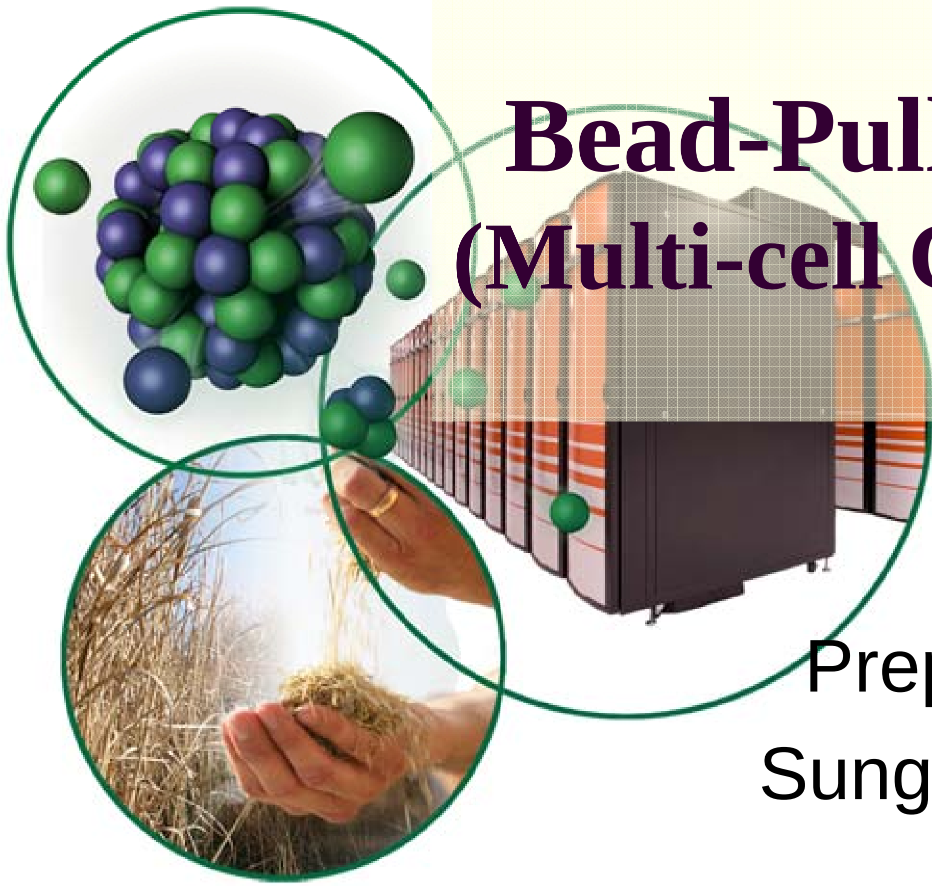

Bead-Pulling Measurement (Multi-cell Cavity Field Flatness)

Prepared by
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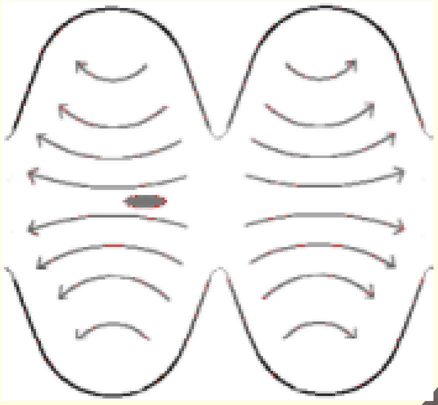
Outline

- Introduction
- Bead-Pulling Measurement
- Perturbation Theory
- Methods
- Tuning Mechanism
- Examples
- Conclusion

Introduction

- Accelerating mode of multi-cell cavities is π-mode.
- Cells operate at same frequency with out-of-phase from neighboring cell.
- Frequency deviation of each cell must be quantified.
- Mechanical tuning required.

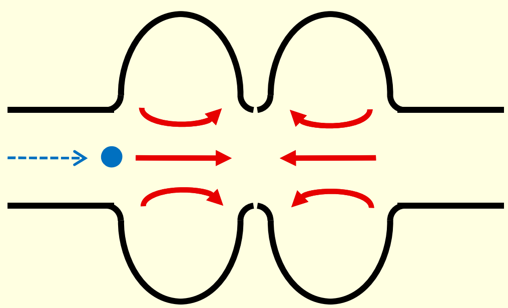


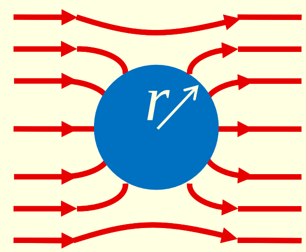
Bead-Pulling Measurement

- In manufacturing or tuning multi-cell cavities it is required to investigate the field profile inside cavities.
- The field can be “sampled” by introducing a perturbing object and measuring the change in resonant frequency.
- The object must be so small that the field do not vary significantly over its largest linear dimension: it is a perturbation method.
- Phase deviation is much easier to observe than frequency change especially for small perturbation.

Perturbation Theory

- Finding approximate solution starting from the exact solution adding “small” deviation.

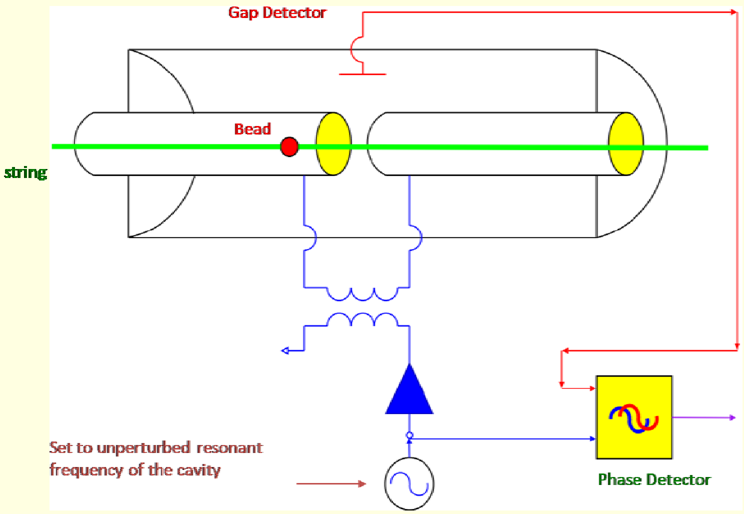


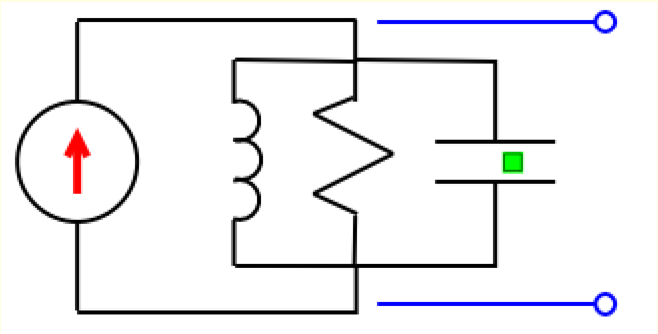


- Change of the field profile by very small bead (stored energy change) produces the frequency deviation.

$$\frac{\Delta\omega}{\omega_0} = \frac{\Delta U}{U} = -\frac{\pi r^3}{U}\left[\varepsilon_0\left(\frac{\varepsilon_r - 1}{\varepsilon_r + 2}\right)E_0^{\ 2} + \mu_0\left(\frac{\mu_r - 1}{\mu_r + 2}\right)H_0^{\ 2}\right]$$

Bead Pull Setup





$$\frac{\Delta\omega}{\omega_o} = \frac{\Delta U_E - \Delta U_H}{U}$$

$$F = \pi a^3 \varepsilon_o \left(\frac{\varepsilon_r - 1}{\varepsilon_r + 2} \right) \rightarrow \pi a^3 \varepsilon_o$$

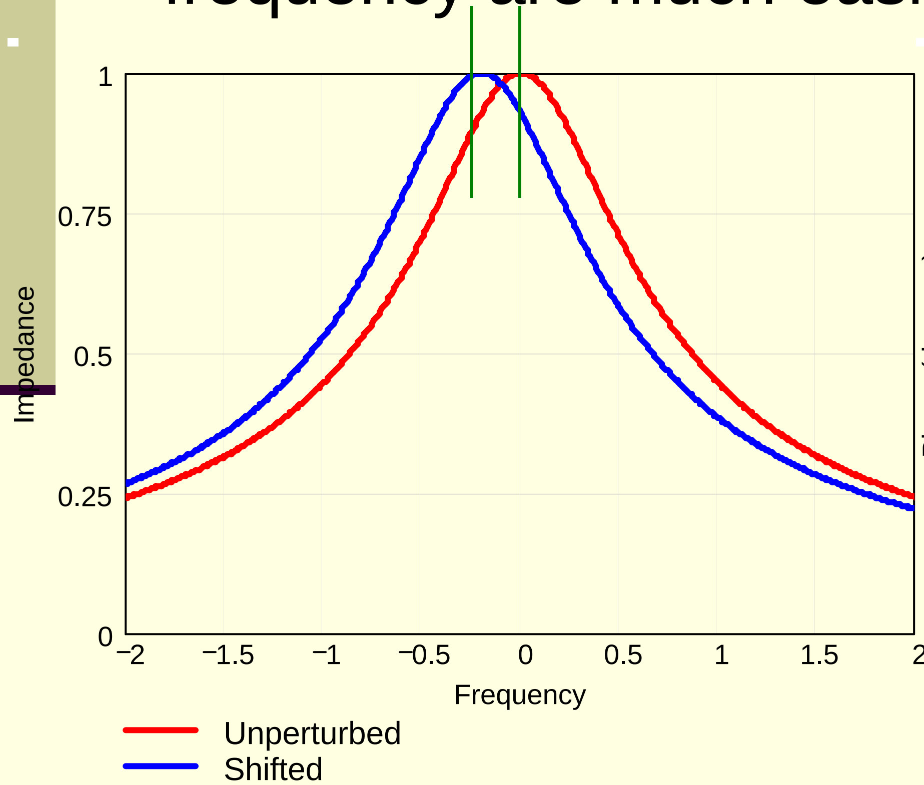
The shape of the bead will distort the field in the vicinity of the bead so a geometrical form factor must be used.

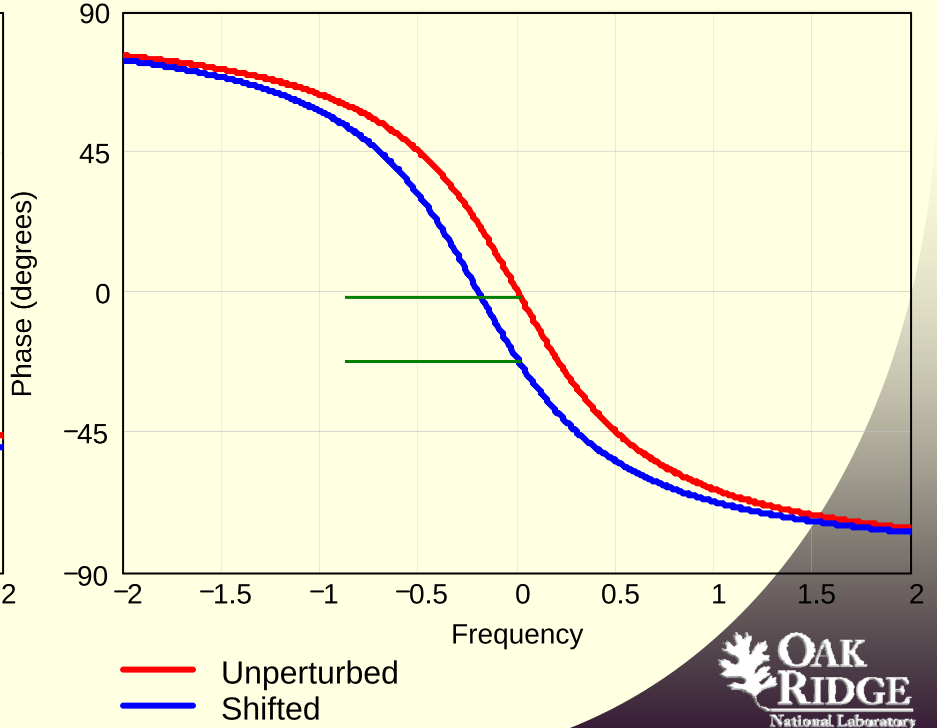
Due to the H field is zero on the axis of the cavity where the small bead moving,

$$\frac{\Delta\omega}{\omega_o} = -\frac{\pi a^3}{U}\left[\varepsilon_o E_b^{\ 2} + \frac{\mu_o}{2} H_b^{\ 2} \right]$$

Bead Pulls

- For small perturbations, shifts in the peak of the cavity response is hard to measure.
- Shifts in the phase at the unperturbed resonant frequency are much easier to measure.





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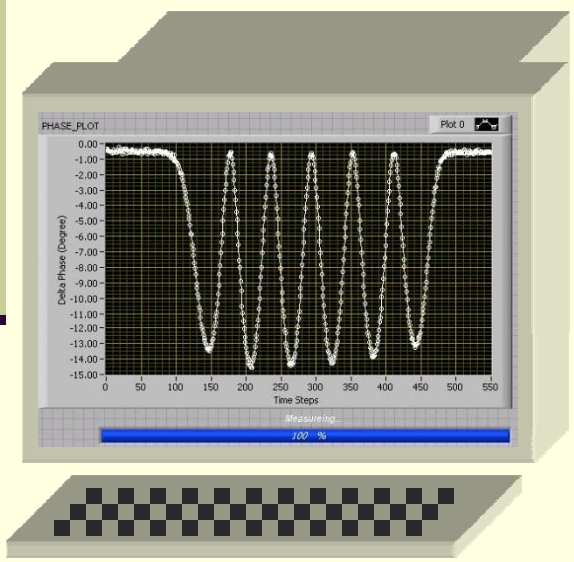
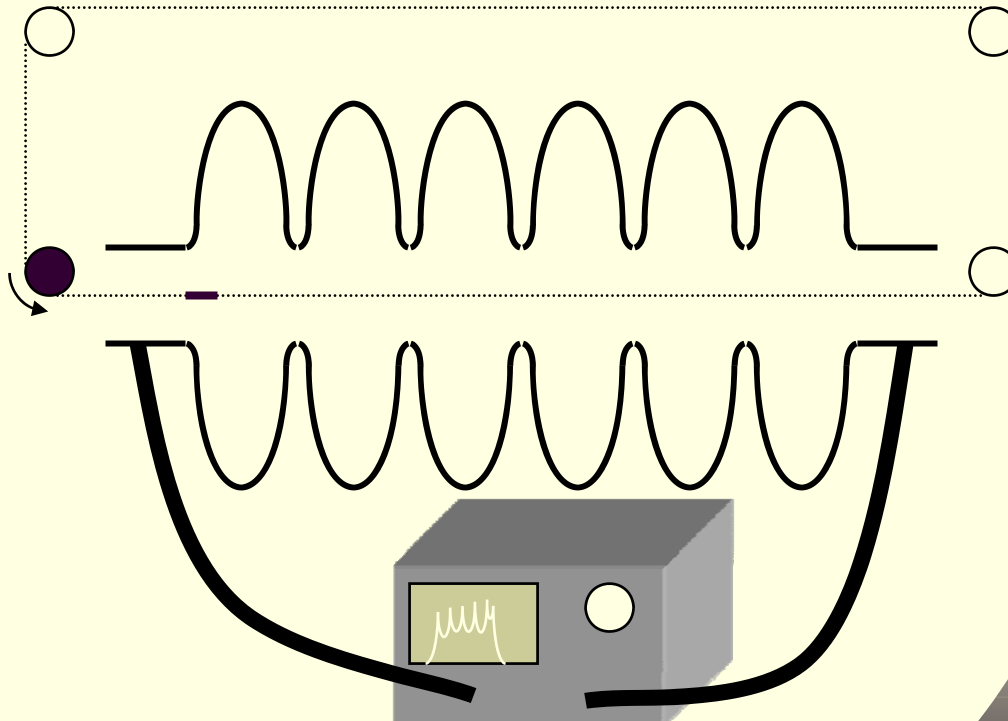
Measurement Setup

- Bead pull setup for phase shift measurement





S21=~-44.5dB

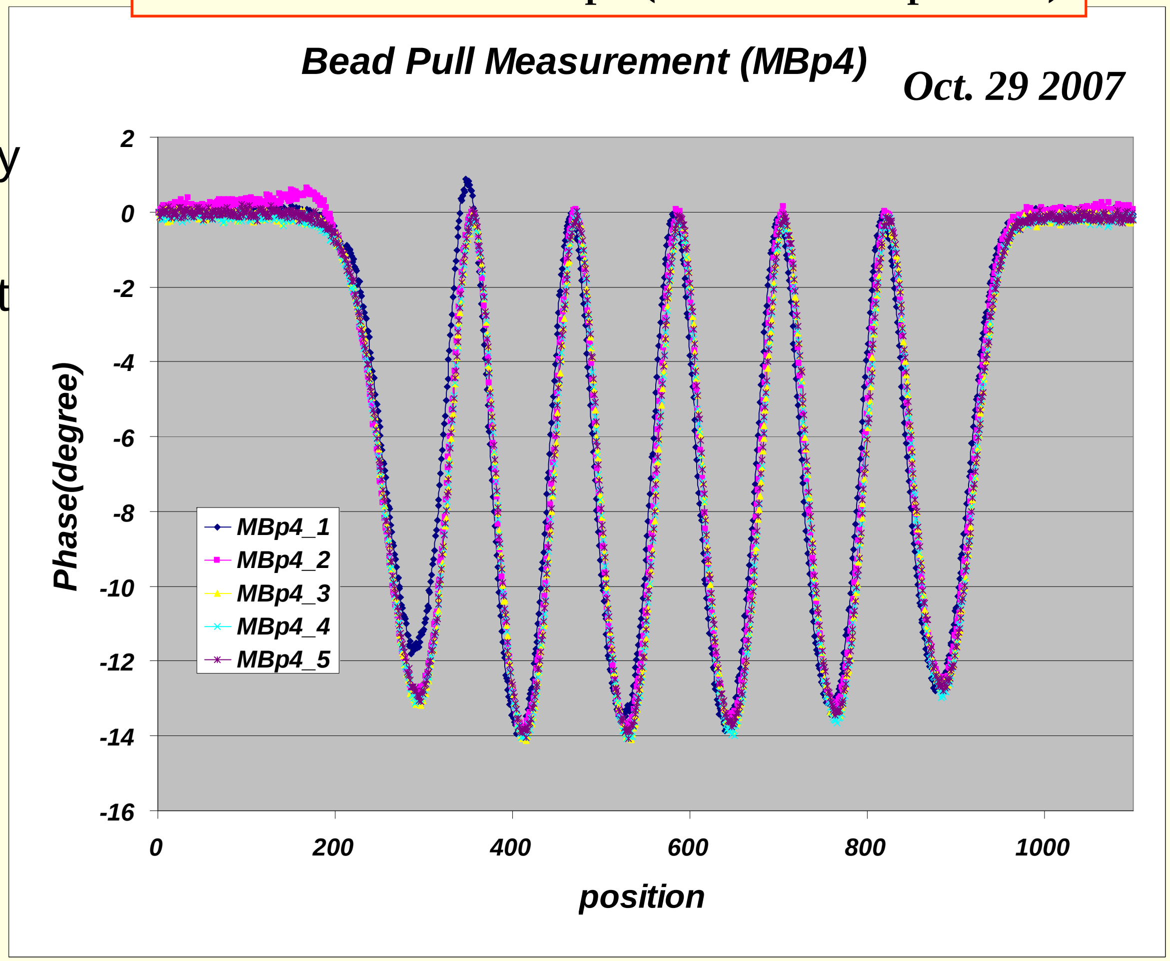
Phase Measurement Result (5 measurements)

- Procedure
  1. Pick and set the desired mode (π) as CW frequency
  2. Calculated Q factor
  3. Start bead pulling motor at constant speed
  4. Sample phase data and record
  5. Translate phase into frequency shift

$$\frac{f_p - f_0}{f_0} = \frac{\tan\phi(f_0)}{2Q}$$

(f_p: perturbed frequency)

Measurement on MB_P4 (5 times: $MB_P4\_1\sim5$)

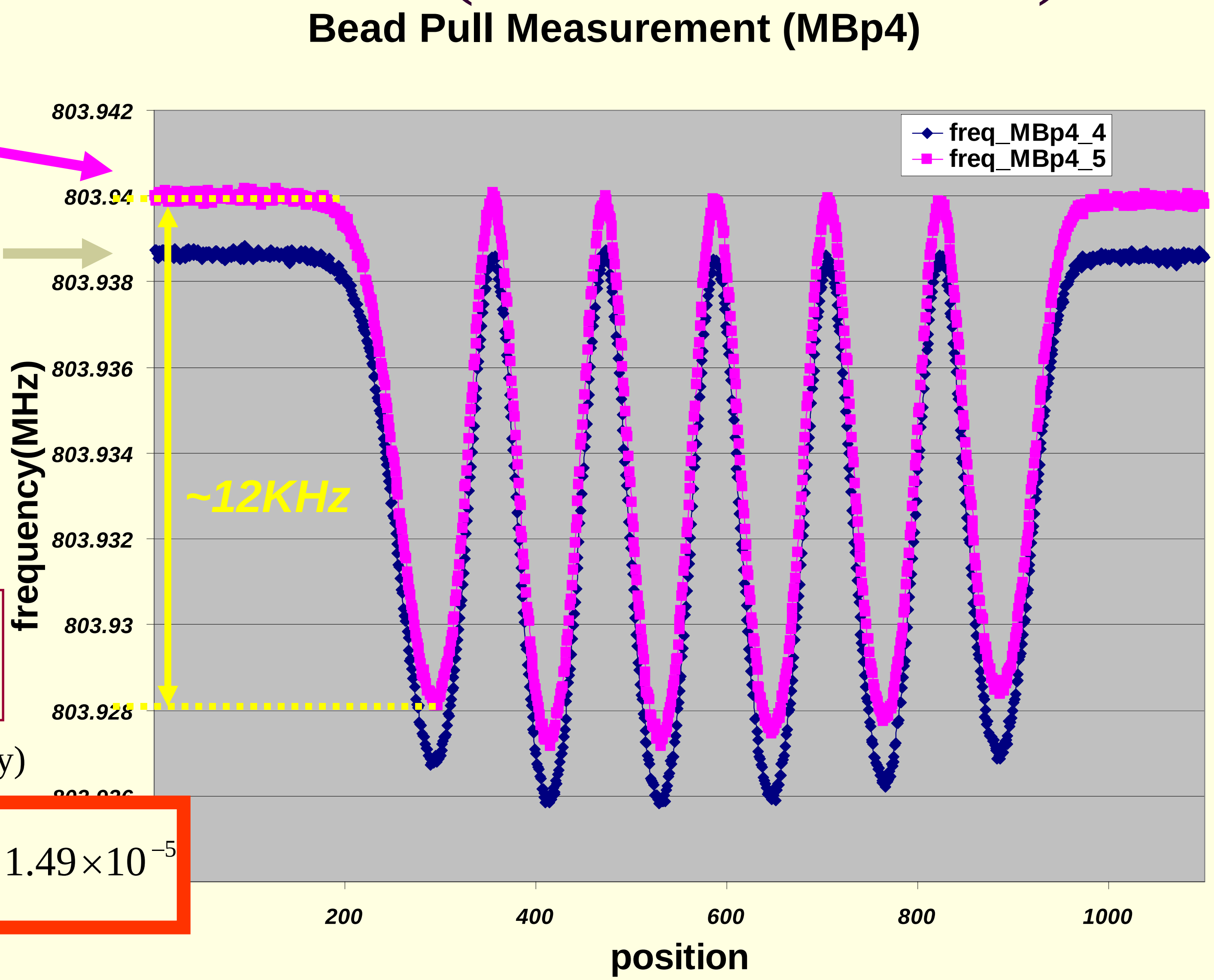


Frequency Shift data

(2 measurements)

f_0=803.94MHz
Q=7845

03.93875MHz
795

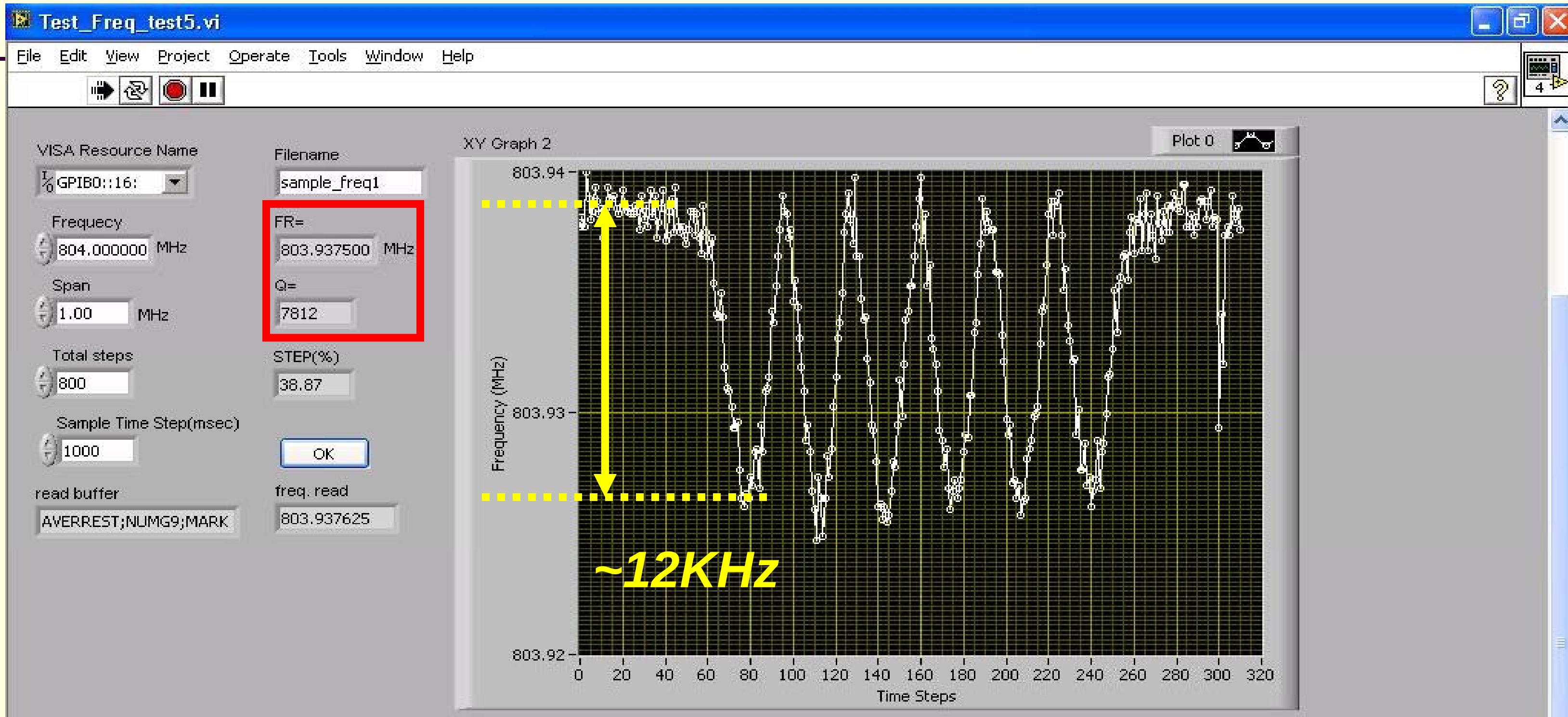


$$\frac{f_p - f_0}{f_0} = \frac{\tan\phi(f_0)}{2Q}$$

(f_p: perturbed frequency)

$$\frac{f_p - f_0}{f_0} = \frac{-0.012}{803.94} = 1.49\times10^{-5}$$

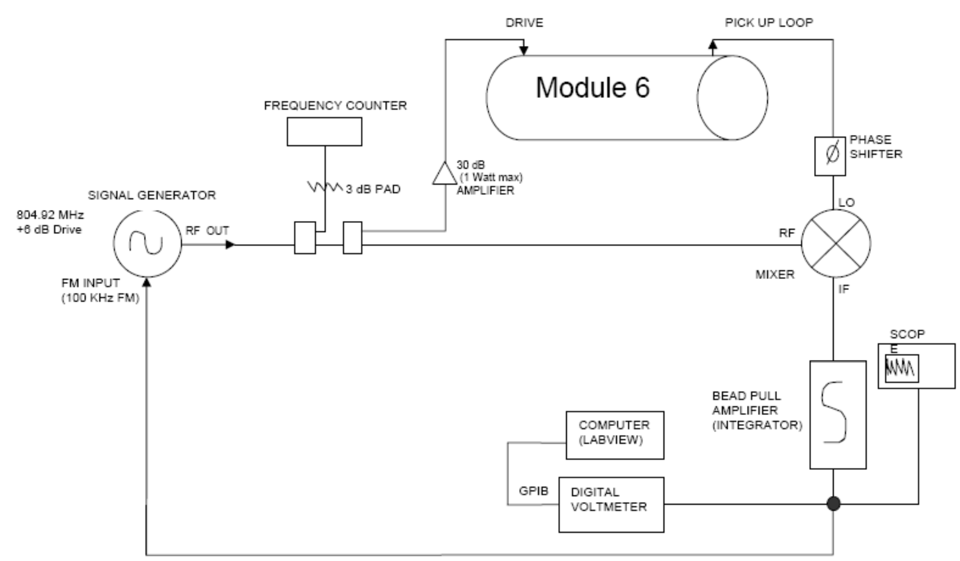
Direct Frequency Measurement

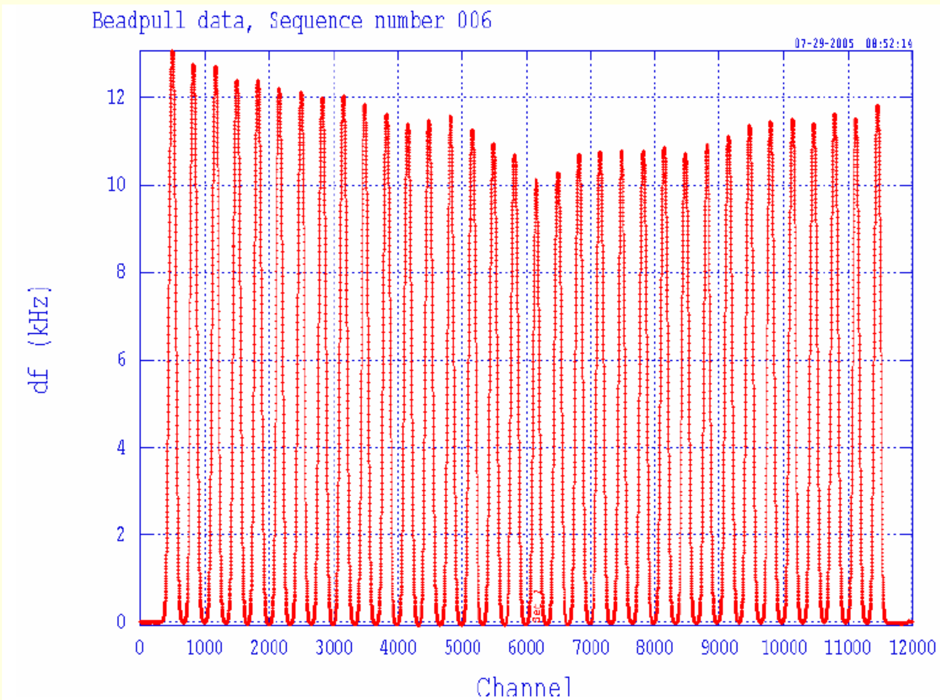


It is difficult to get frequency shift data directly from frequency sweeping mode in Vector Network Analyzer (VNA) for very small perturbation. Phase locking (PLL-VCO) is required to track the frequency deviation at π-mode.

Direct Frequency Measurement (using PLL system)

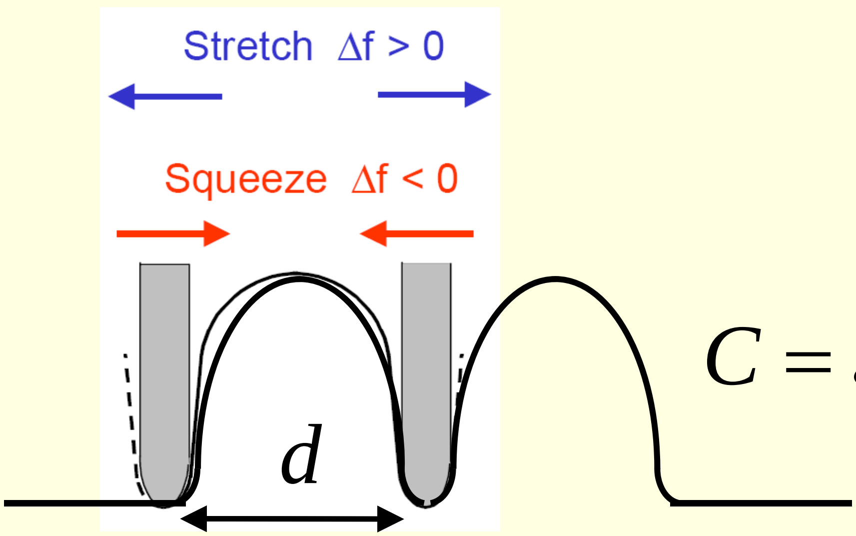
Phase Lock Loop



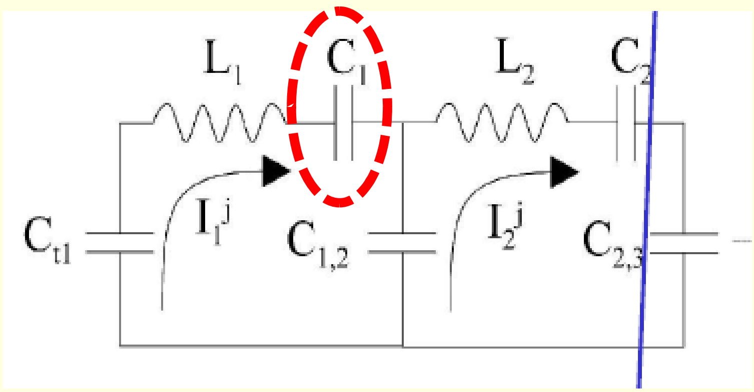


Multi-cell Cavity Tuning

- Individual cell tuning



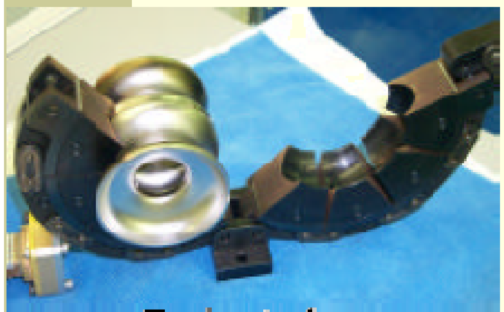
$$C = \varepsilon \frac{A}{d}$$



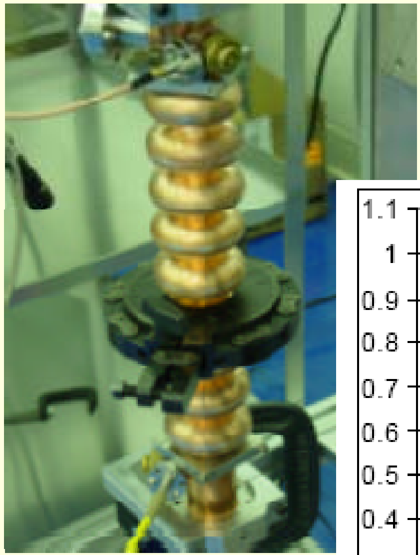
$$f \propto \frac{1}{\sqrt{C}}$$

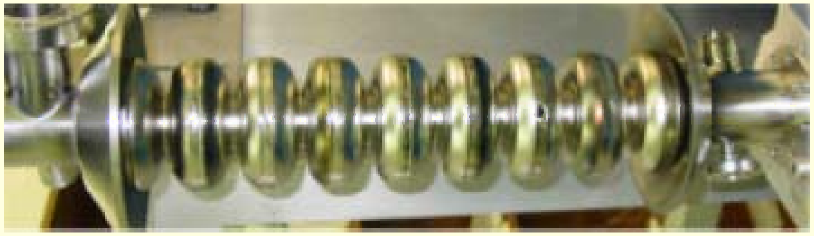
Manual Tuning Example

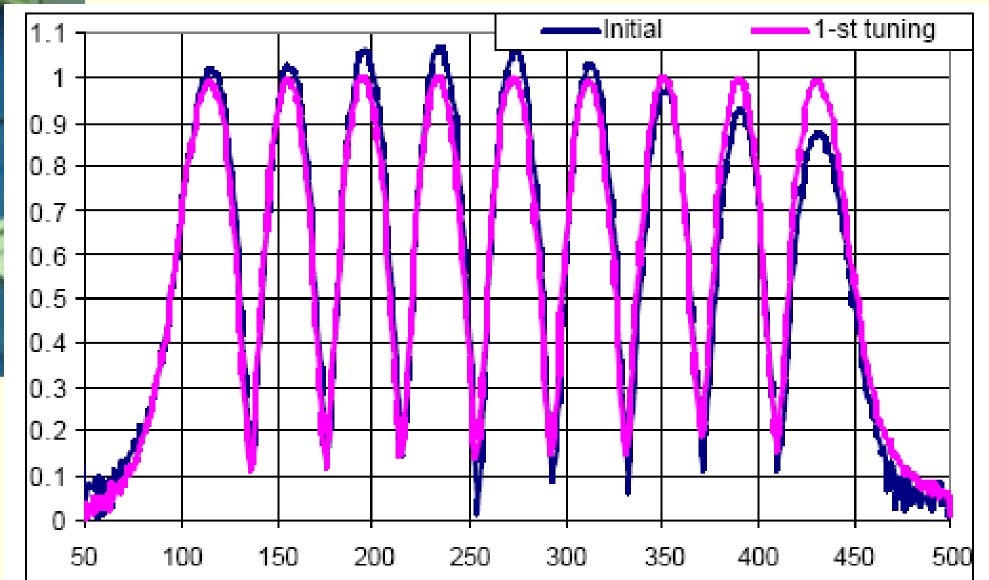
- Individual cell manual tuning (FermiLab)



Tuning tools.

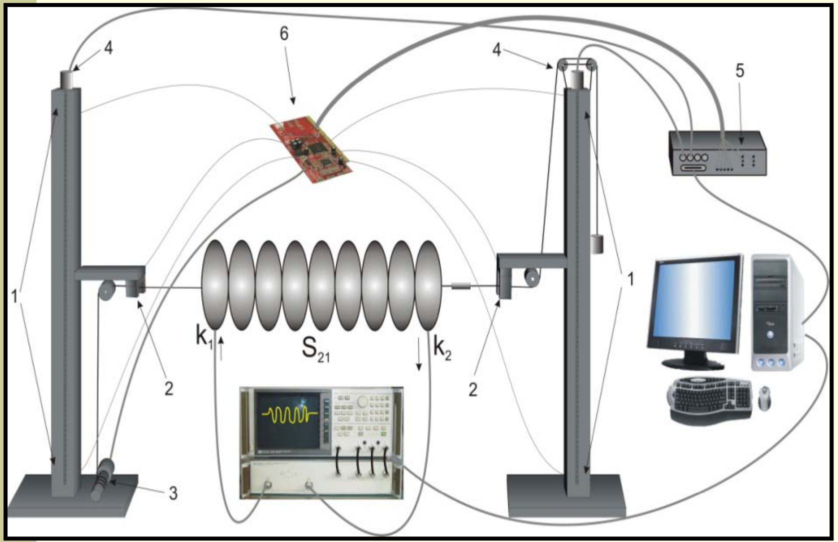




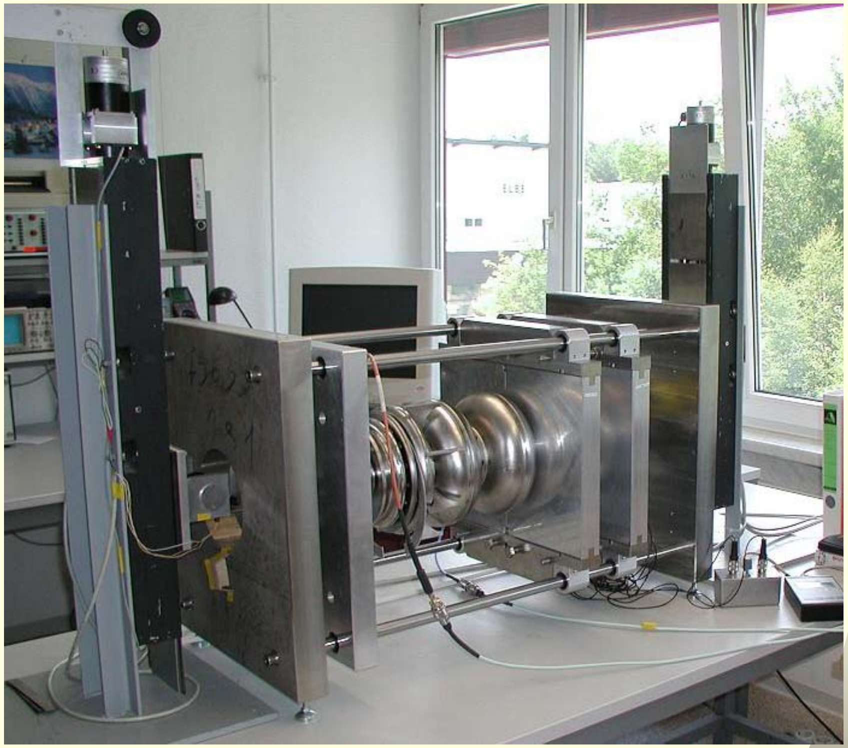


Cu01 cavity field flatness and frequency tuning.

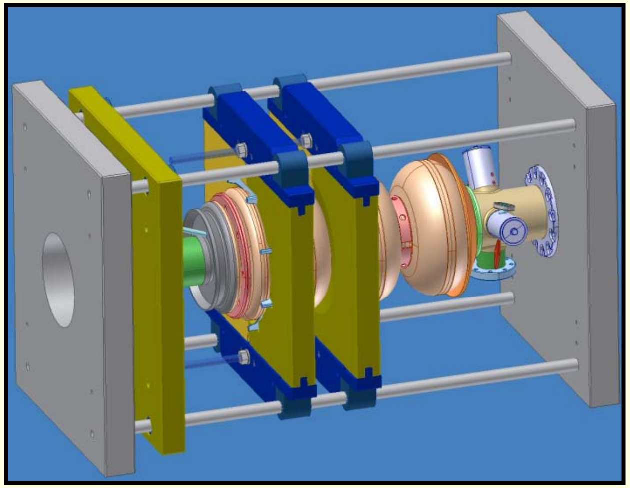
Automatic Tuning Example I (Bead-pull setup integrated)



PC-controlled bead pull measuring device



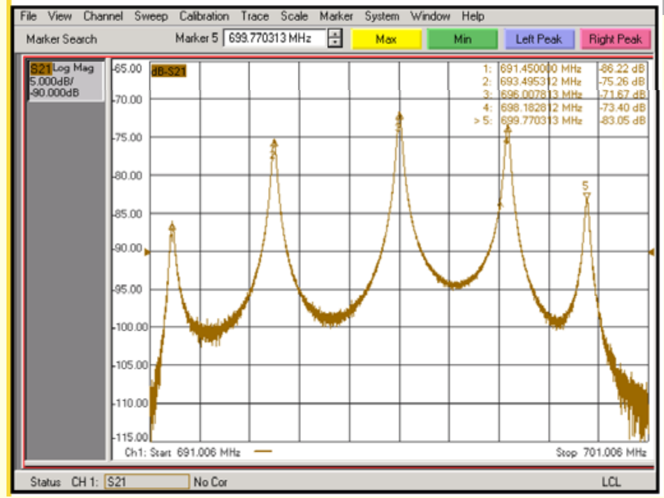
Photograph of the cavity tuning machine with integrated bead pull measuring device.

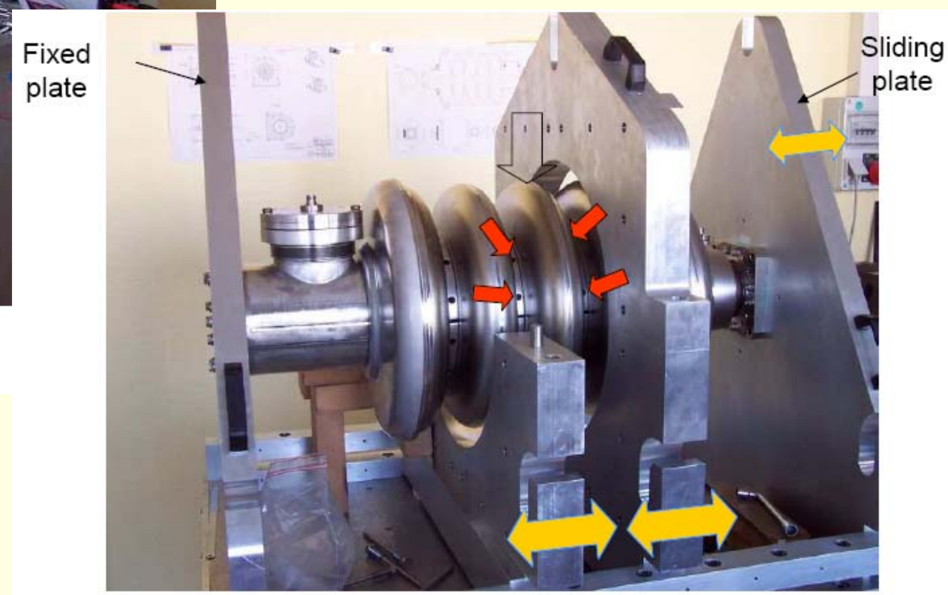


3D-CAD-Model of the tuning machine Used to push and pull each cell to the right frequencies.

Automatic Tuning Example II (Bead-pull setup integrated)

Cavity installed on the tuning bench





Conclusion

- Multi-cell(N) accelerating cavities have N degenerated modes. (π–mode is desired)
- The modes split when the coupling (k) increases and/or N deceases.
- Each cell has its own resonant frequency. (need to be tuned)
- Frequency deviation can be monitored by bead-pulling based on perturbation theory.
- Phase measurement can be effectively used under small perturbation.
- Frequency correction can be done by mechanical tuning(squeezing/extending) procedure.