Superconducting cavities for the detection of high frequency gw

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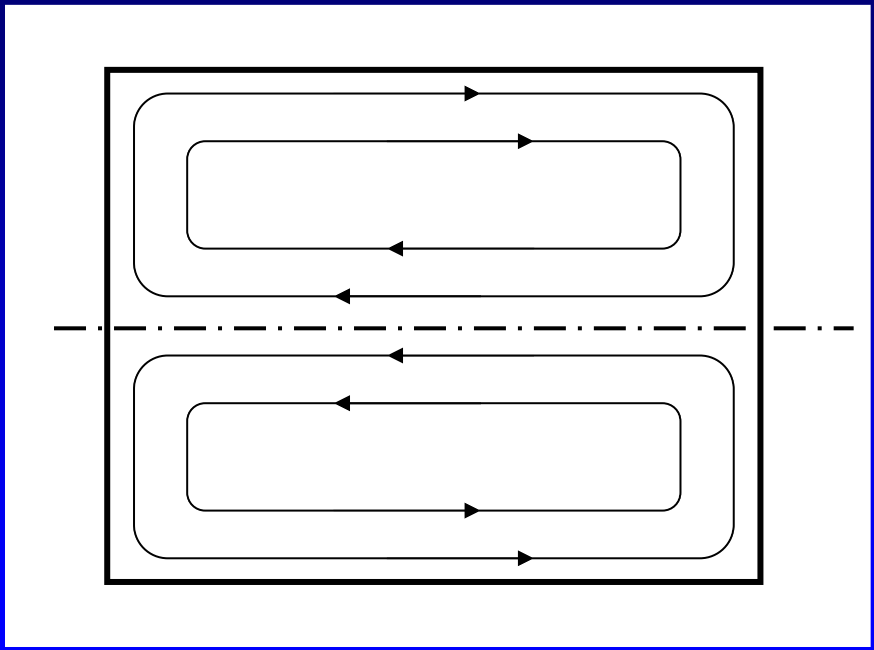
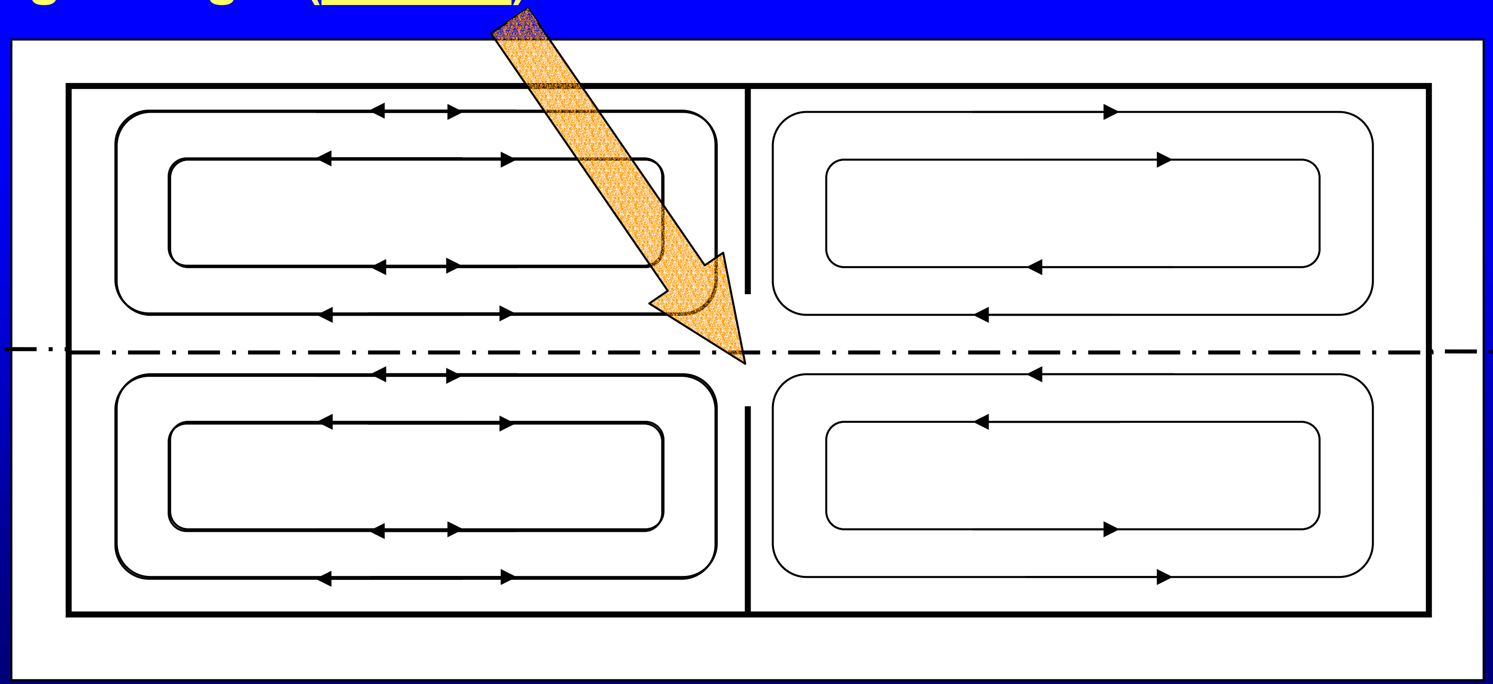
Pill-box cavity
TE011 mode



Symmetric mode: ω_s

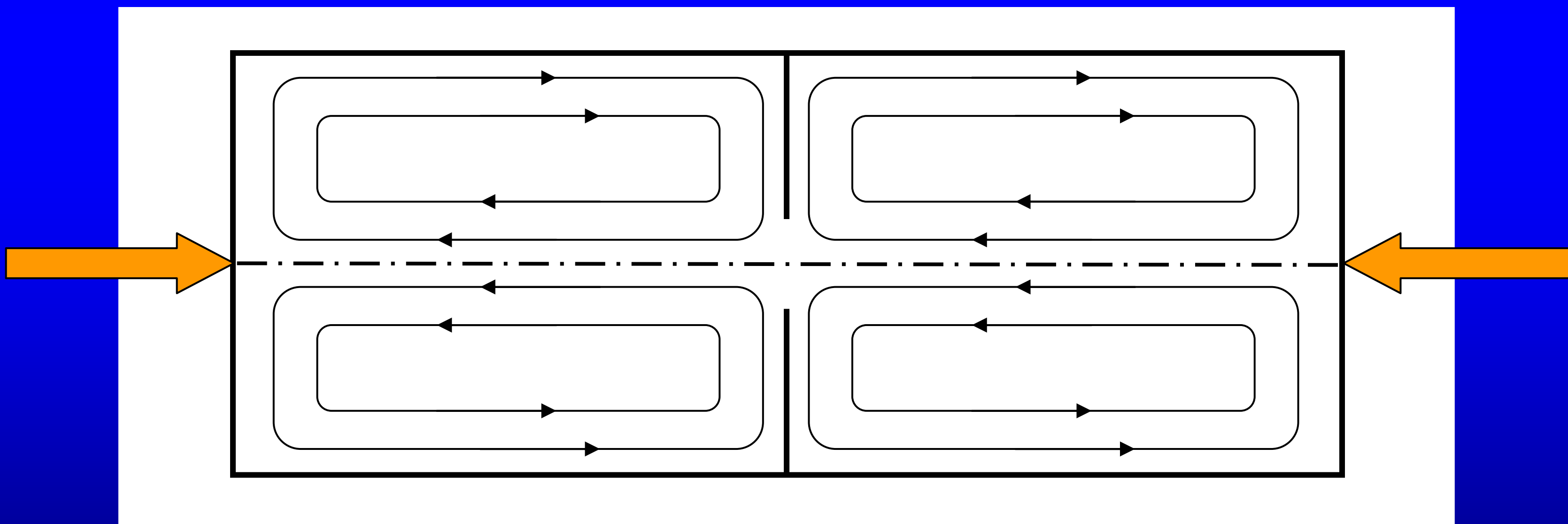
Antisymmetric mode: ω_a

$\omega_a - \omega_s$ proportional to the coupling strength (*tunable*)



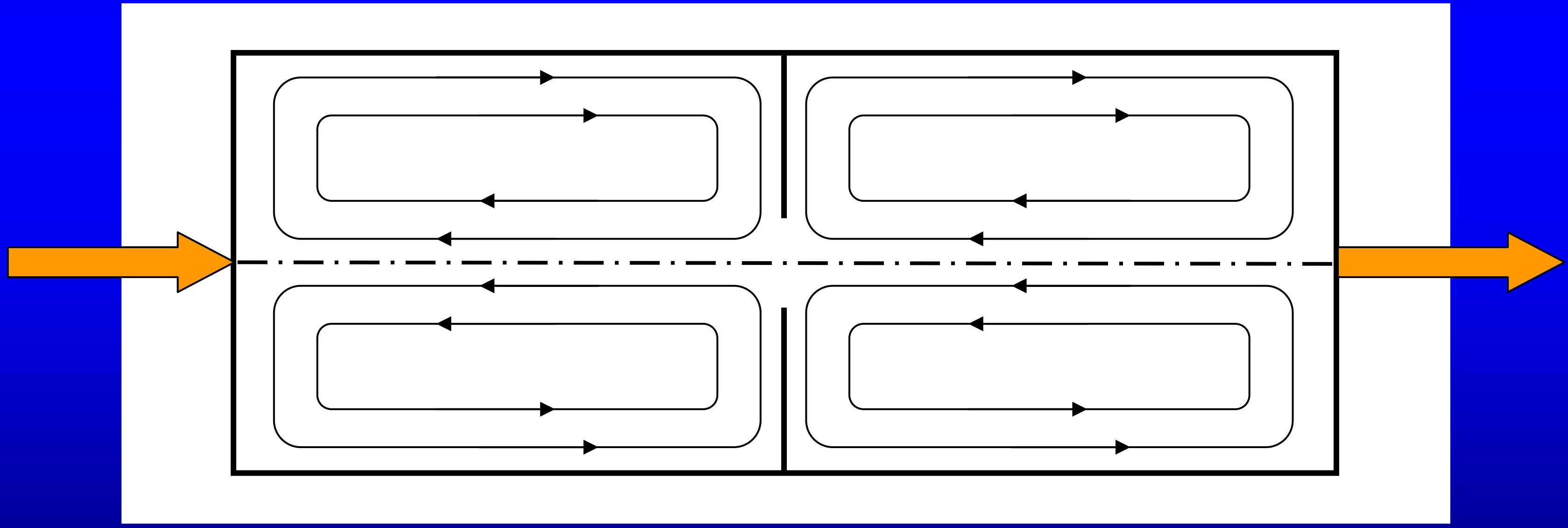
If the symmetric mode is initially excited and we perturb one system parameter (e.g. the length of the cavity) with a characteristic frequency much lower than the normal mode frequency ($\Omega \ll \omega_0$)...

...we can just have a modulation of the mode frequency, ***without any mode mixing***...



...or we can have a ***coupling*** between the two normal modes of the unperturbed system → there is transfer of energy from one mode to the other;

the energy transfer is maximum when the frequency of the external perturbation equals the normal modes frequency difference: $\Omega = \omega_a - \omega_s$



Let us note that this effect depends on ***how we perturb*** the system

Field equations in an e.m. resonator with perturbed boundaries

$$\vec{u}(\vec{r},t)=\sum_\alpha q_\alpha(t)\vec{\xi}_\alpha(\vec{r})$$

$$f_\alpha(t)=\int_{Vol}\vec{f}(\vec{r},t)\cdot\vec{\xi}_\alpha(\vec{r})\,dV$$

$$\vec{E}(\vec{r},t)=\sum_n \mathcal{E}_n(t)\vec{E}_n(\vec{r})$$

$$\vec{H}(\vec{r},t)=\sum_n \mathcal{H}_n(t)\vec{H}_n(\vec{r})$$

$$H=\frac{1}{2}\left[\mathcal{E}_1^2+\mathcal{H}_1^2+\mathcal{E}_2^2+\mathcal{H}_2^2+\frac{p_m^2}{M}+M\omega_m^2 q_m^2\right]+$$

Free fields

$$-\frac{q_m}{2}\left(C_{11}^m\mathcal{H}_1^2+C_{22}^m\mathcal{H}_2^2+2C_{12}^m\mathcal{H}_1\mathcal{H}_2\right)+$$

Interaction

$$-q_m f_m$$

External force

Coupling coefficient

$$C_{nm}^\alpha=\int_S\left(\vec{H}_n\cdot\vec{H}_m-\vec{E}_n\cdot\vec{E}_m\right)\vec{\xi}_\alpha\cdot d\vec{S}$$

PArametricCOnverter (1998-2000)

Two **pill-box** niobium cavities mounted end-to-end and coupled trough a small aperture on the axis

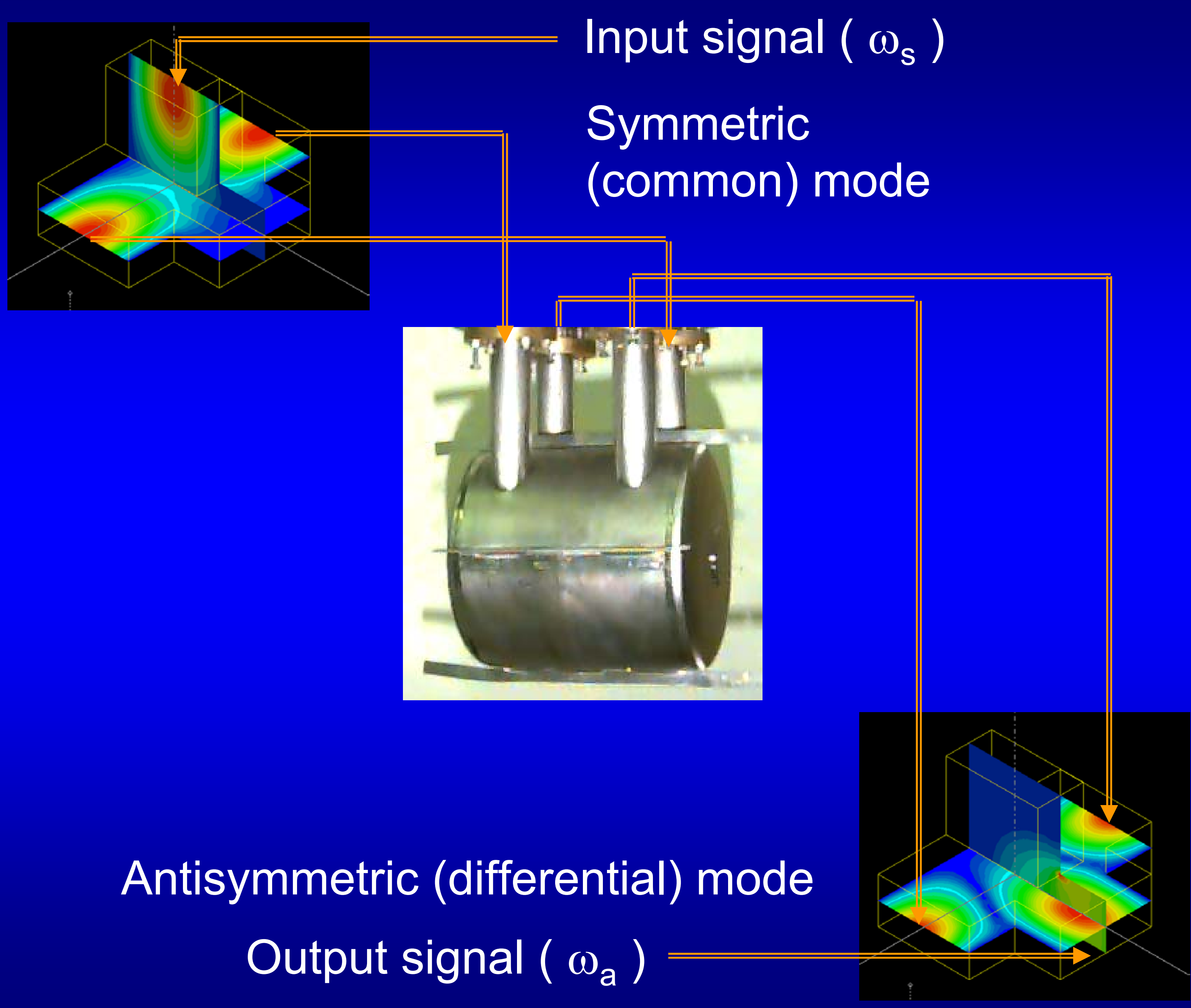
Wall movement induced by a piezo-electric crystal

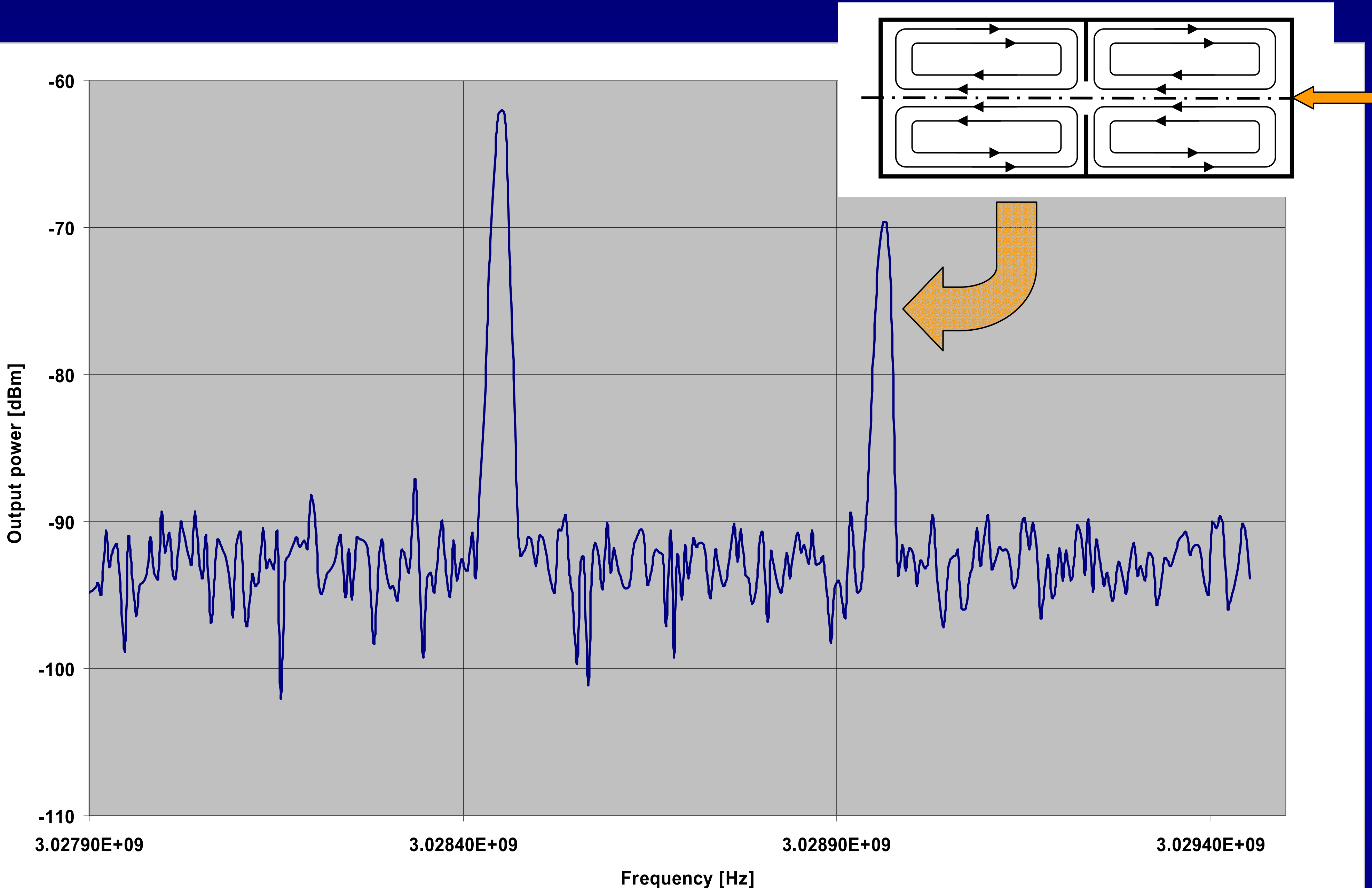
Working frequency ≈ 3 GHz

Mode splitting ≈ 500 kHz

Quality factor (e.m.) **2×10^9 @ 1.8 K**

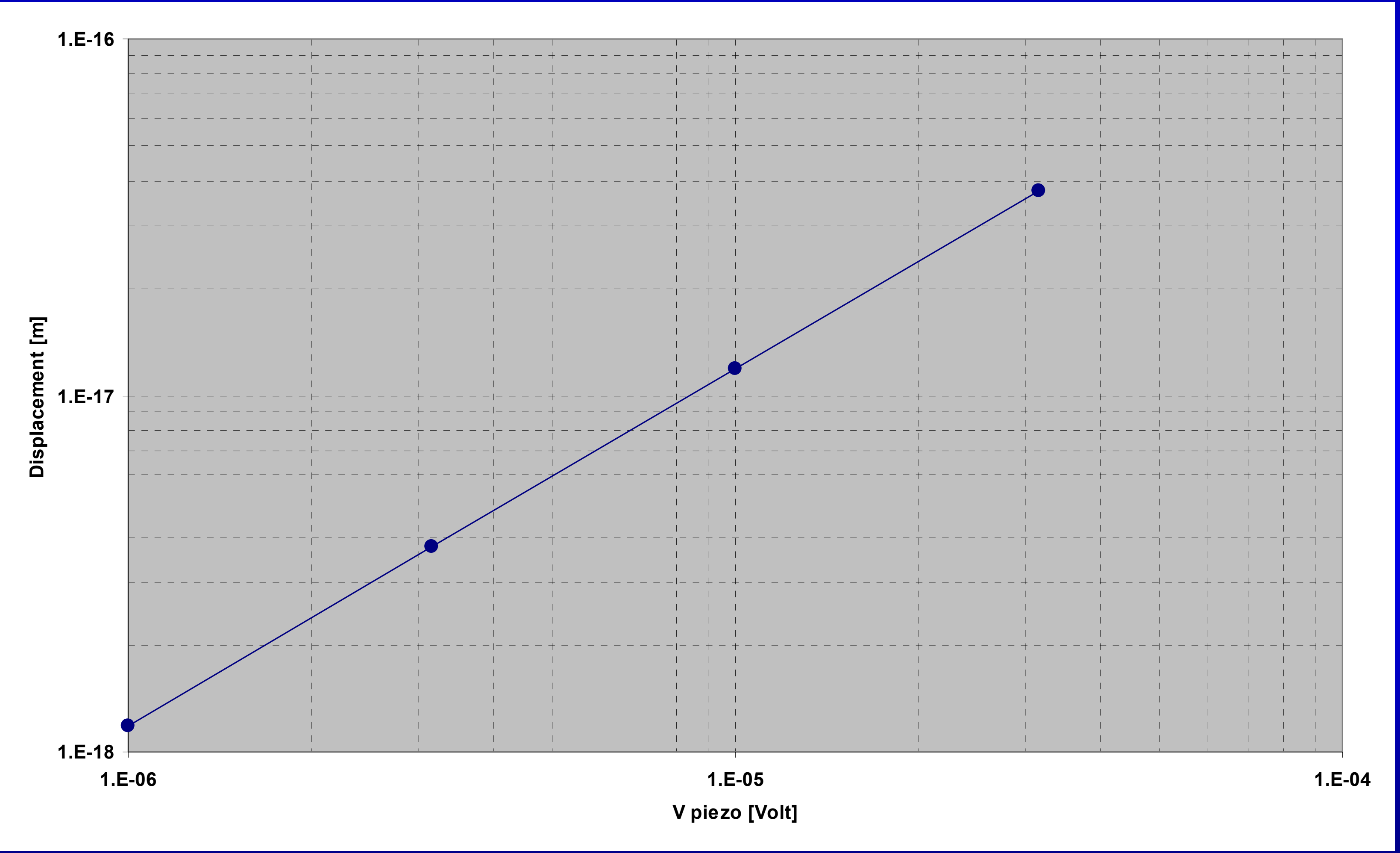
Stored energy **1.8 J**

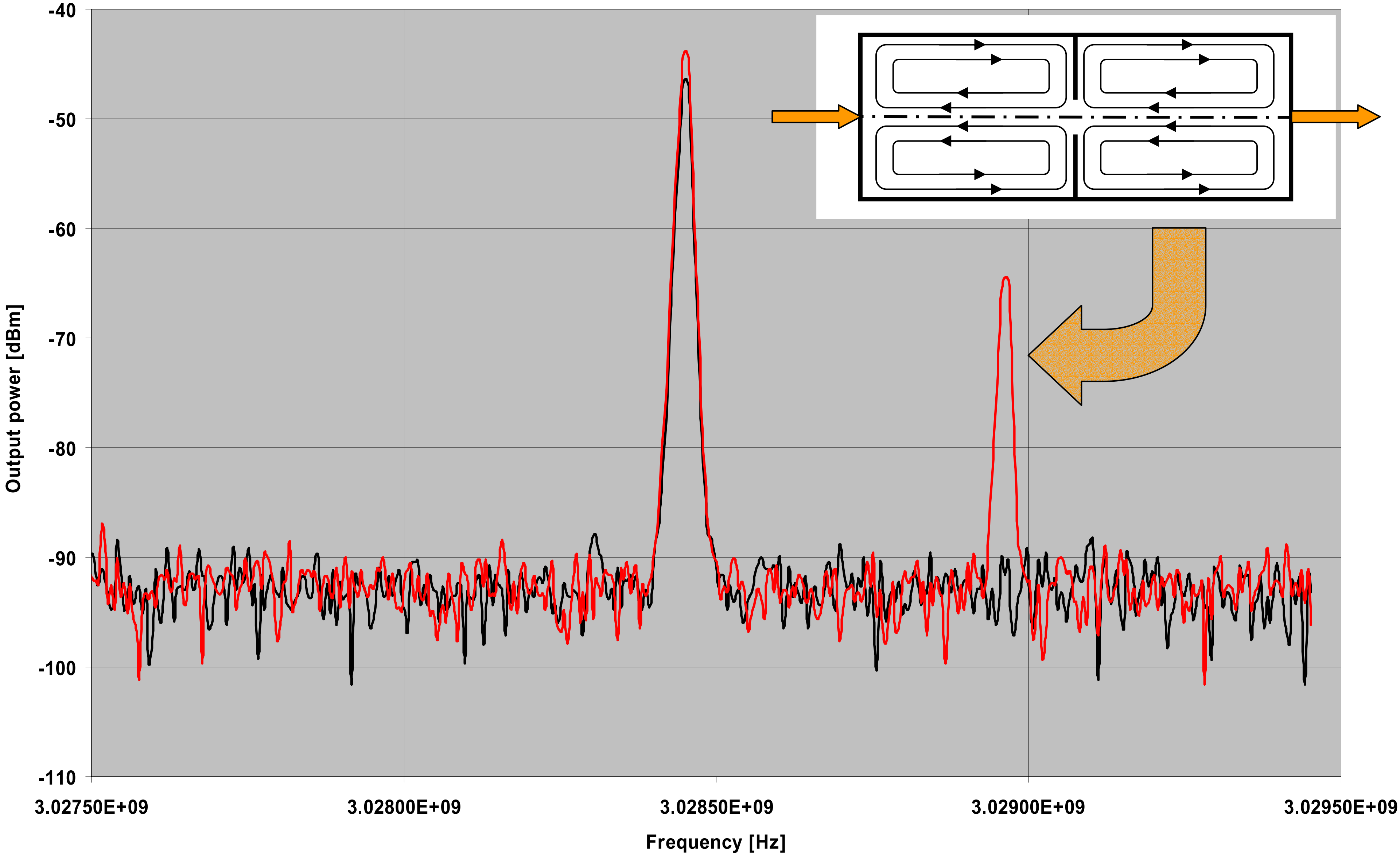

Input signal (ω_s)
Symmetric
(common) mode
Antisymmetric (differential) mode
Output signal (ω_a)



-60
-70
-80
-90
-100
-110
Output power [dBm]
3.02790E+09
3.02840E+09
3.02890E+09
3.02940E+09
Frequency [Hz]

Response to piezo excitation



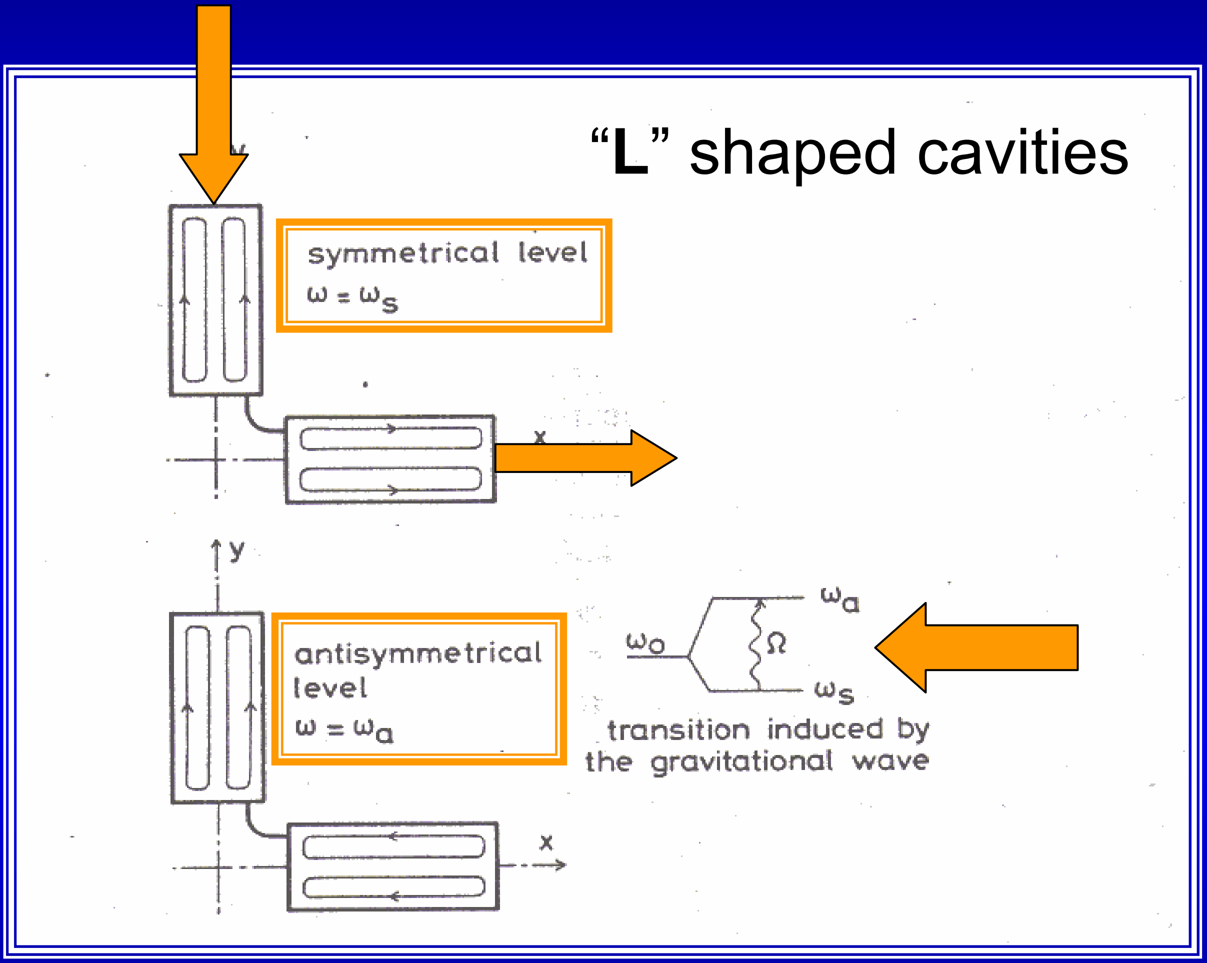

-40
-50
-60
-70
-80
-90
-100
-110
Output power [dBm]
3.02750E+09
3.02800E+09
3.02850E+09
3.02900E+09
3.02950E+09
Frequency [Hz]

PACO - 2 (2001-2003)

- Lower detection frequency (10 kHz)
- Variable coupling → tuning system
- Spherical cavities development (in collaboration with CERN)

When we take into account the quadrupolar character of the gw...

...we realize that the cavity shape has to chosen on order to maximize the energy transfer between the two resonant modes



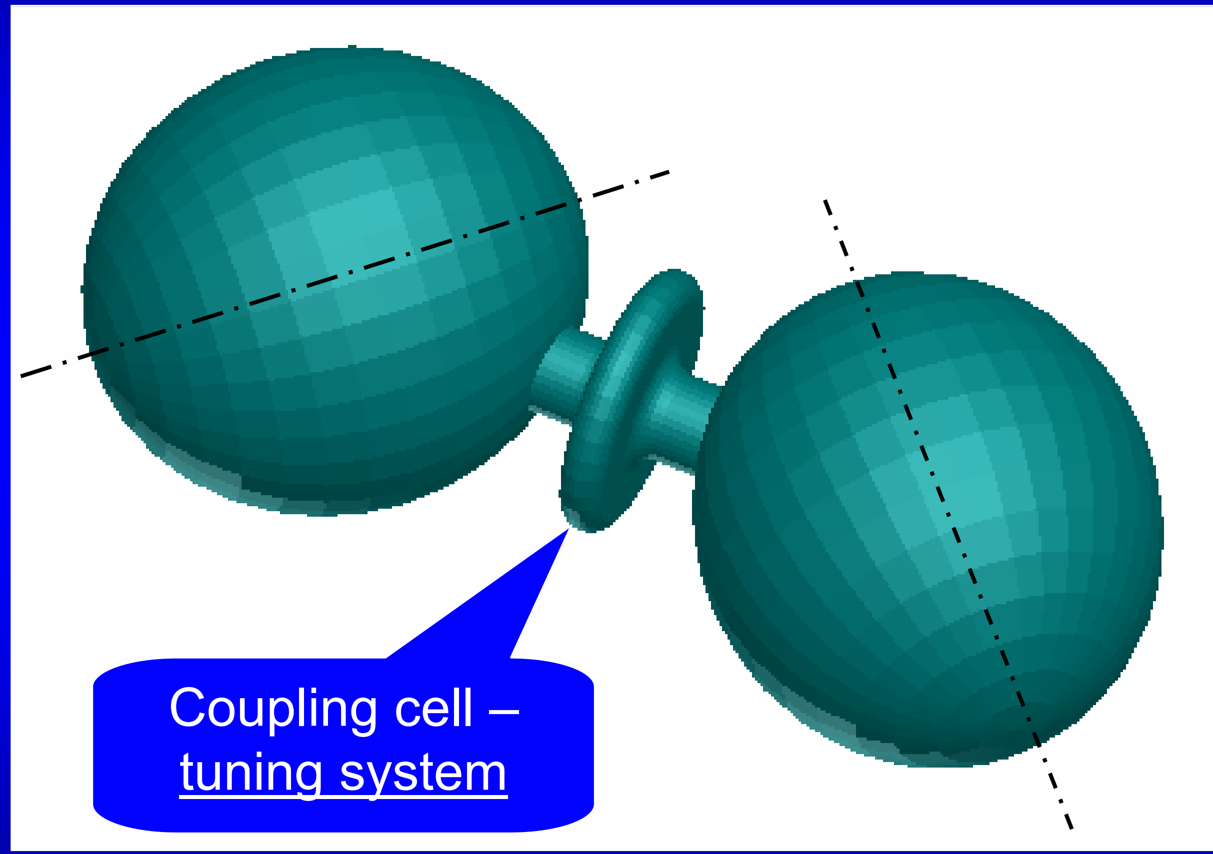
PACO-2 conceptual layout

Cavity internal radius: 100 mm

Operating rf frequency (TE_{011} mode) ≈ 2 GHz

Mode splitting ≈ 10 kHz

Stored energy ≈ 10 J

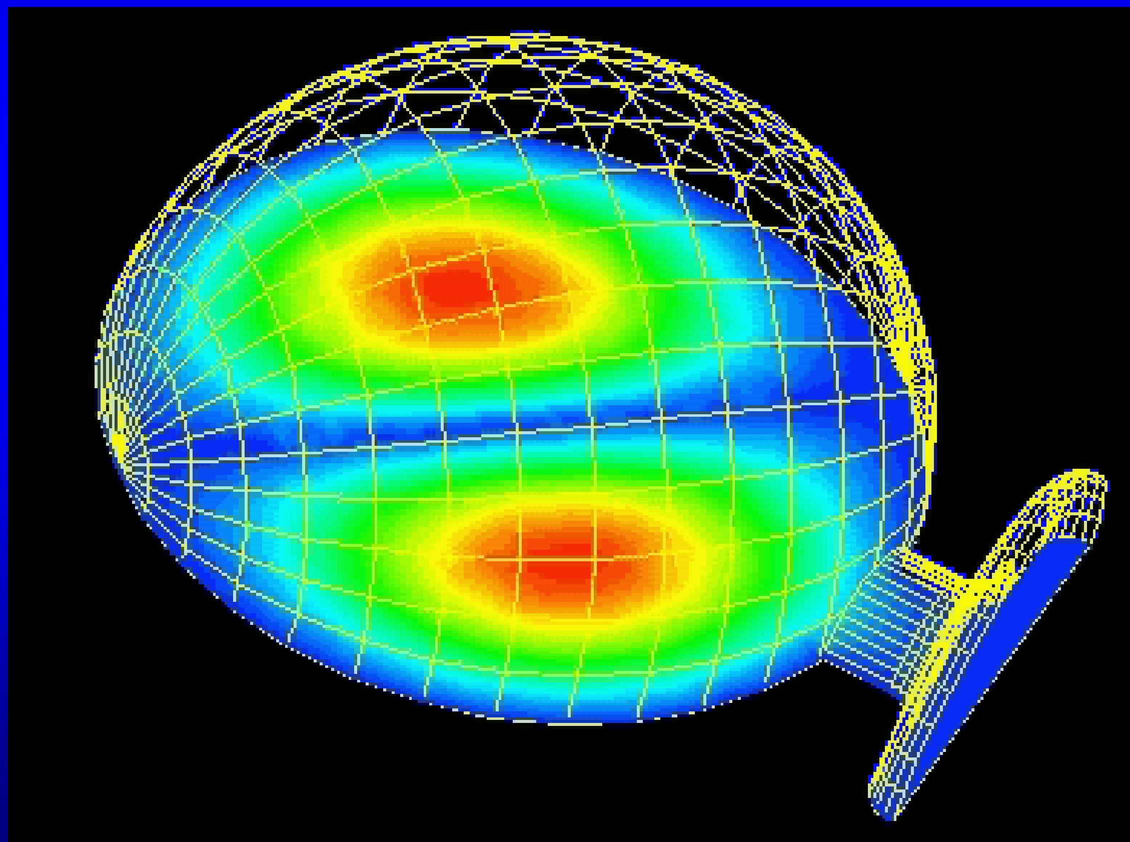


Why spherical cavities?

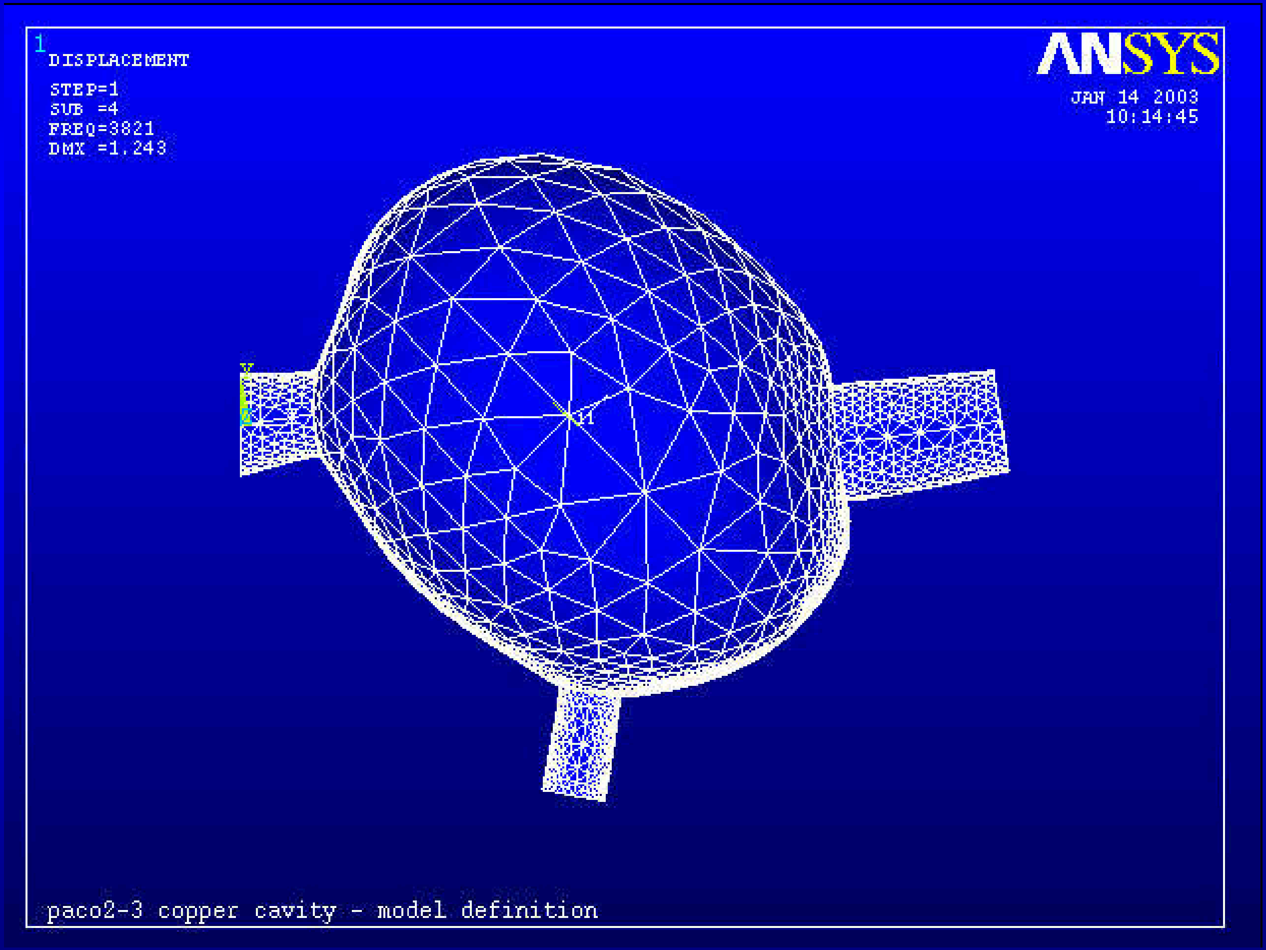
- Highest e.m. geometrical factor → **highest e.m. quality factor** for a given surface resistance (Q = G/Rs)
  - For the TE_{011} mode of a sphere G ~ 850 Ω,
  - For the TM_{010} mode of a standard elliptical accelerating cavity, G ~ 250 Ω
- Typical values of quality factor of accelerating cavities (TM modes) are in the range **10^{10} – 10^{11}**
- The quality factor of the TE_{011} mode of a spherical cavity may well exceed 10^{11}

- The spherical cell can be easily deformed in order to remove the e.m. modes degeneracy and to induce the field polarization suitable for g.w. detection
- The interaction between the stored e.m. field and the time-varying boundary conditions depends both on **how the boundary is deformed** and on **the spatial distribution of the fields** inside the resonator
- **The optimal field spatial distribution is with the field axis in the two cavities orthogonal to each other**

TE011 mode @ 2 GHz
Electric field magnitude



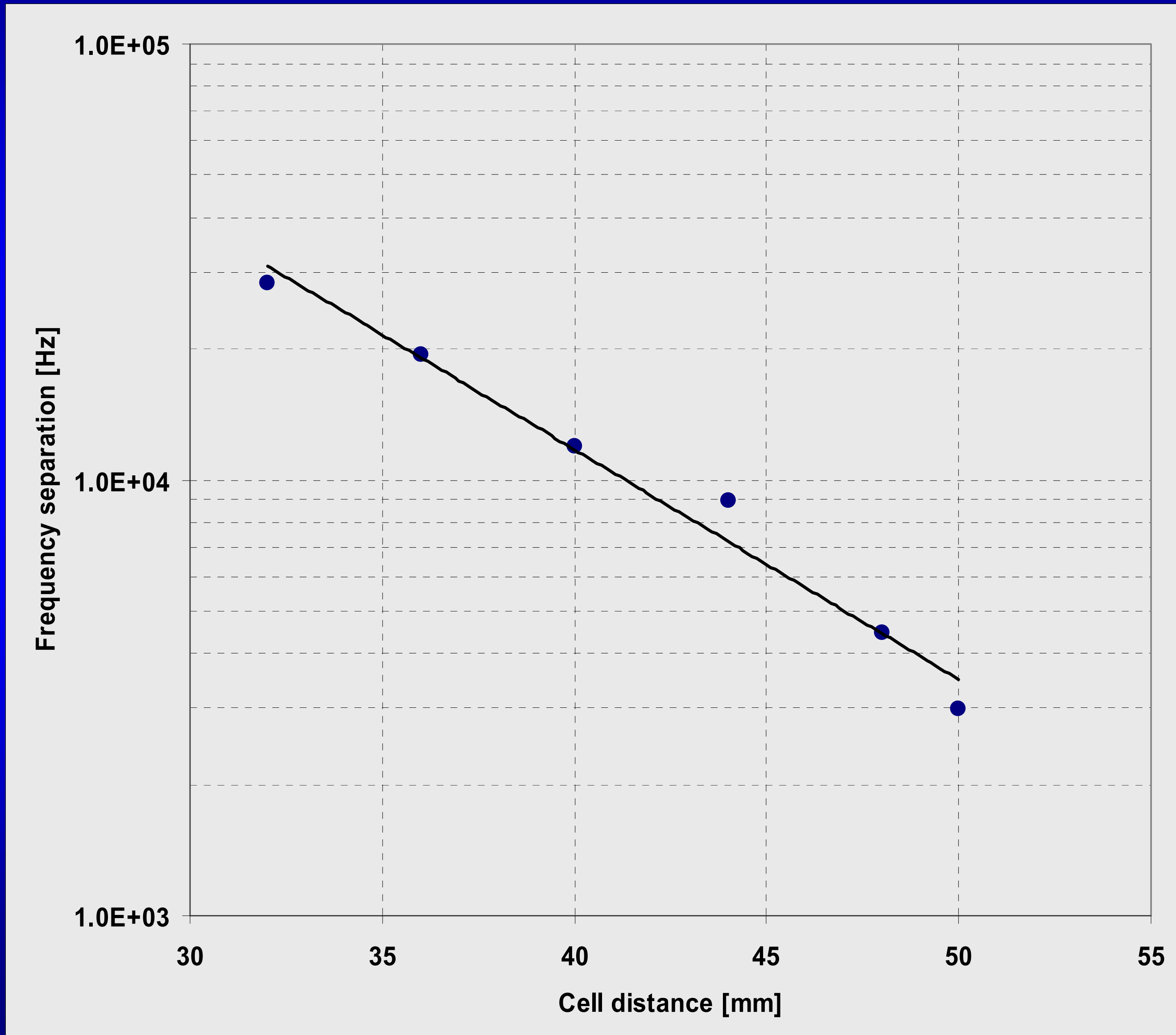
Quadrupolar mode @ 4 kHz



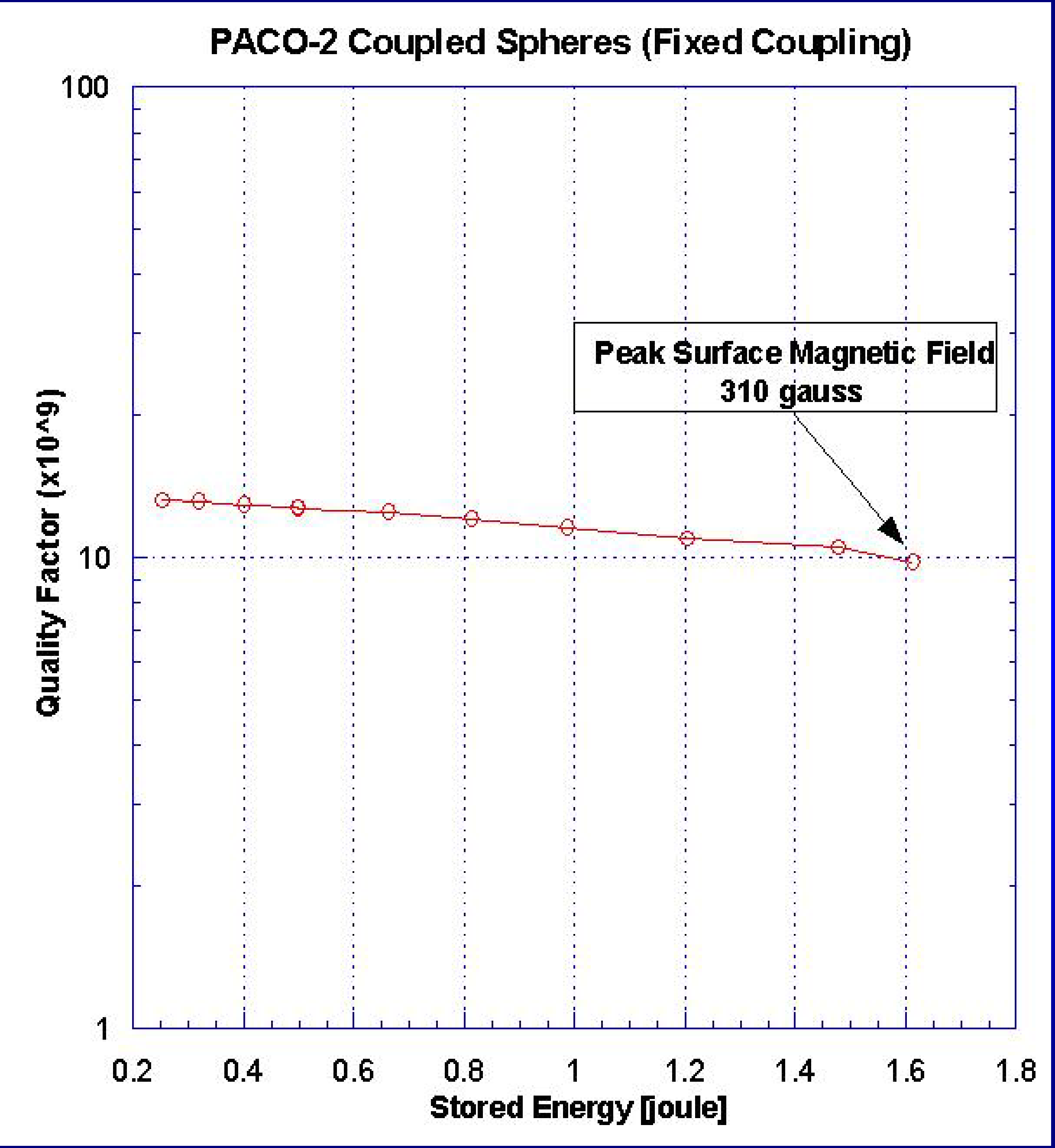

Tuning cell


Tuning system

Mode splitting vs. coupling cell length



Niobium cavity built and tested at CERN

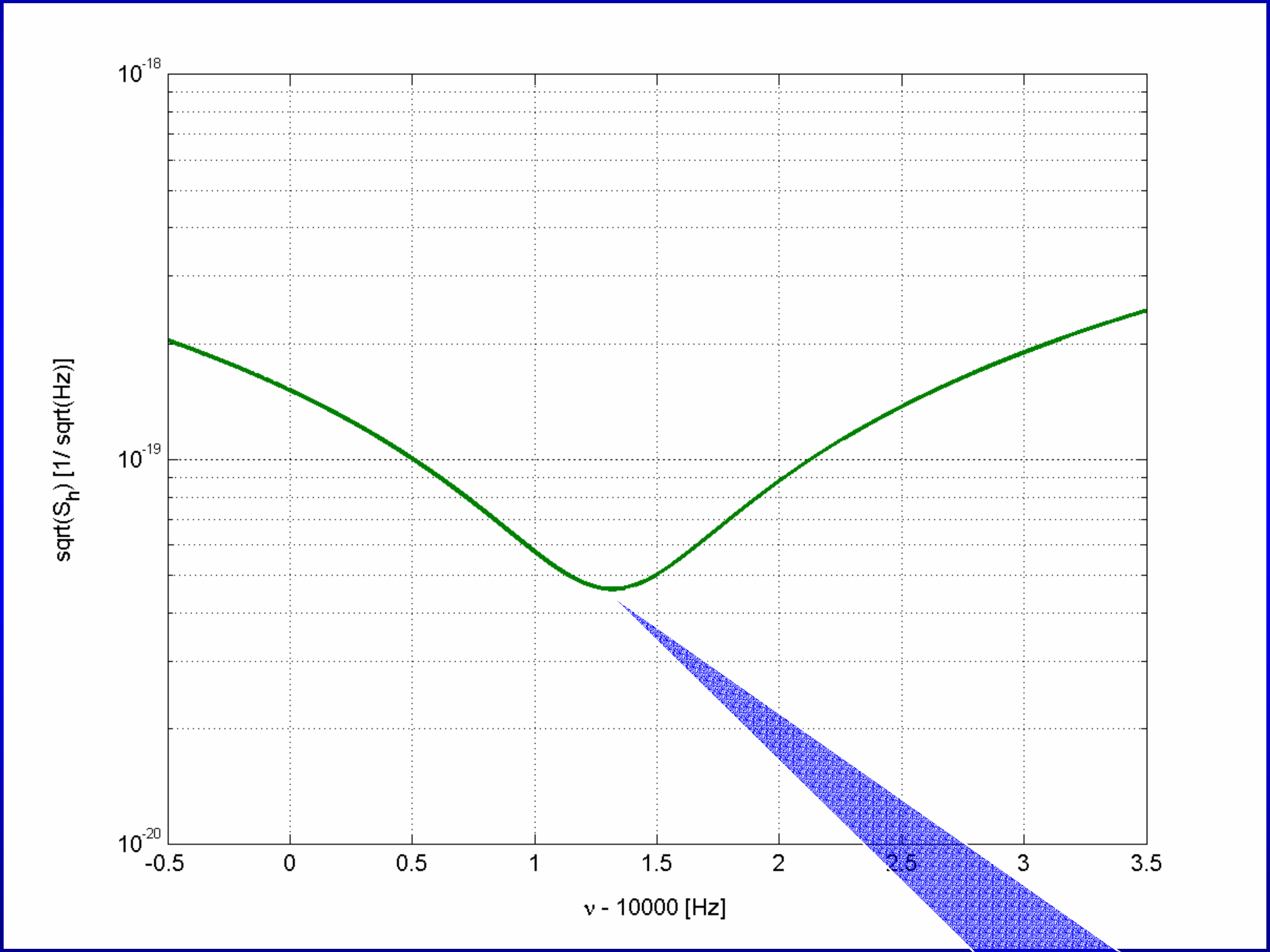


Electromagnetic test of the niobium cavity

Tunable cavity at CERN

(Jan, 31th 2003)

Expected sensitivity



Detection frequency (mode splitting) = 10 kHz

Mechanical resonant frequency = 4 kHz

U_1 = 10 J

$Q = 10^{10}$

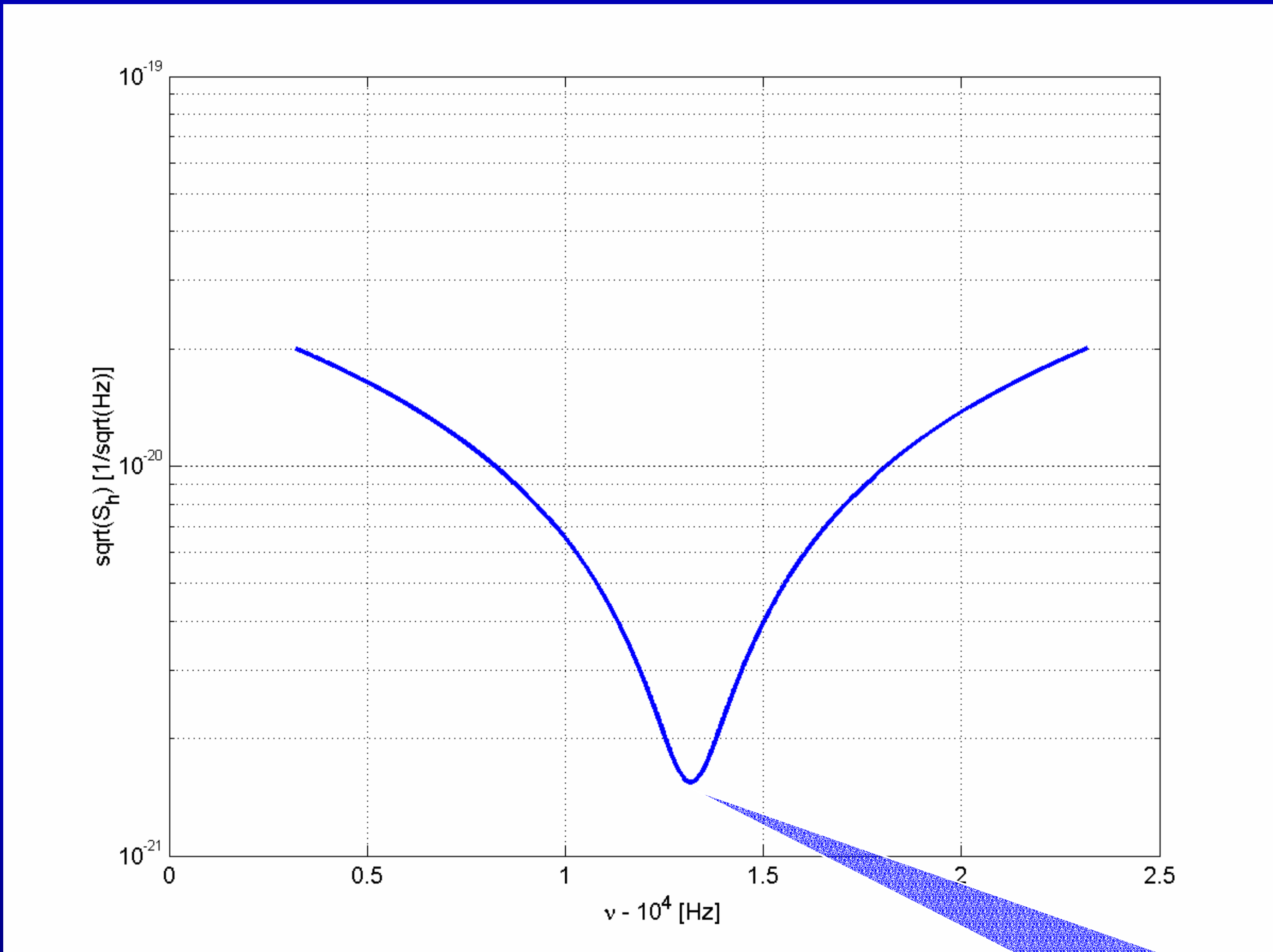
$Q_m = 10^3$

T = 1.8 K

T_n = 30 K

$(S_h)^{1/2} \approx 4 \times 10^{-20}\ (\mathrm{Hz})^{-1/2}$

Expected sensitivity



Detection frequency (mode splitting) = 10 kHz

Mechanical resonant frequency = 4 kHz

U_1 **= 10 J**

Q **=** 10^{10}

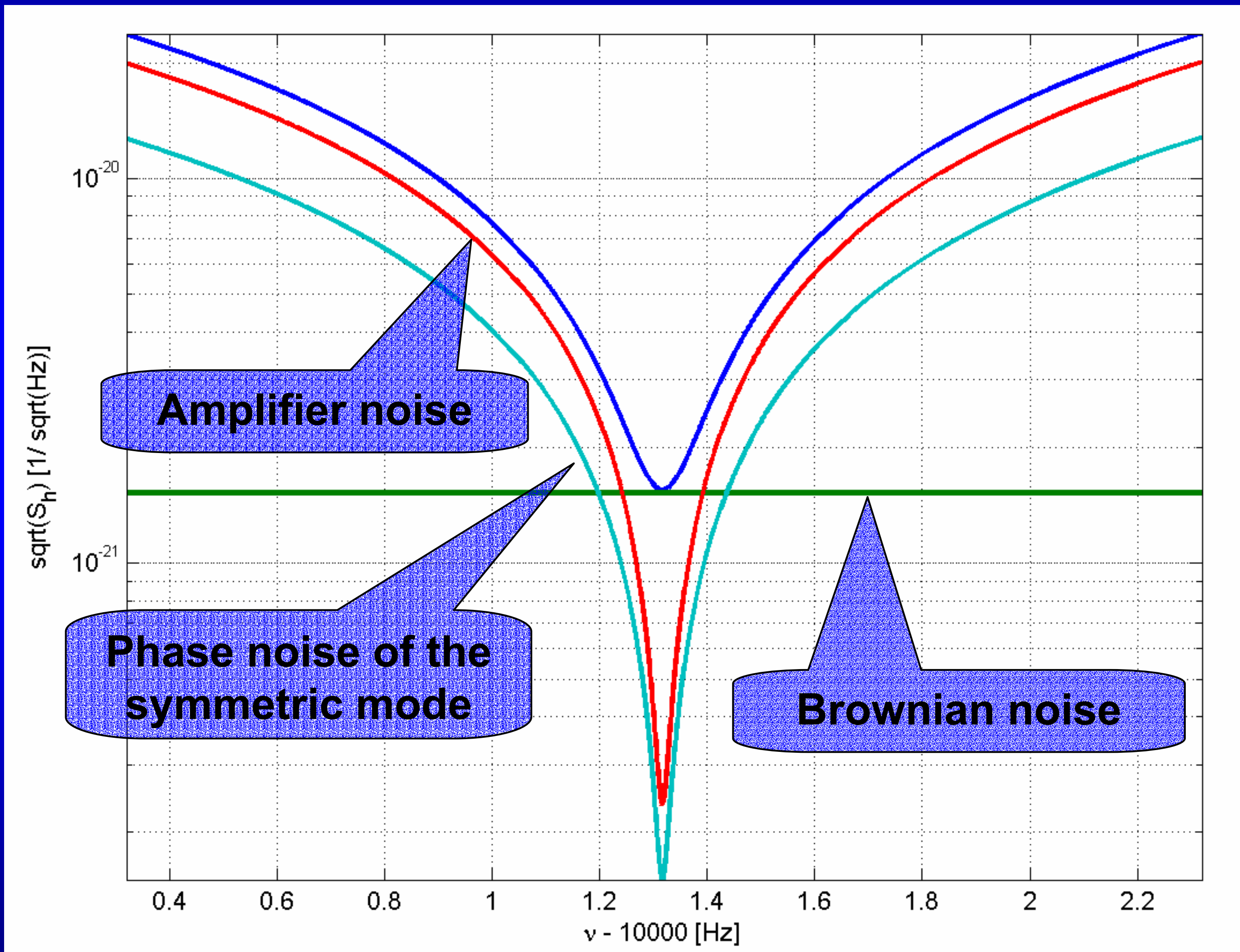
$Q_m = 10^6$

T **= 1.8 K**

T_n **= 1 K**

$(S_h)^{1/2} \approx 2 \times 10^{-21}\ (\text{Hz})^{-1/2}$

Expected sensitivity



Detection frequency (mode splitting) = 10 kHz

Mechanical resonant frequency = 4 kHz

U_1 **= 10 J**

Q **=** 10^{10}

Q_m **=** 10^6

T **= 1.8 K**

T_n **= 1 K**

Conclusions

- Design and realization of an experiment based on the two existing cavities:
    - $\omega \approx 2$ GHz
    - **detection frequency ≈ 10 kHz (tunable between 7 - 20 kHz)**
    - $(S_h)^{1/2} \approx 10^{-21} - 10^{-20}$
  - – Design of the cryogenic system;
  - – Design of the suspension system;
  - – Low noise electronics;
  - – Data analysis
- Timescale: four years (2004-2007)