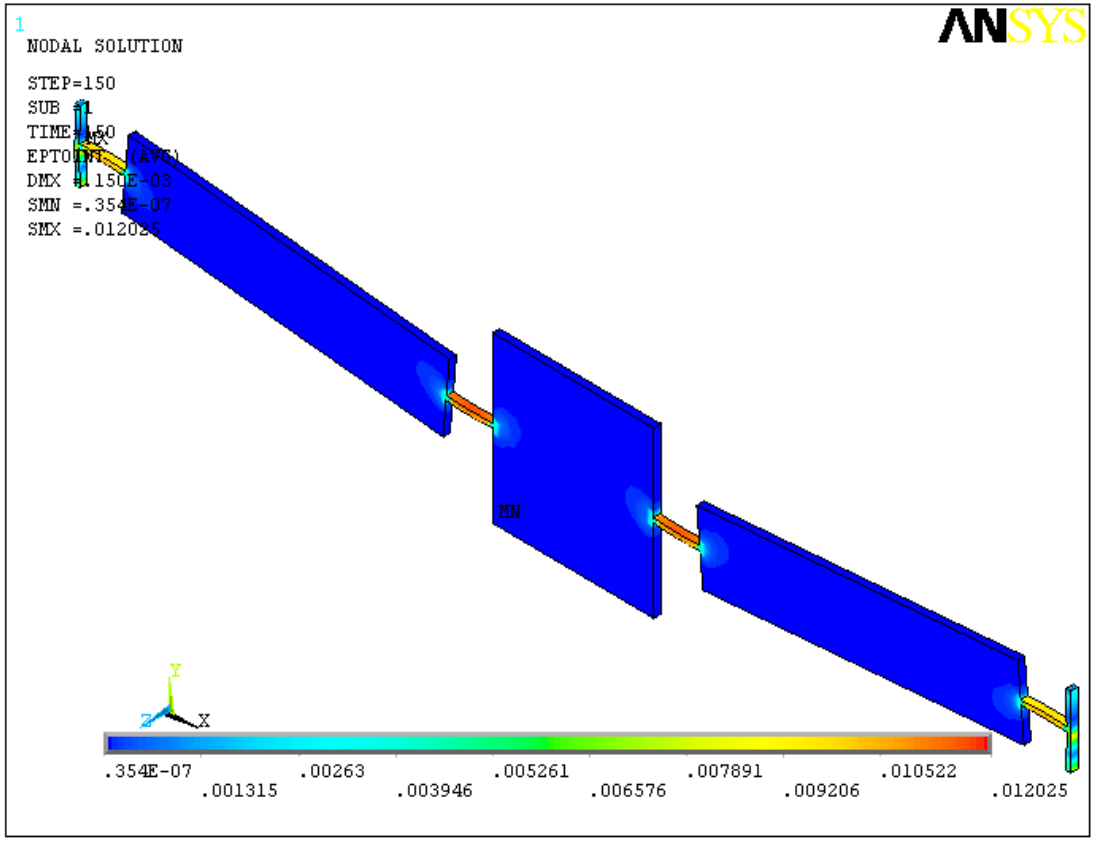






Magnetic versus Nonmagnetic

- ***Parameter sensitivity analysis***



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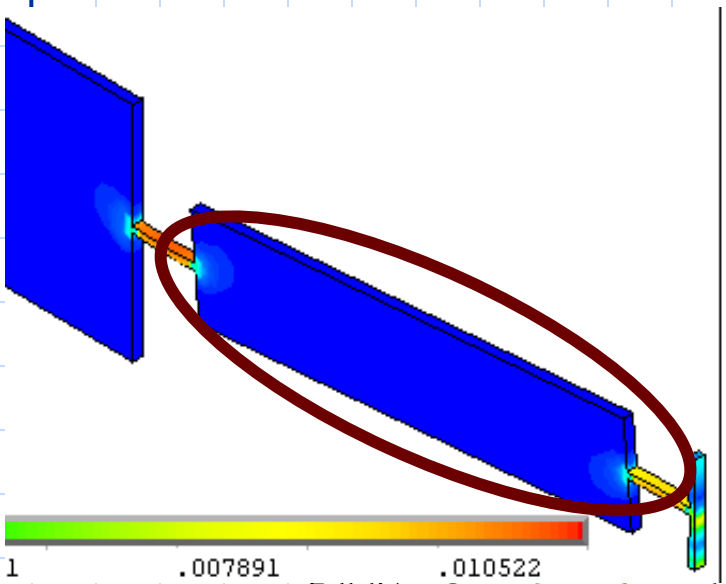

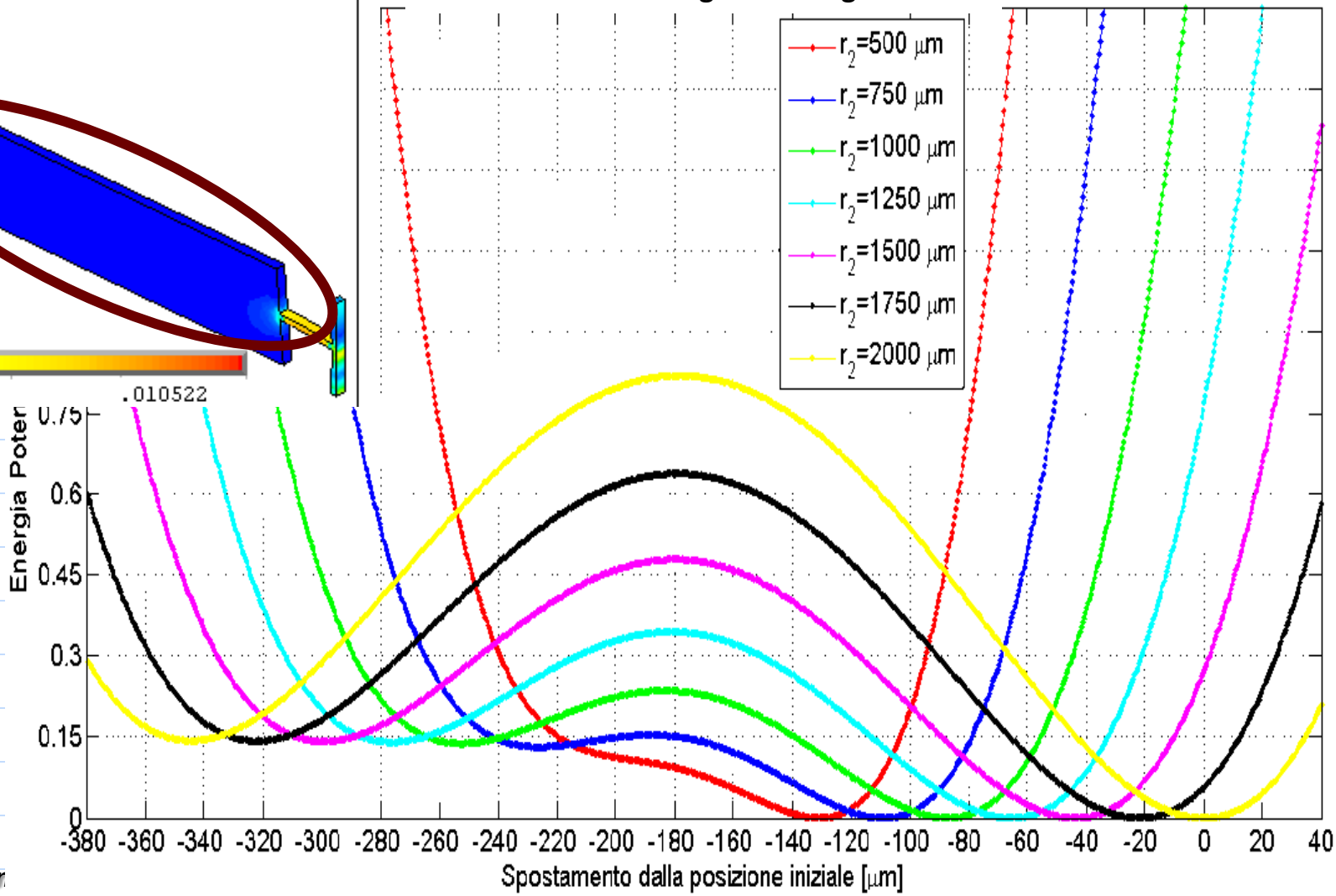

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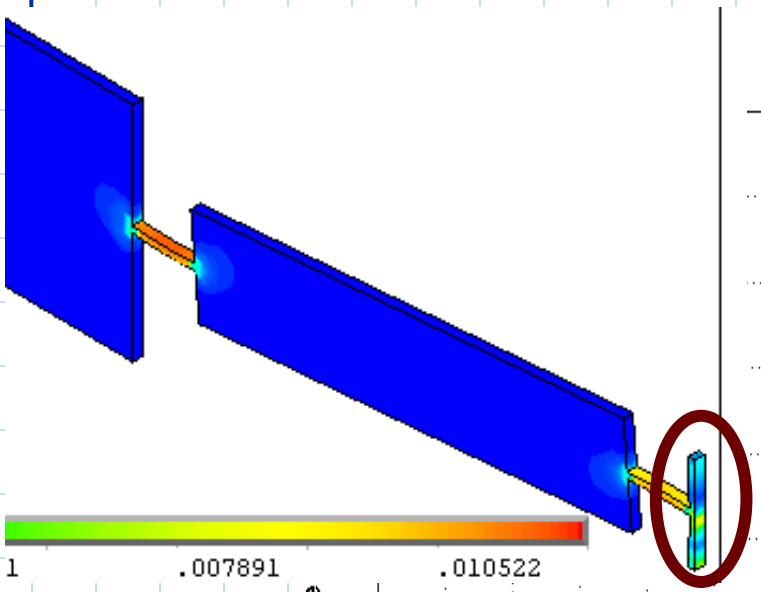
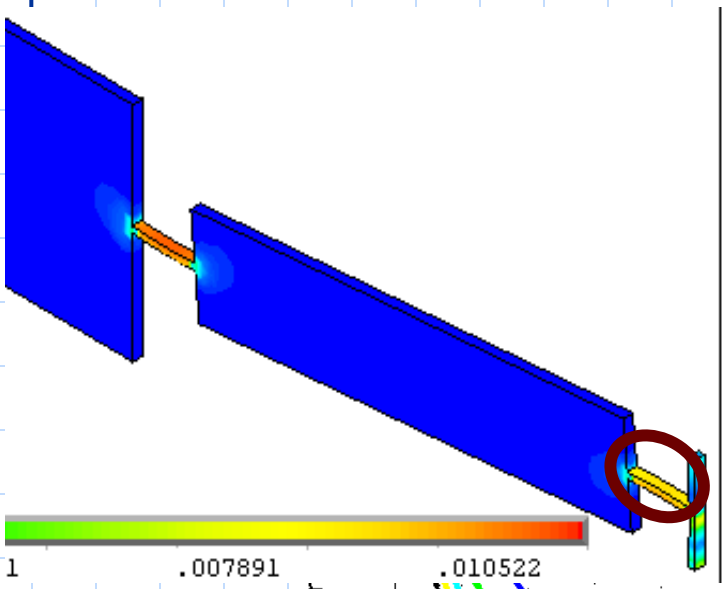


Parameter: Lateral bridge lenght

Magnetic versus Nonmagnetic

- ***Parameter sensitivity analysis***



Magnetic versus Nonmagnetic

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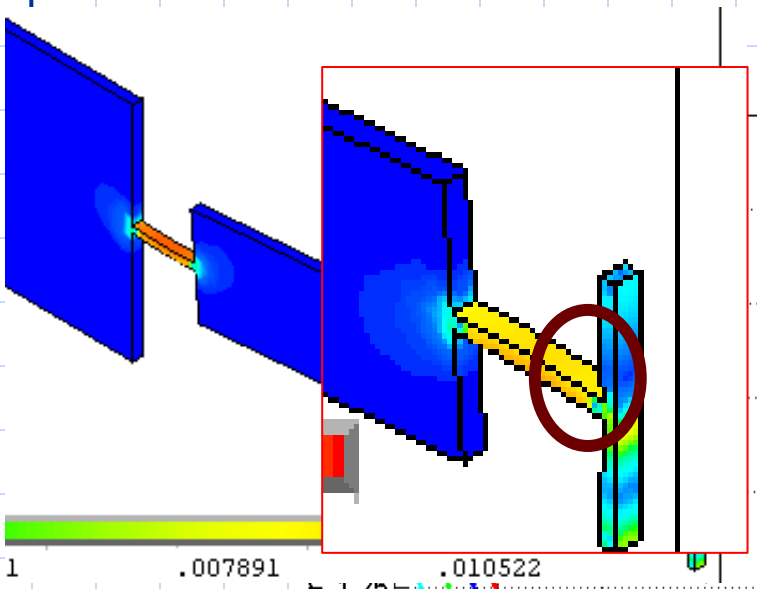
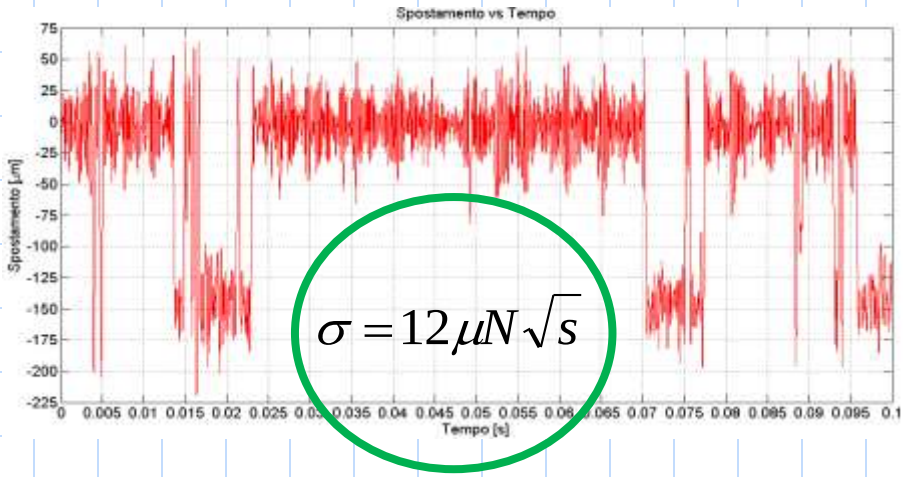


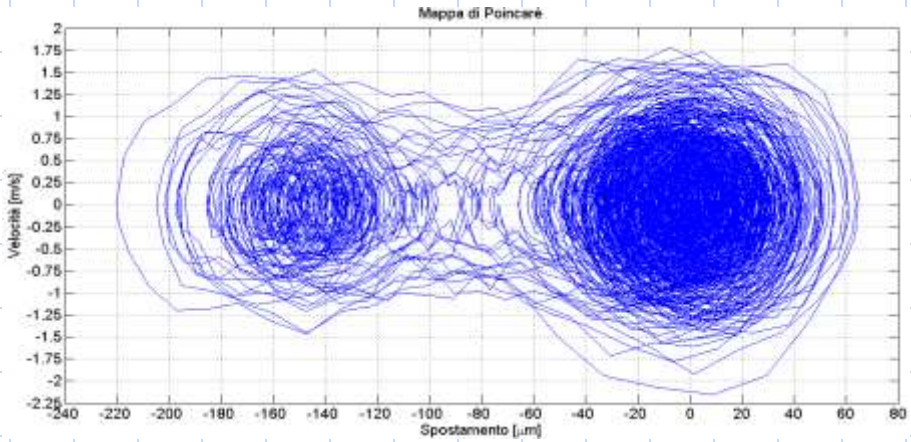
Magnetic versus Nonmagnetic

Dynamic simulations

$$\begin{cases} dx_1 = x_2 dt \\ dx_2 = \frac{1}{m}\left[-cx_2 - \psi(x_1)\right]dt + \frac{\sigma}{m} dW_t \end{cases}$$

- SDE, Itō *form*.
- **Input:** *Wiener* process(dW_t).
- **State variables:** position (x_1), *velocity* (x_2).





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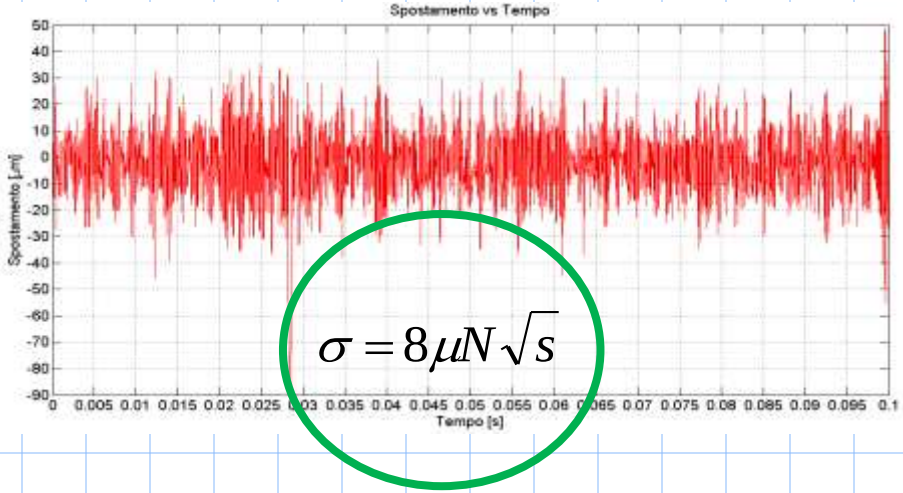

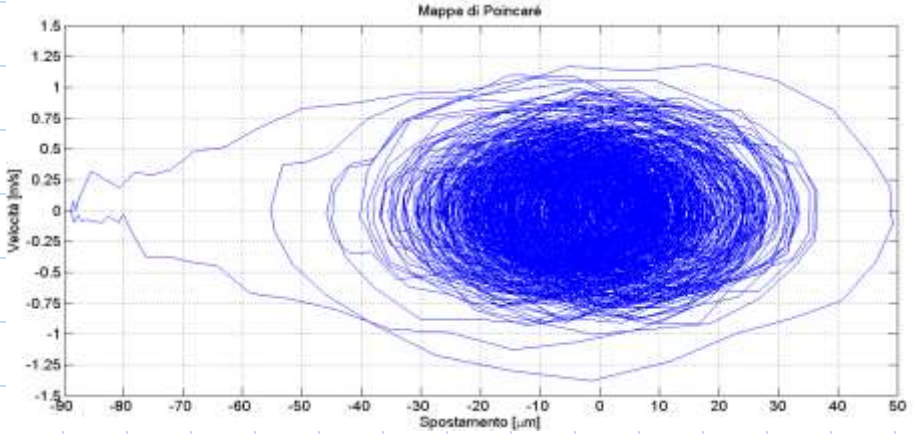

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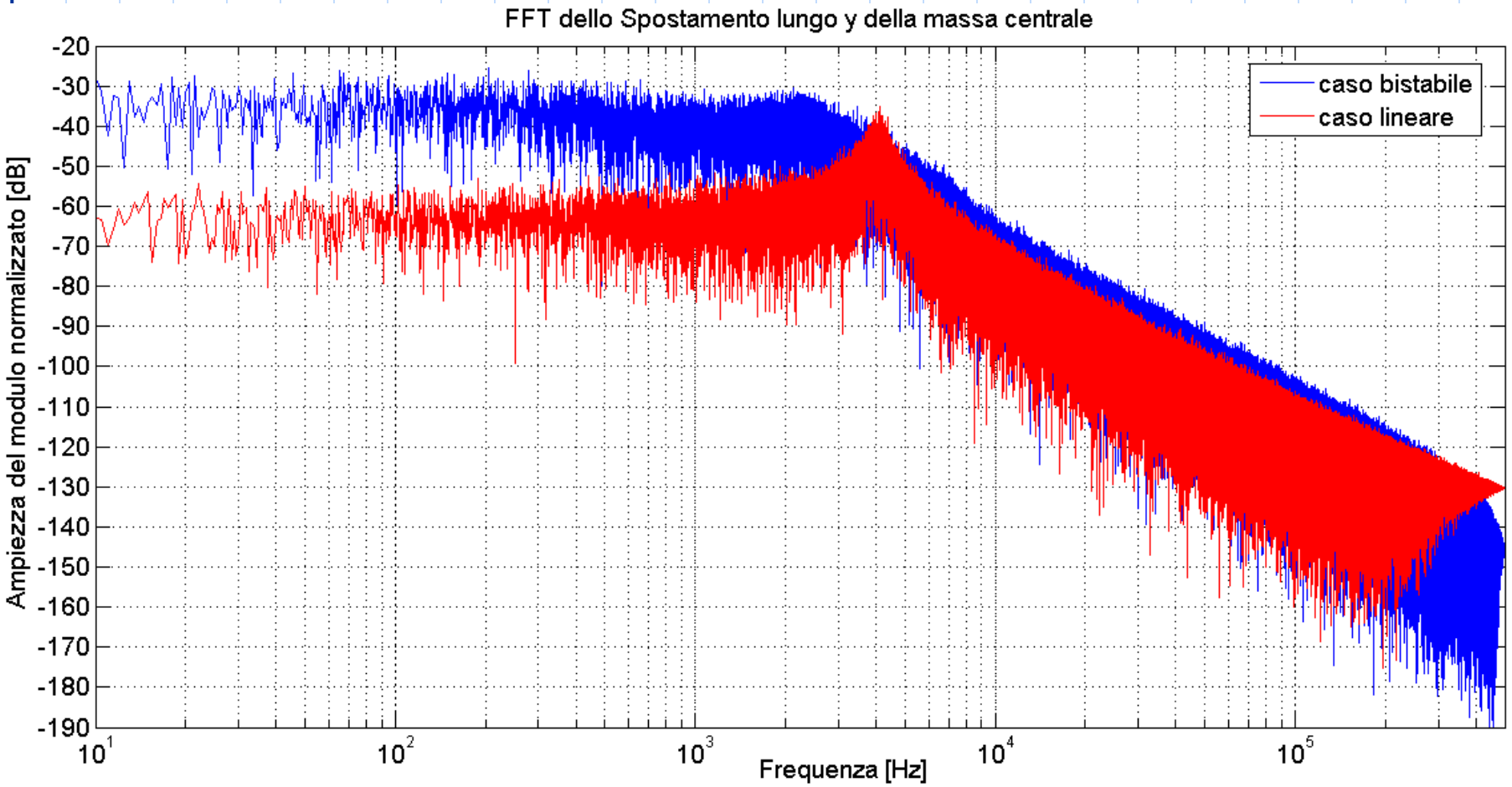
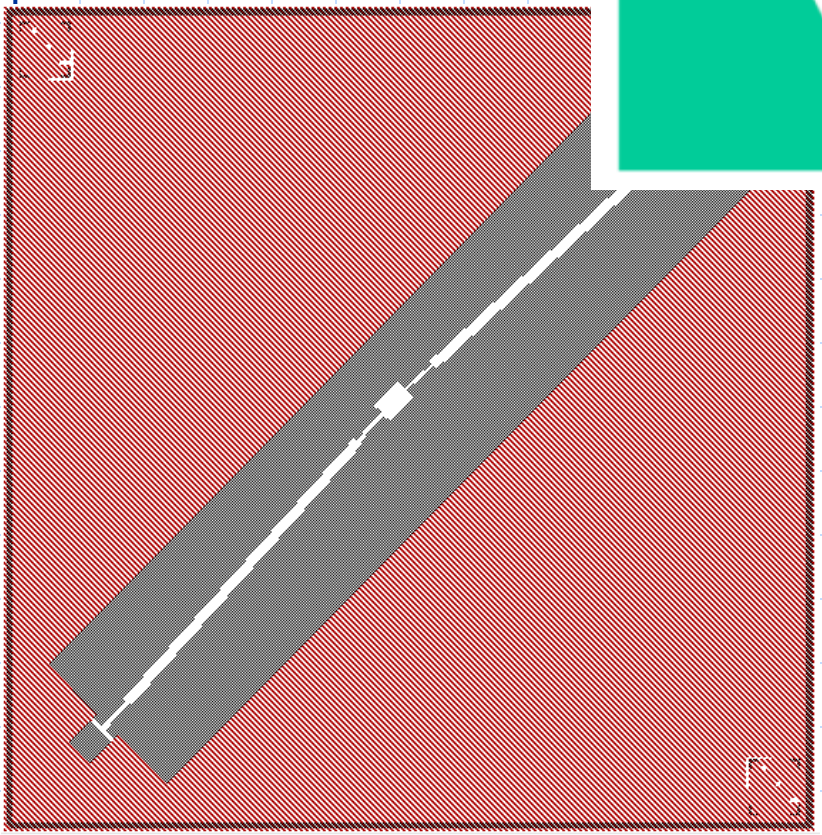
- ***Dynamic simulations***



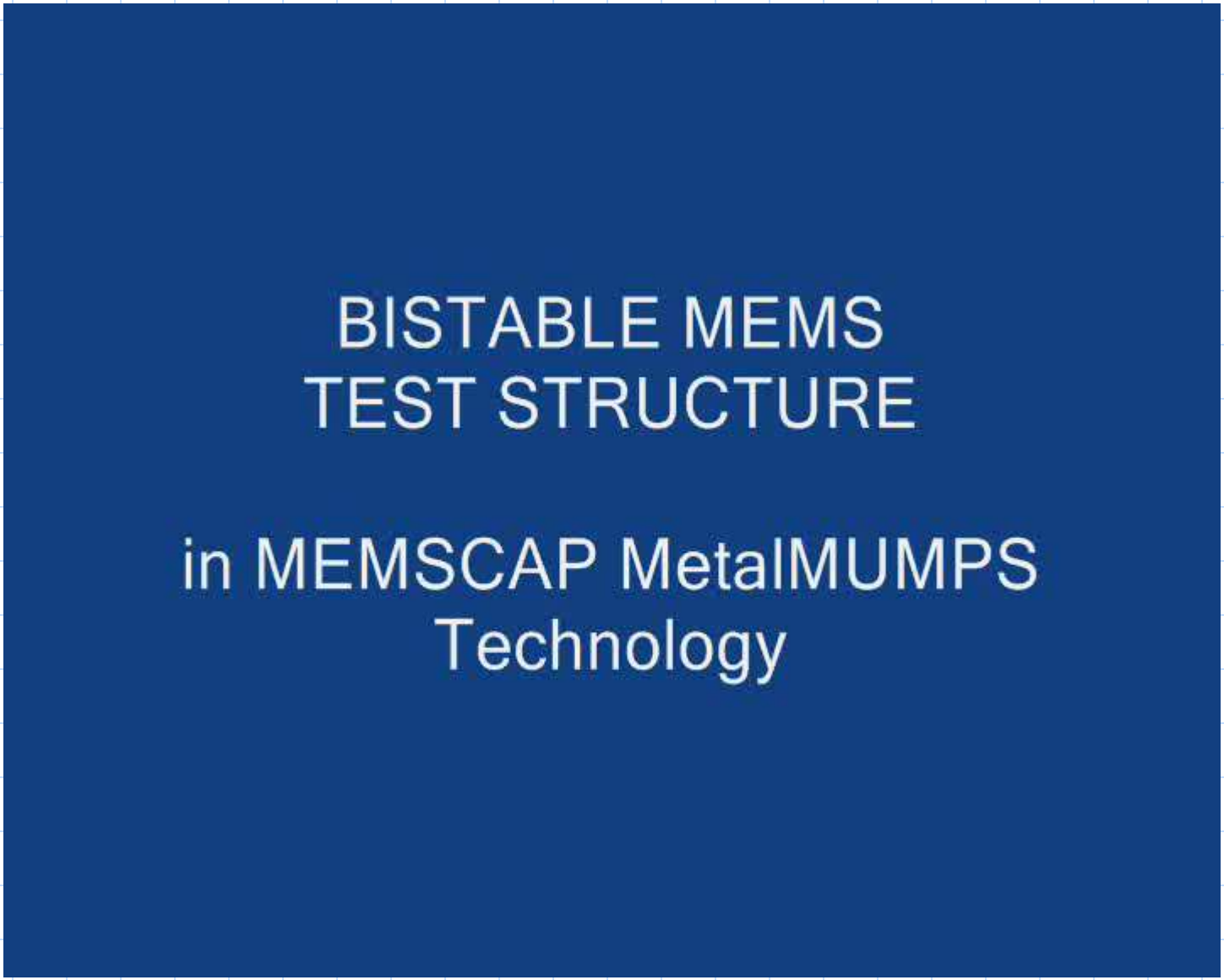
Magnetic versus Nonmagnetic

- ***Device design***



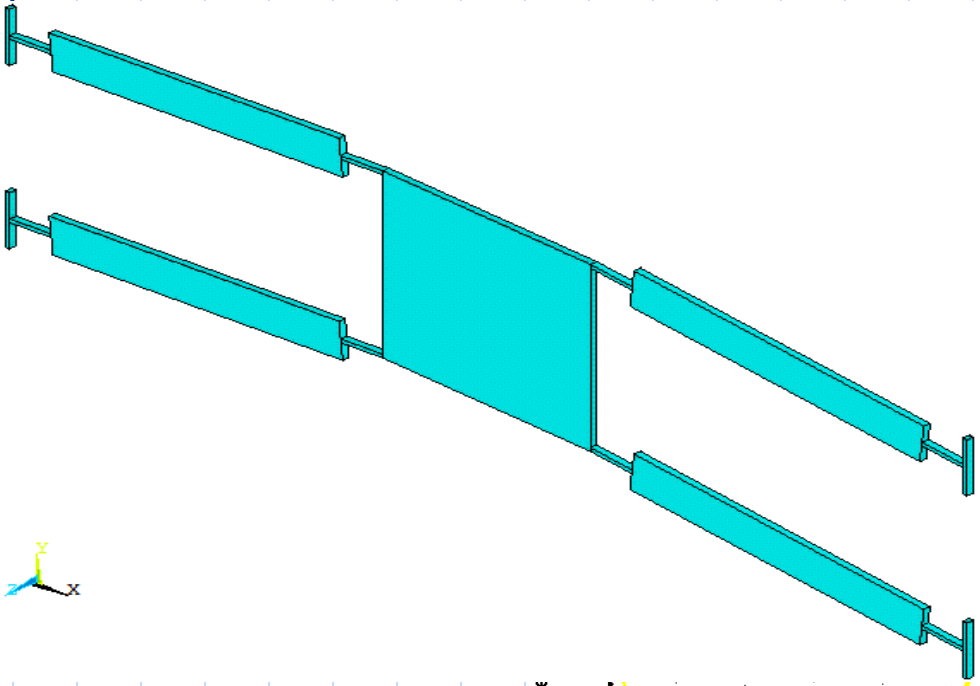
- ***Metal MUMPS***

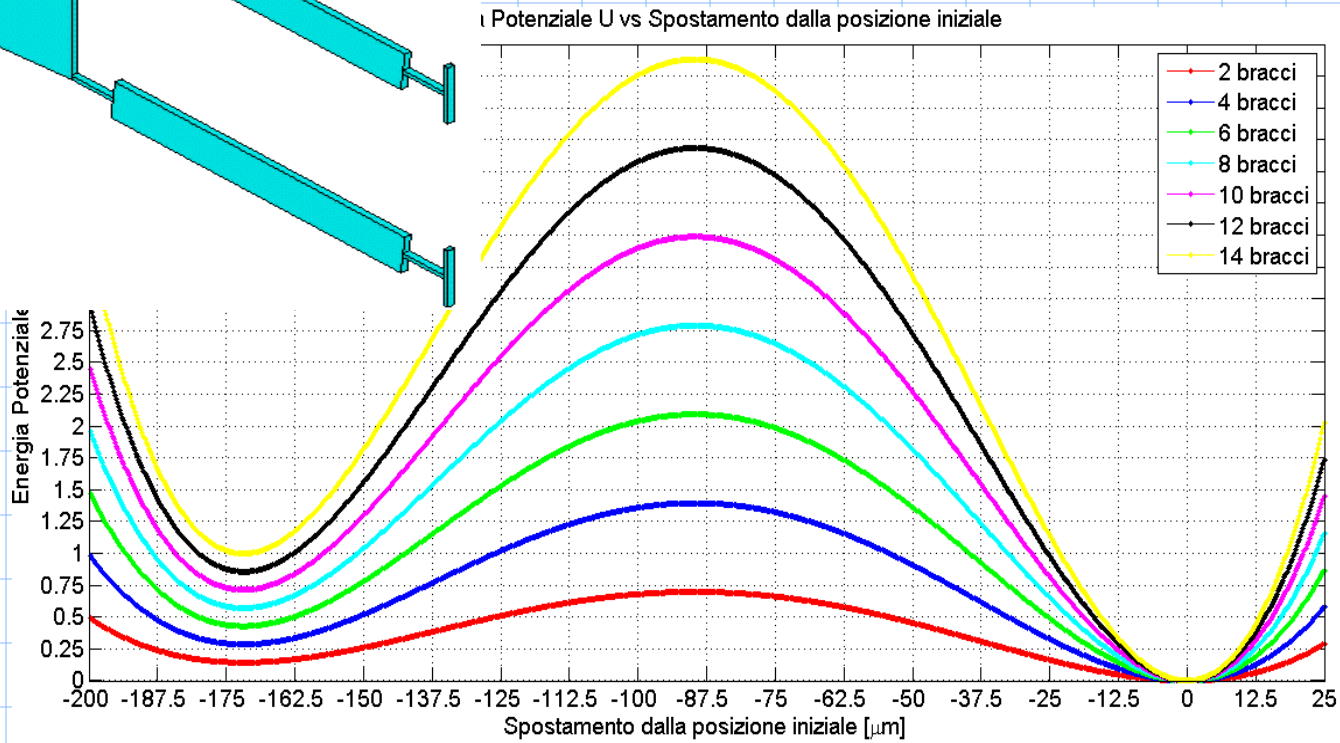
Magnetic versus Nonmagnetic



Magnetic versus Nonmagnetic

- ***Device design: multiple rigid links***





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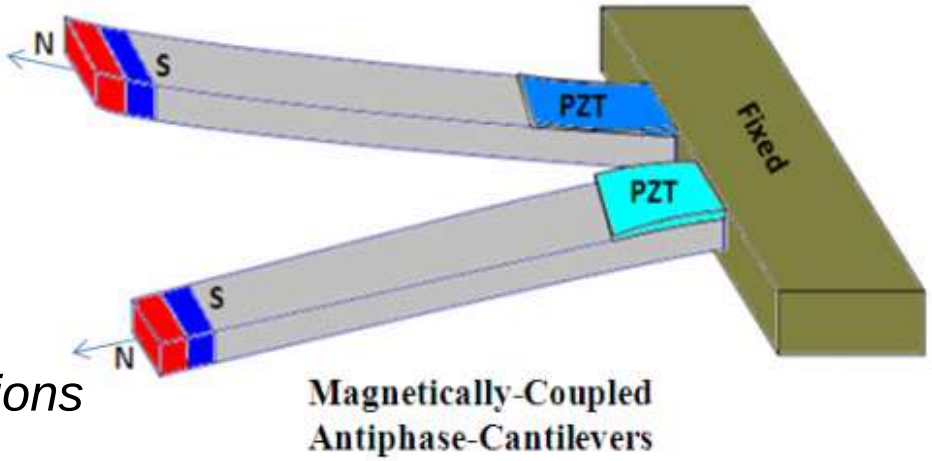
Two “working” magnets

- The magnetic bistable cantilever uses TWO magnets
- One of these DOESN’T contribute to the energy harvesting process
- It is possible to improve the efficiency by making BOTH the magnets contributing to the energy harvesting process

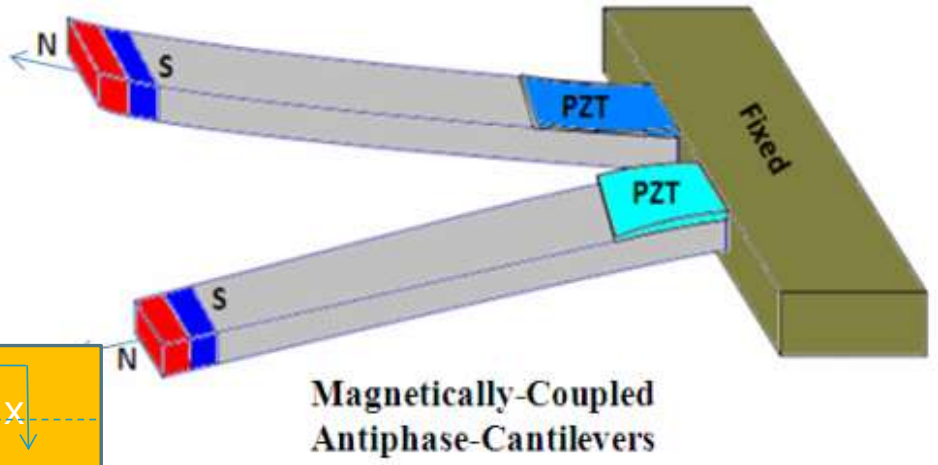
- *Fabrication process will also be facilitated by the adoption of two magnets having the same orientations in magnetization*



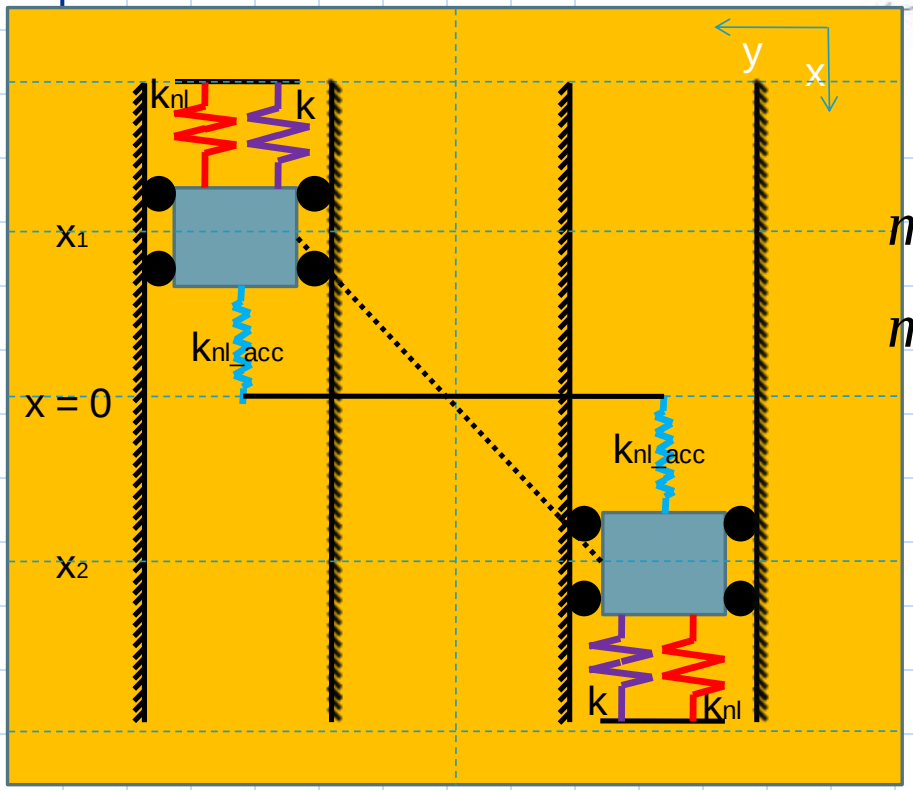
Magnetically-Coupled Antiphase-Cantilevers

Two “working” magnets

- Modeling



Magnetically-Coupled Antiphase-Cantilevers



$$m\ddot{x}_1 = -d\dot{x}_1 - kx_1 + k_{nl1}x_1 + k_{nl\_acc}(x_2 - x_1)$$

$$m\ddot{x}_2 = -d\dot{x}_2 - kx_2 + k_{nl2}x_2 - k_{nl\_acc}(x_2 - x_1)$$

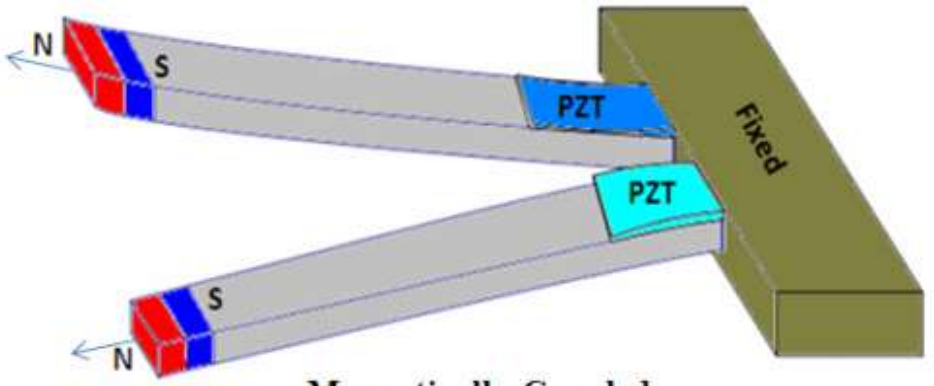
$$k_{nl1} = \alpha_1 - \beta_1 x_1^{\,2}$$

$$k_{nl2} = \alpha_2 - \beta_2 x_2^{\,2}$$

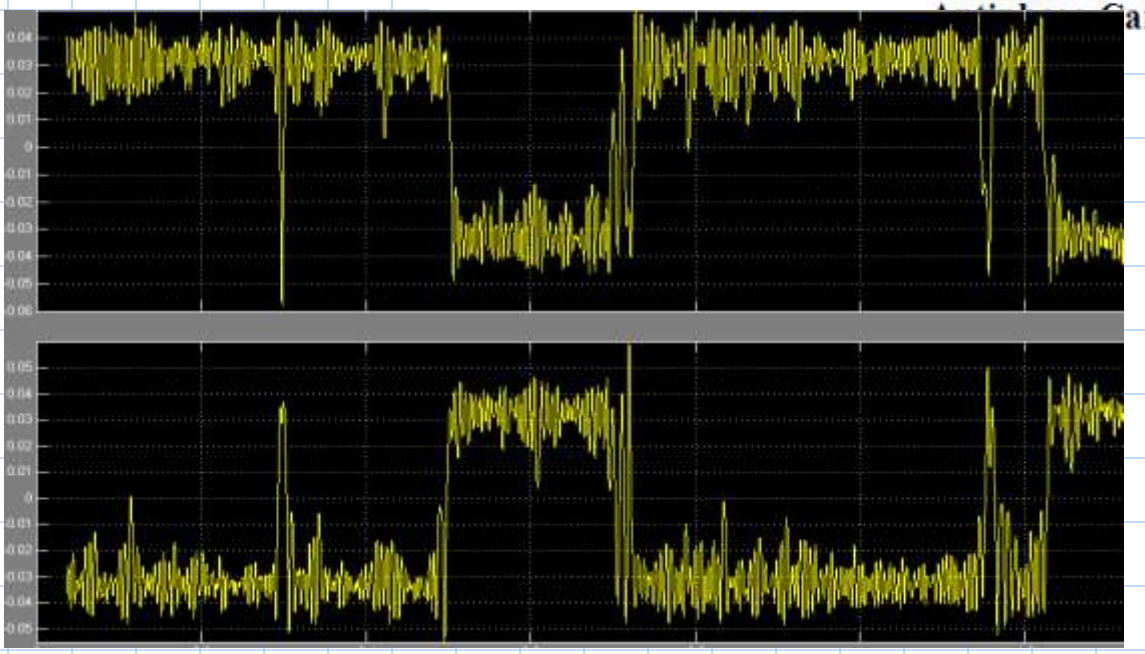
$$k_{nl\_acc} = \gamma - \delta(x_2 - x_1)^2$$

Two “working” magnets

- Simulations

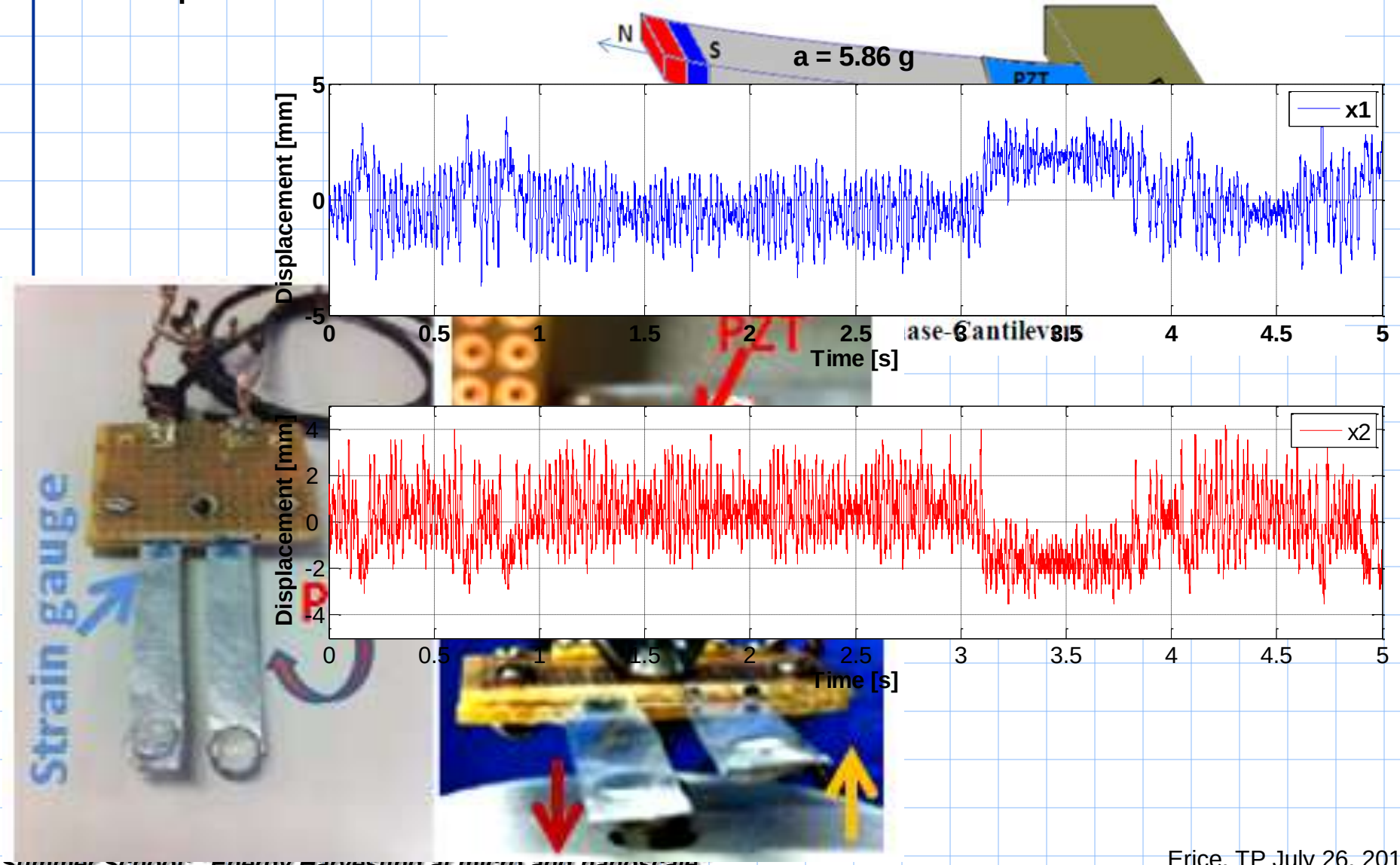


Magnetically-Coupled
antilevers



Two “working” magnets

- Experimental results



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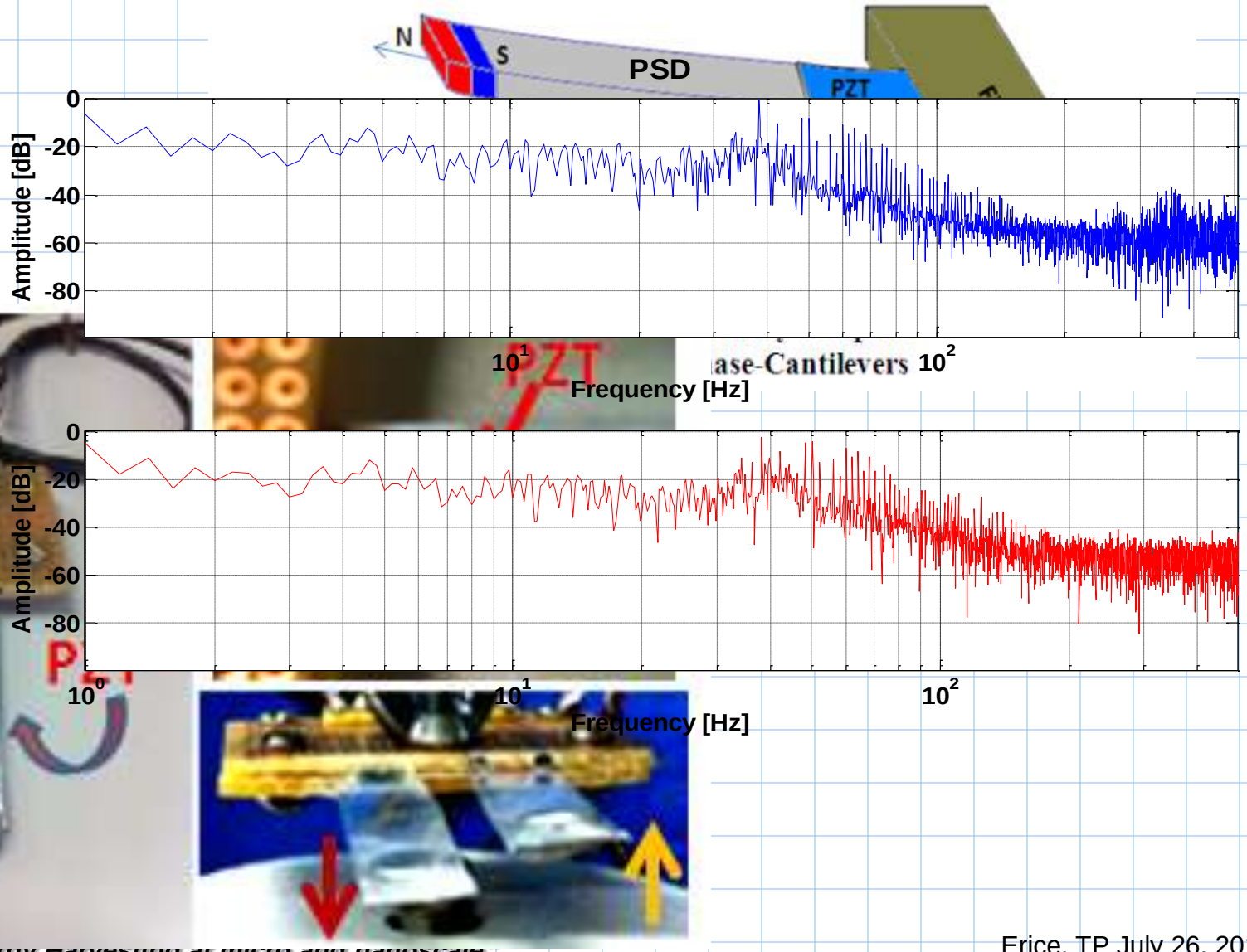

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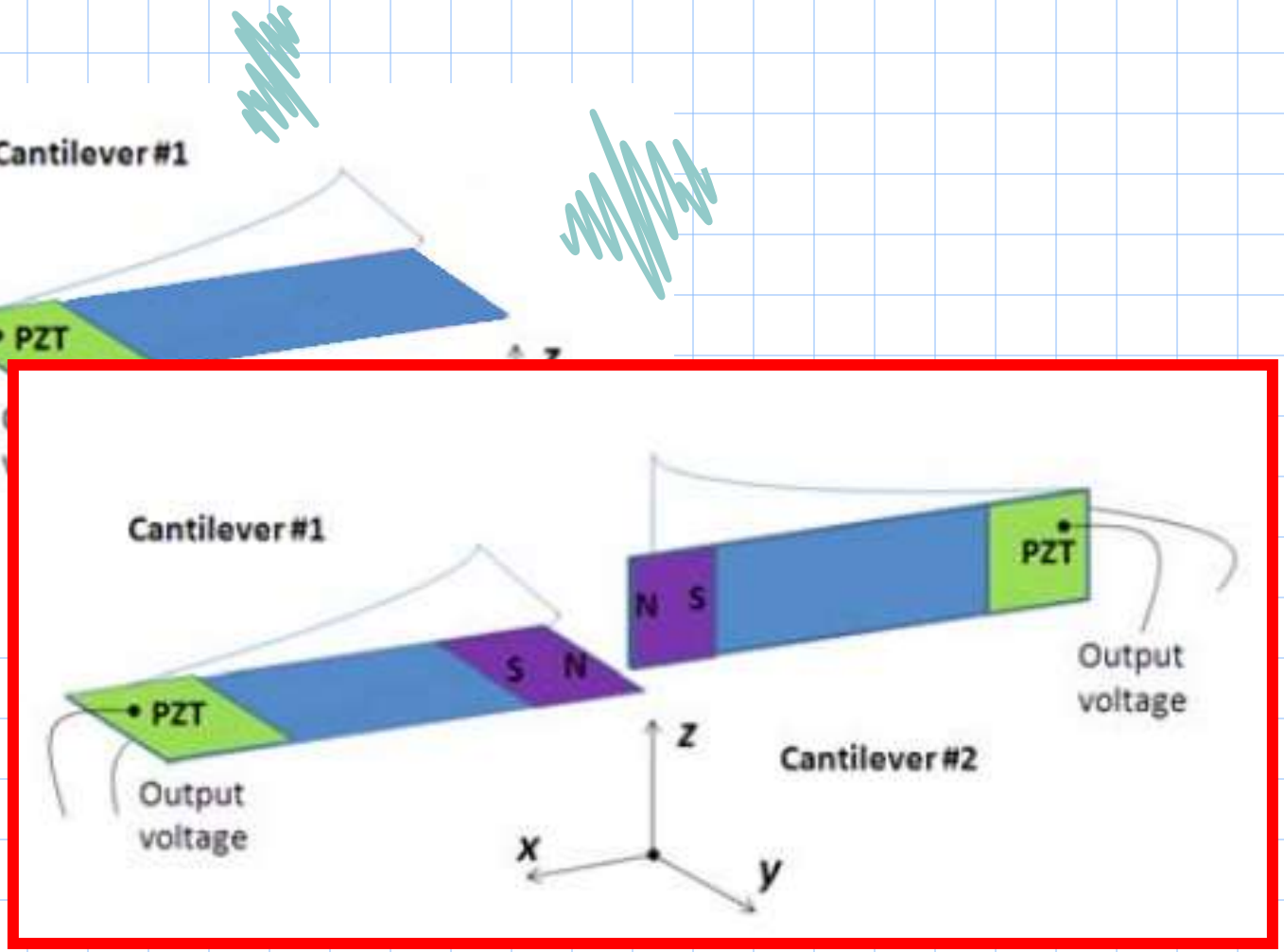
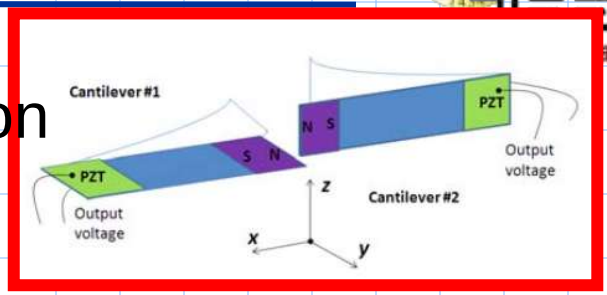
Two Dimensional vibrations harvester

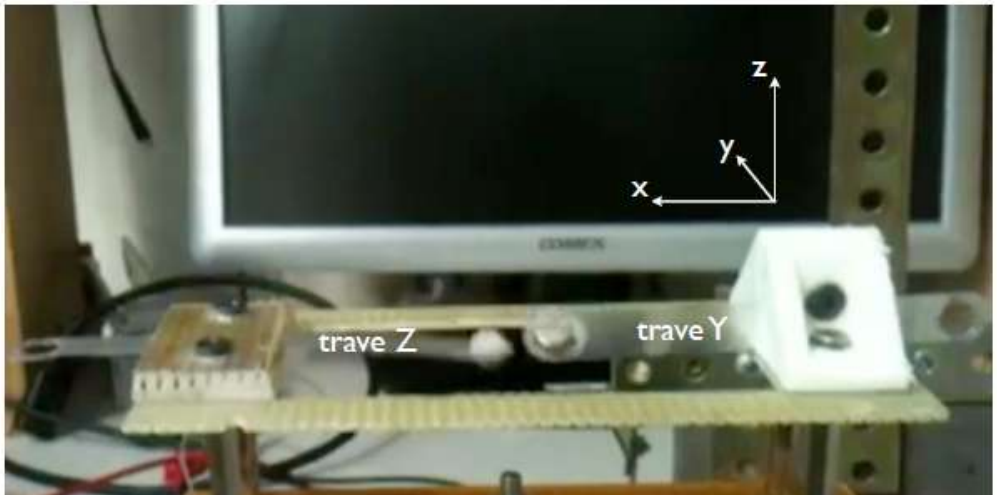
- The idea: from 1-D to 2-D

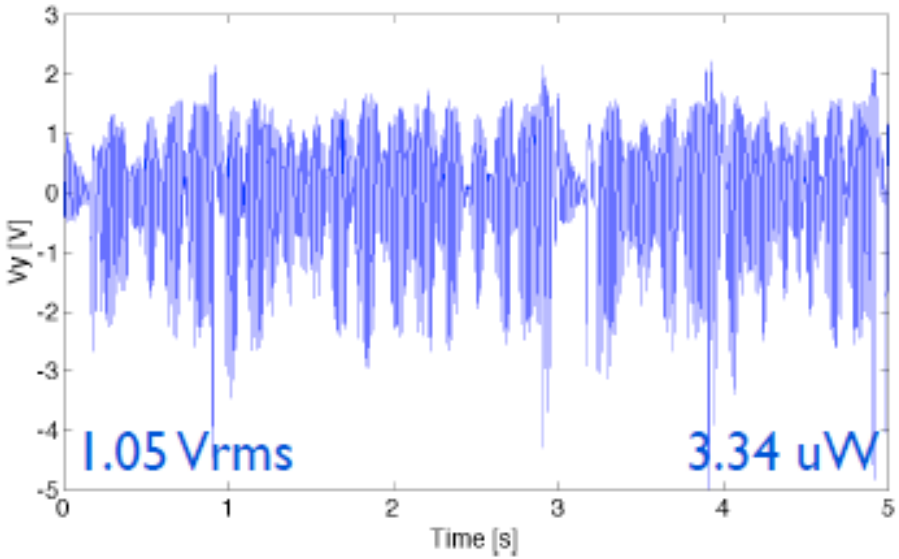


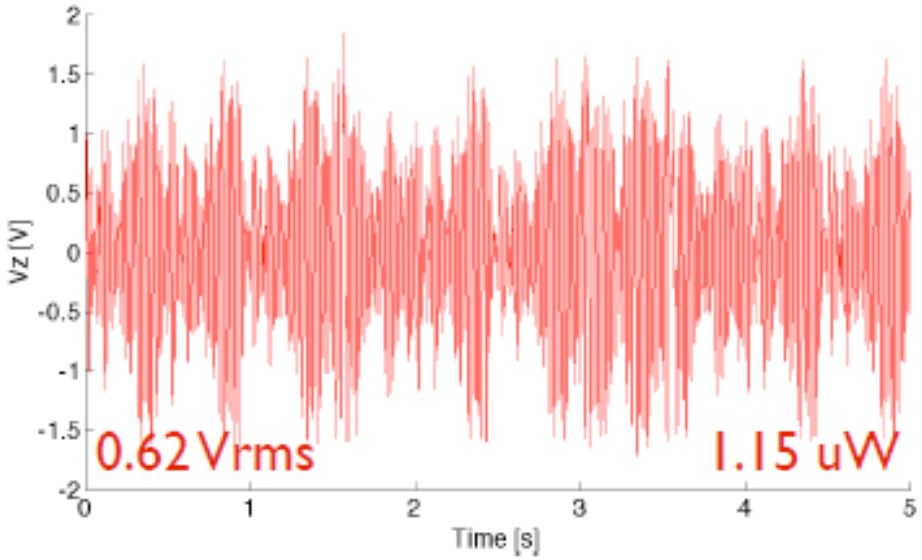
Two Dimensional vibrations harvester

- Experimental validation: 45° acceleration









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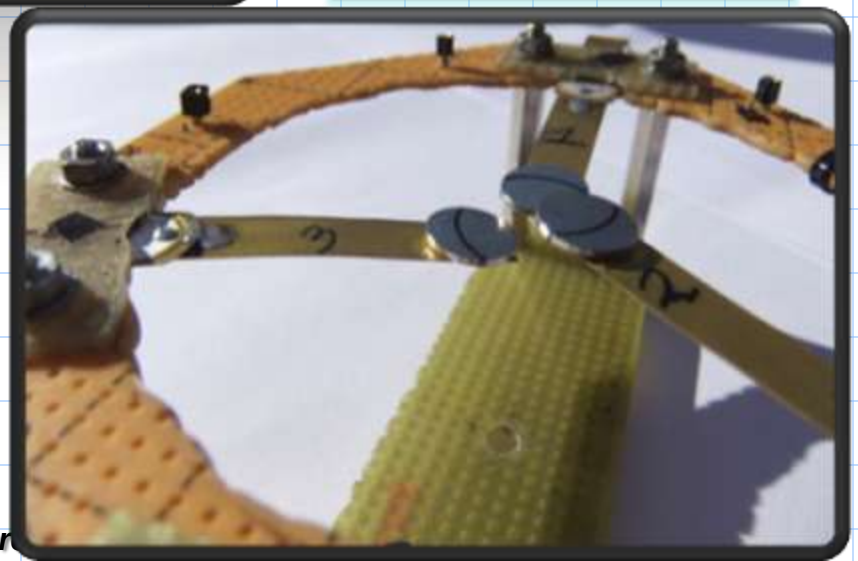
TriStable vibrations harvester

totype

Middle state (C3)

Up state (C3)

Down state (C3)



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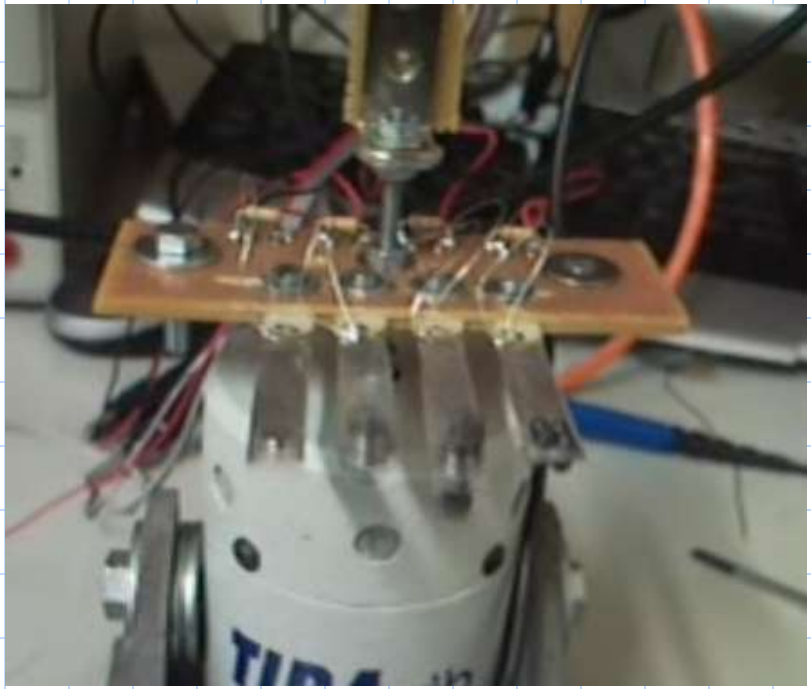
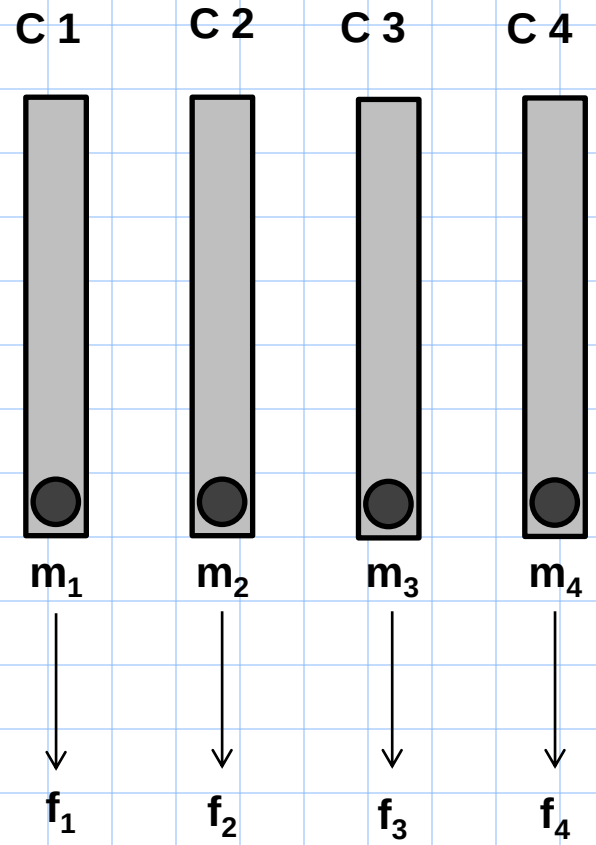
Magnetically coupled array

- *Four cantilevers with magnetic coupling and different resonant frequency*





$m_1 = 0.82\ g$ - $f_1 = 32Hz$

$m_2 = 1.26\ g$ - $f_2 = 20Hz$

$m_3 = 2.52\ g$ - $f_3 = 17Hz$

$m_4 = 0.88\ g$ - $f_4 = 24Hz$

$$m_i = m_{magnet} + m_{additional\_load}$$

… wrapping up …

- *Linear versus **bistable approach***

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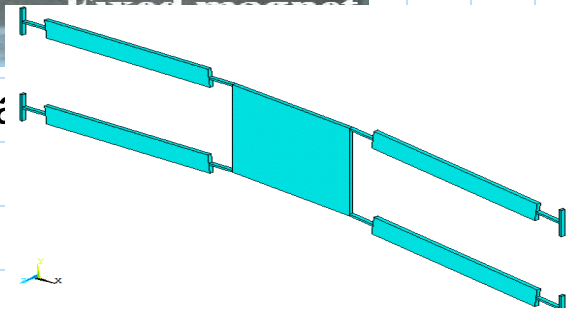
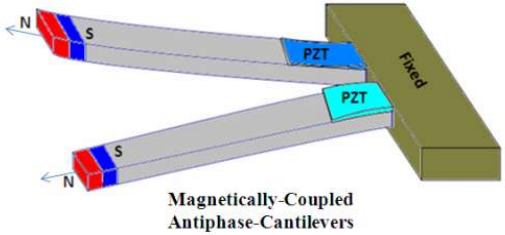


- *MEMS technologies: mechanically bistable*

- ***Magnetic**: One “working” magnet versus two “*



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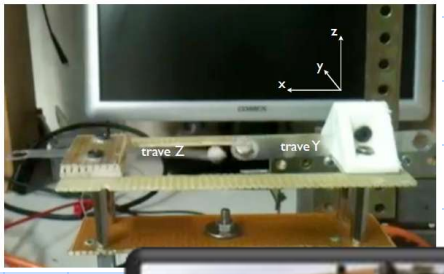
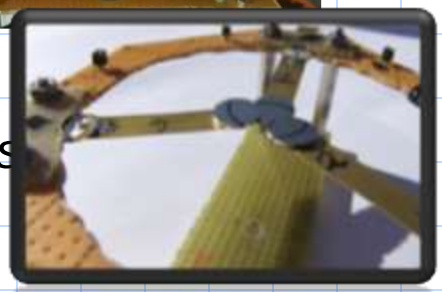
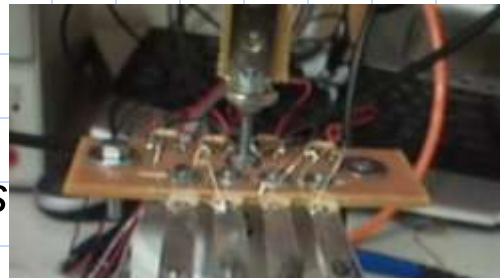




- ***Magnetic**: Bi-stable versus Tri-s*

- ***Magnetic**: magnetically coupled cantilever array versus*



Thanks for your attention