Tuning of multi-cell Super-Conducting Radio Frequency Cavities

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Outline

- What is tuning?
- Why multi-cell cavity needs tuning?
- Factors causing a multi-cell cavity to de-tune.
- Estimation of multi-cell cavity tuning parameters.
- Basics of tuning methodology
- Types of tuners
- Structural analysis for estimation of tuning forces
- Tuning results

What is tuning?

Tuning of multi-cell

Super-Conducting Radio Frequency Cavities

Analog Radio

Frequency Indicator

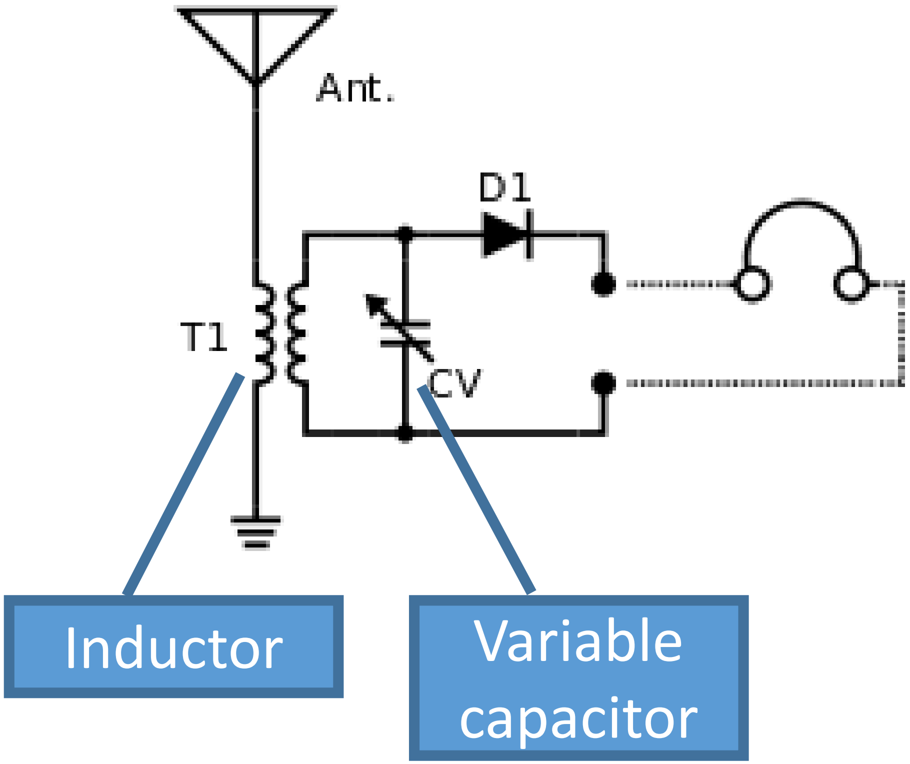
Frequency Scale

Frequency Tuner Knob

Volume Knob

Band Selector Knob

Basic Radio Tuning Circuit



- A simple tuner consists of an inductor and capacitor connected in parallel.
- The capacitor or inductor is made to be variable.

Resonant Frequency

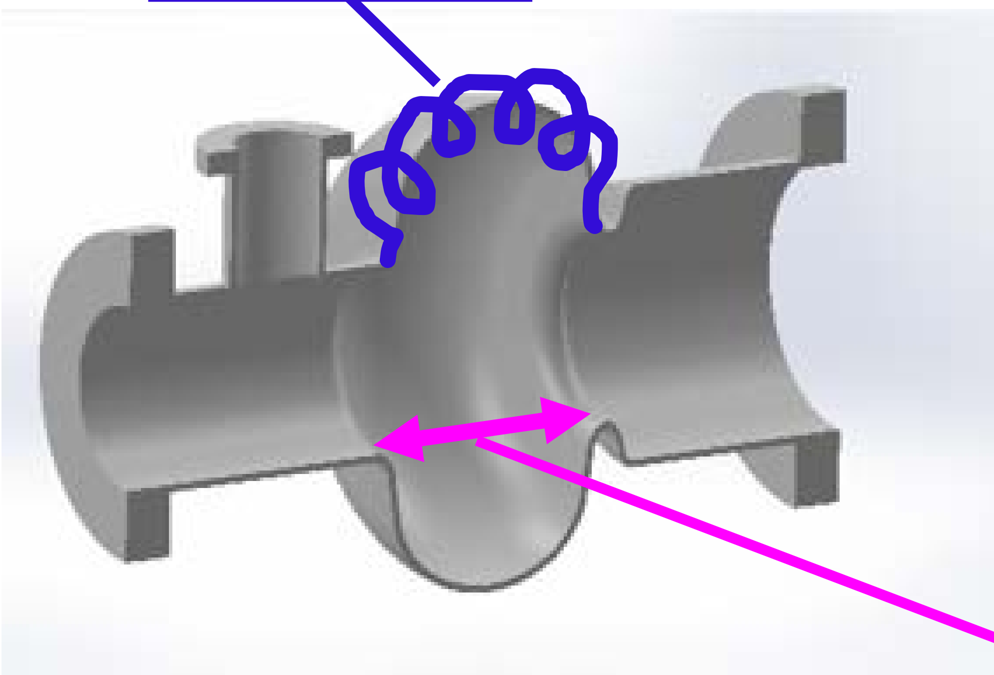
$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

- When the frequency of LC circuit matches with the radio station frequency resonance takes place and the station is said to be tuned

So, LC circuit can be made resonant by varying inductance / capacitance

Analogy of LC Circuit with SCRF Cavity

L - Inductor



Single Cell SCRF Cavity

C – Capacitor (Cell Length)

Resonant Frequency

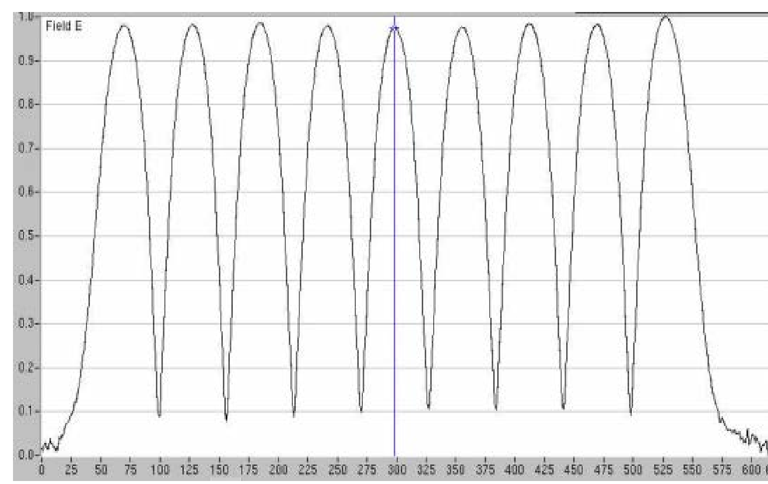
$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

Multi-cell SCRF Cavity ---- Requirement

For efficient acceleration of charged particles

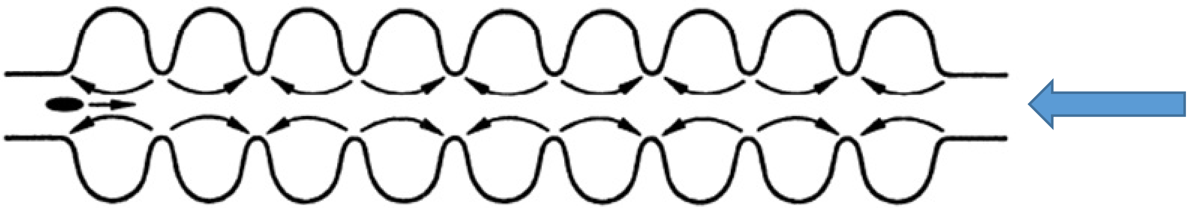
- Cavity frequency should be equal to the design frequency
  - o **To get a resonating condition**
  - o **To maximizes the power transmission**

- Equal electric fields in all cells
  - o **Minimizes peak surface electromagnetic fields**
  - o **Maximizes net accelerating voltage**



Why a multi-cell cavity needs tuning?

- A multi-cell cavity is made by joining multiple cells
  - o It is a structure with multiple resonators (cells) coupled together.
  - o For a set of coupled oscillators, there are multiple modes of excitation



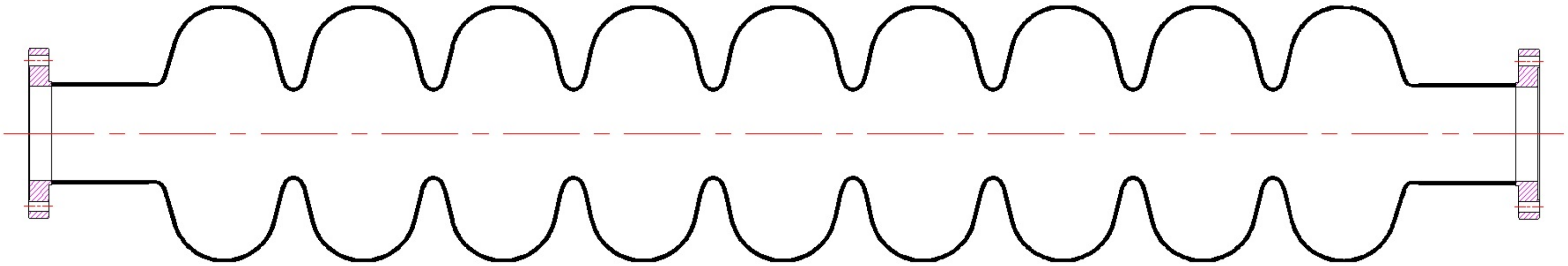
Multi-cell SCRF cavity

- Each cell is made by joining two half cells
- Due to fabrication errors, each cell has different frequency

So, in a fabricated multi-cell cavity, all cells would have

- ➢ **Different electric field levels and**
- ➢ **Different frequencies**

Possible Fabrication Errors



Ideal multi-cell SCRF cavity

Possible Fabrication Errors

A. Profile Error

Introduced during forming due to

- Improper design / fabrication of die & punch
- Anisotropy in material

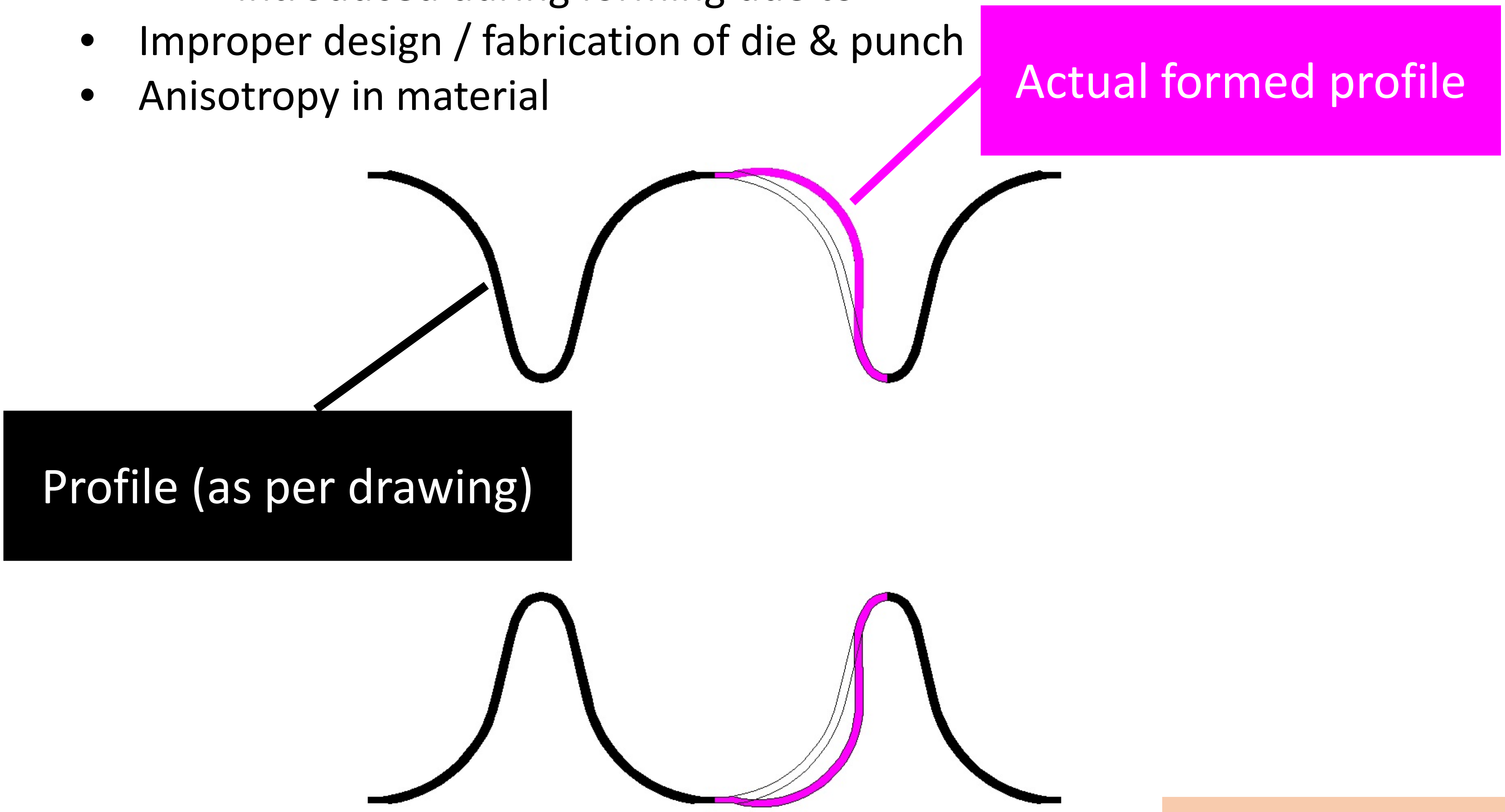
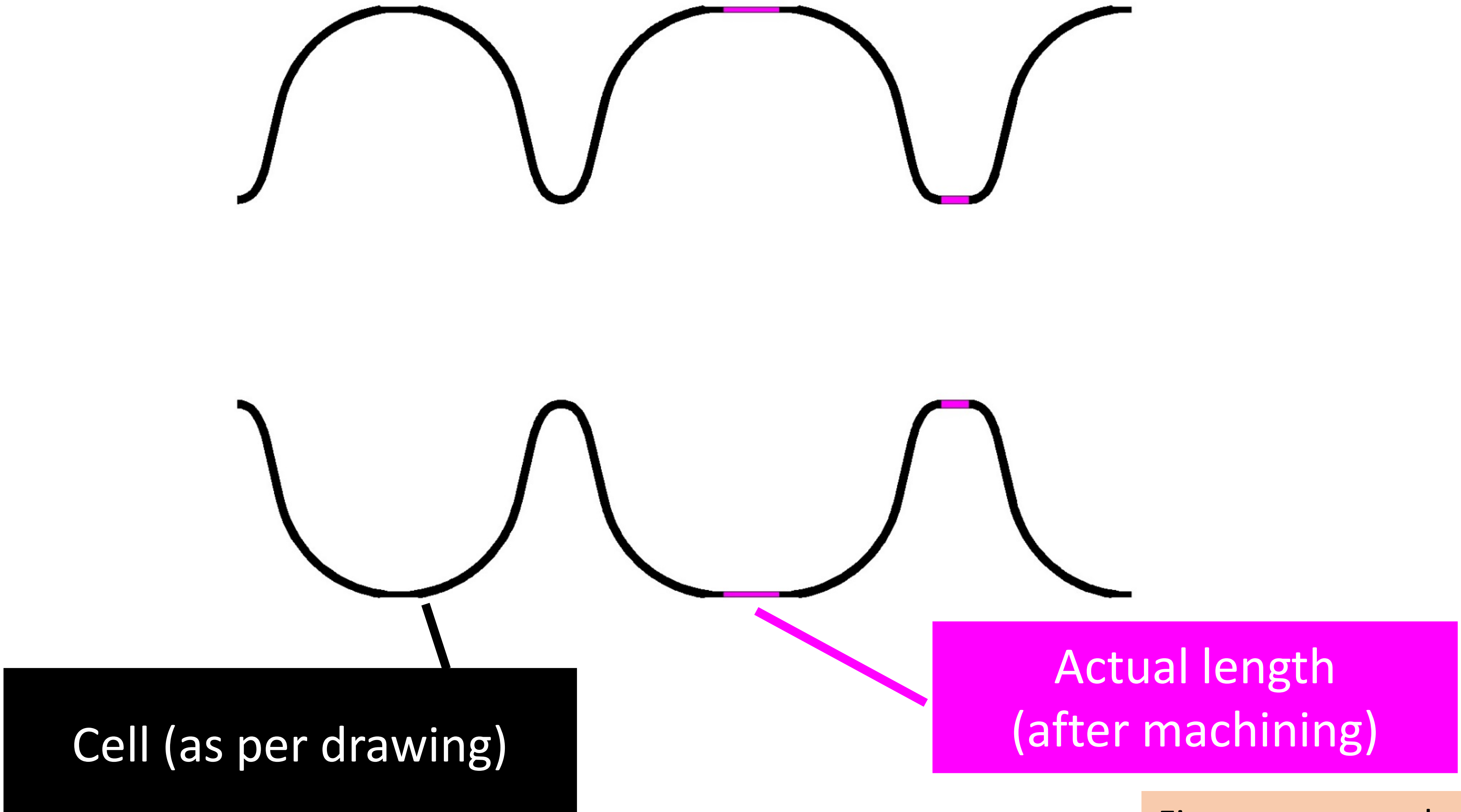


Figure not to scale

Fabrication Errors

B. Unequal lengths at equator and iris

Gets introduced during machining of half cell



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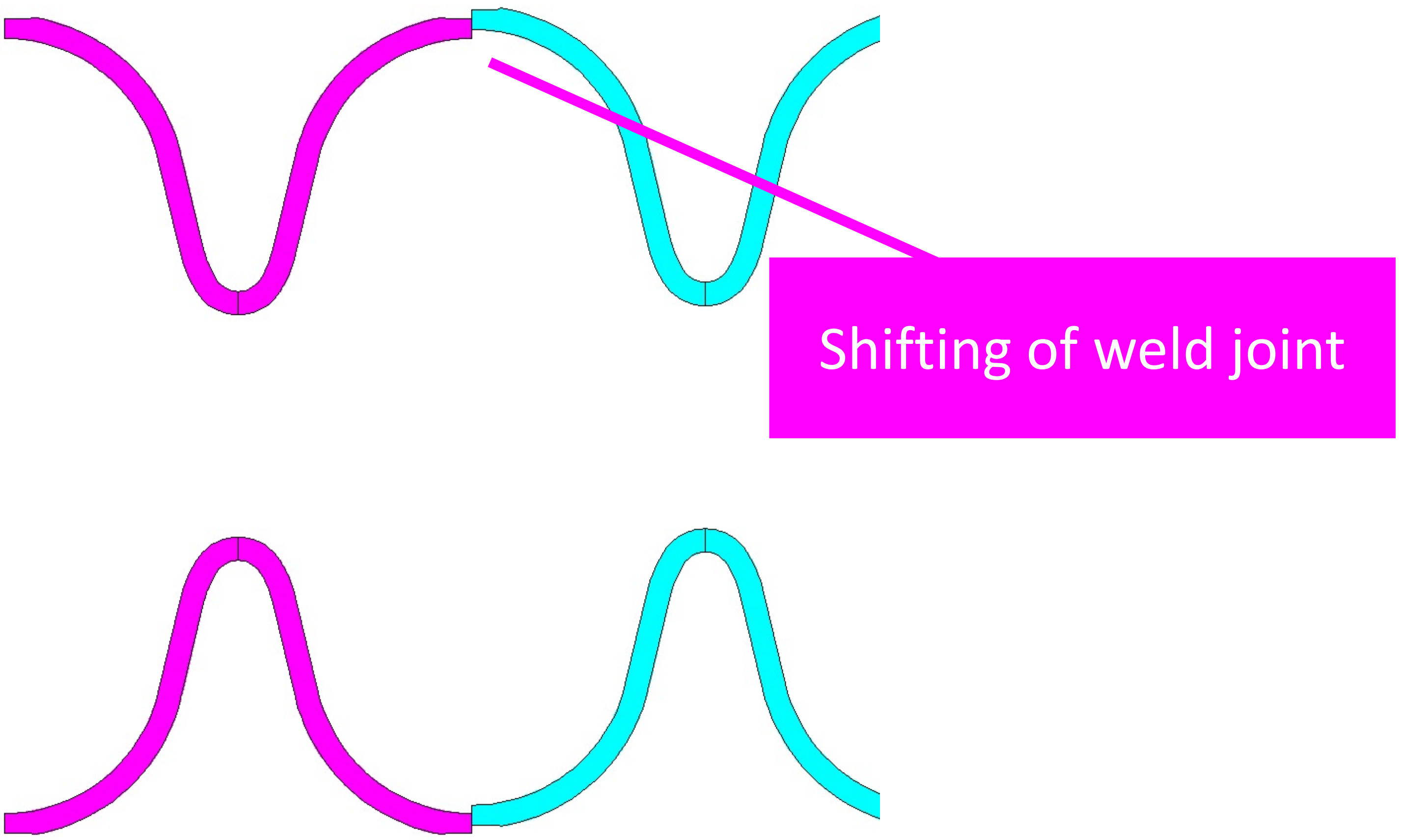
Fabrication Errors

C. Surface mismatches

Introduced due to improper / inaccuracies of welding fixture



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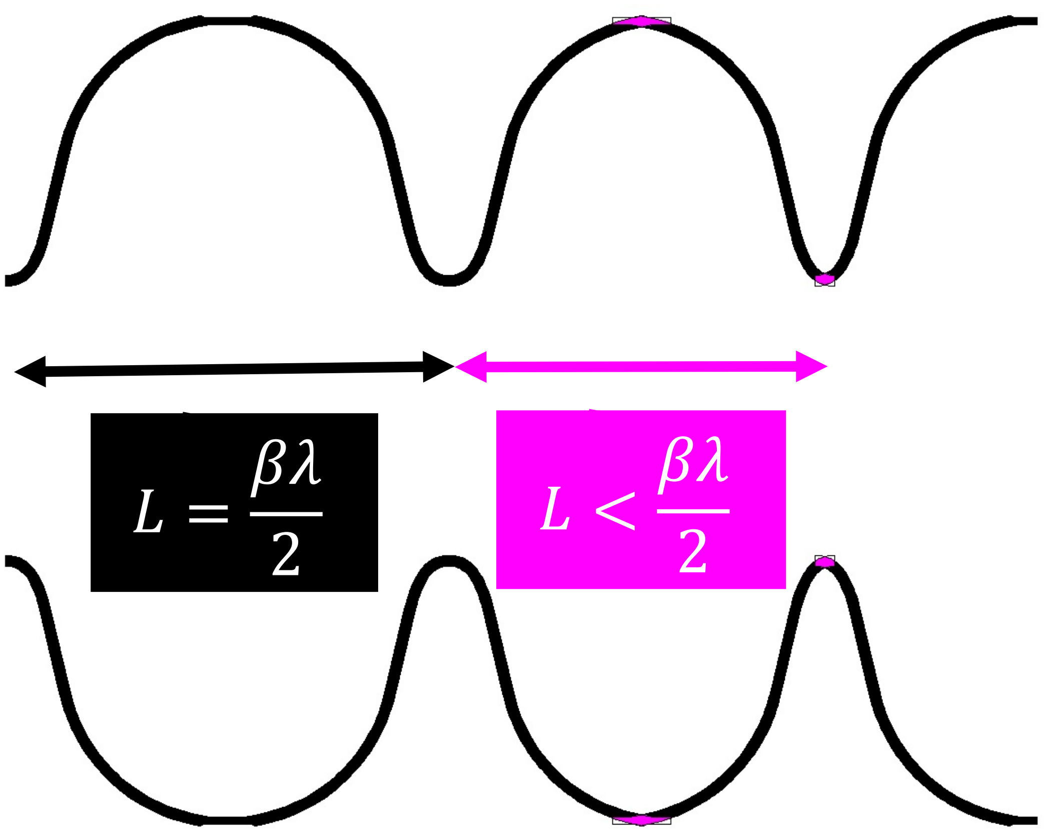
Fabrication Errors

D. Unequal cell lengths

Gets introduced due to welding shrinkage



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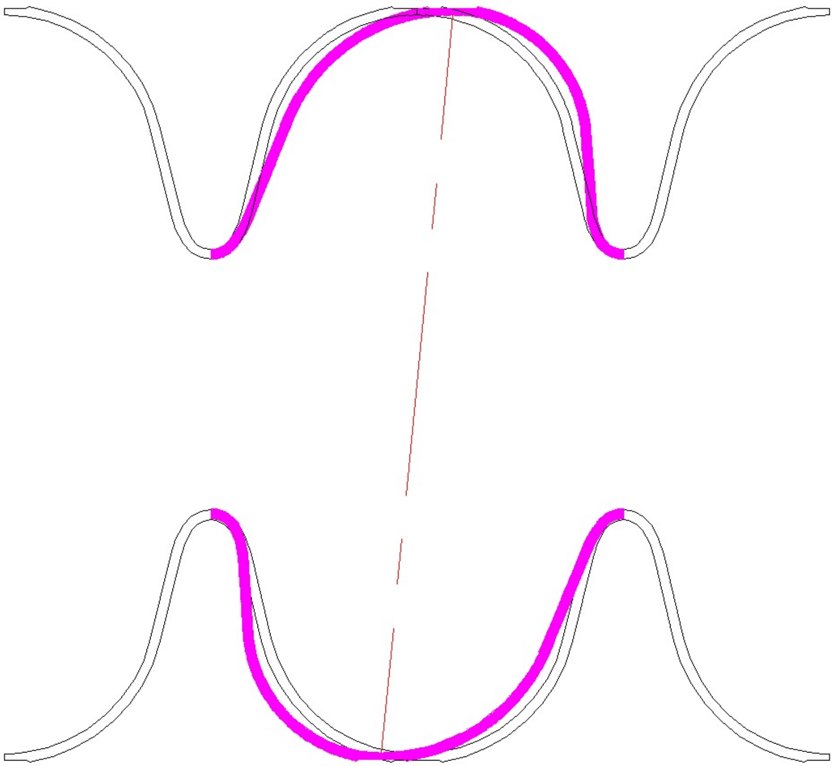
Fabrication Errors

E. Cell bend

Gets introduced due fabrication errors / errors in welding fixtures / mishandling



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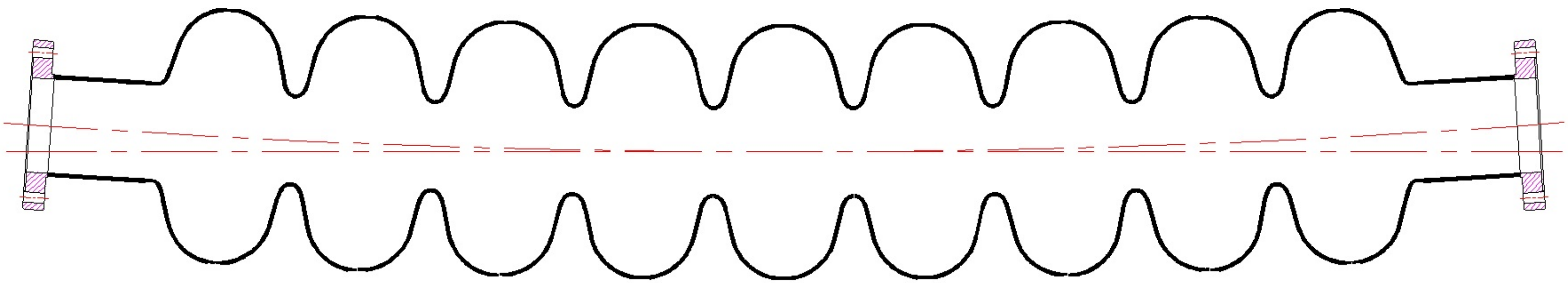
Fabrication Errors

F. Deformed shape

Gets introduced due to fabrication and handling errors



Deformed cavity shape (Banana / S)

Figure not to scale

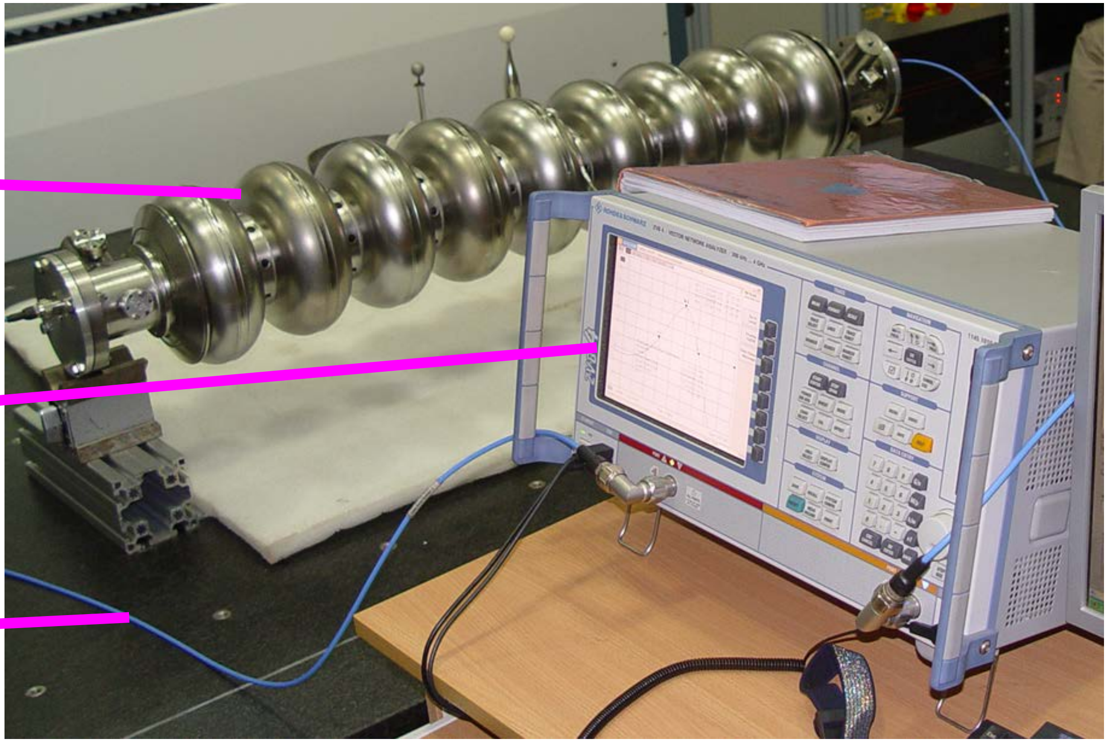
Measurement of tuning parameters of a multi-cell Cavity

Frequency measurement

Multi-cell cavity
(9 cell 1.3 GHz SCRF cavity)

Vector Network Analyzer

Connecting cables

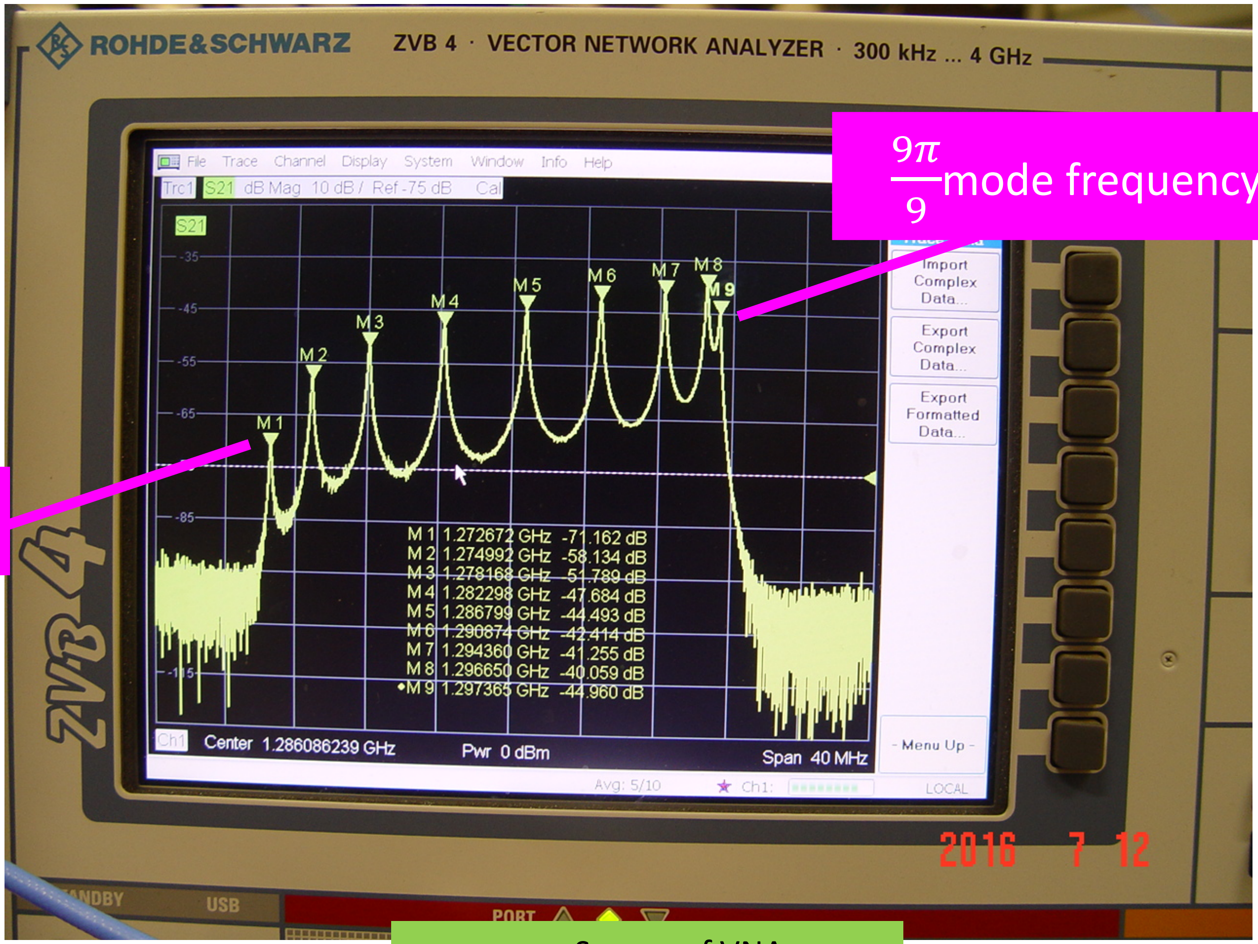


Multi-cell SCRF cavity connected to VNA

Measurement of tuning parameters of a multi-cell Cavity

Frequency measurement

Record multiple resonating modal frequencies of a multi-cell SCRF cavity

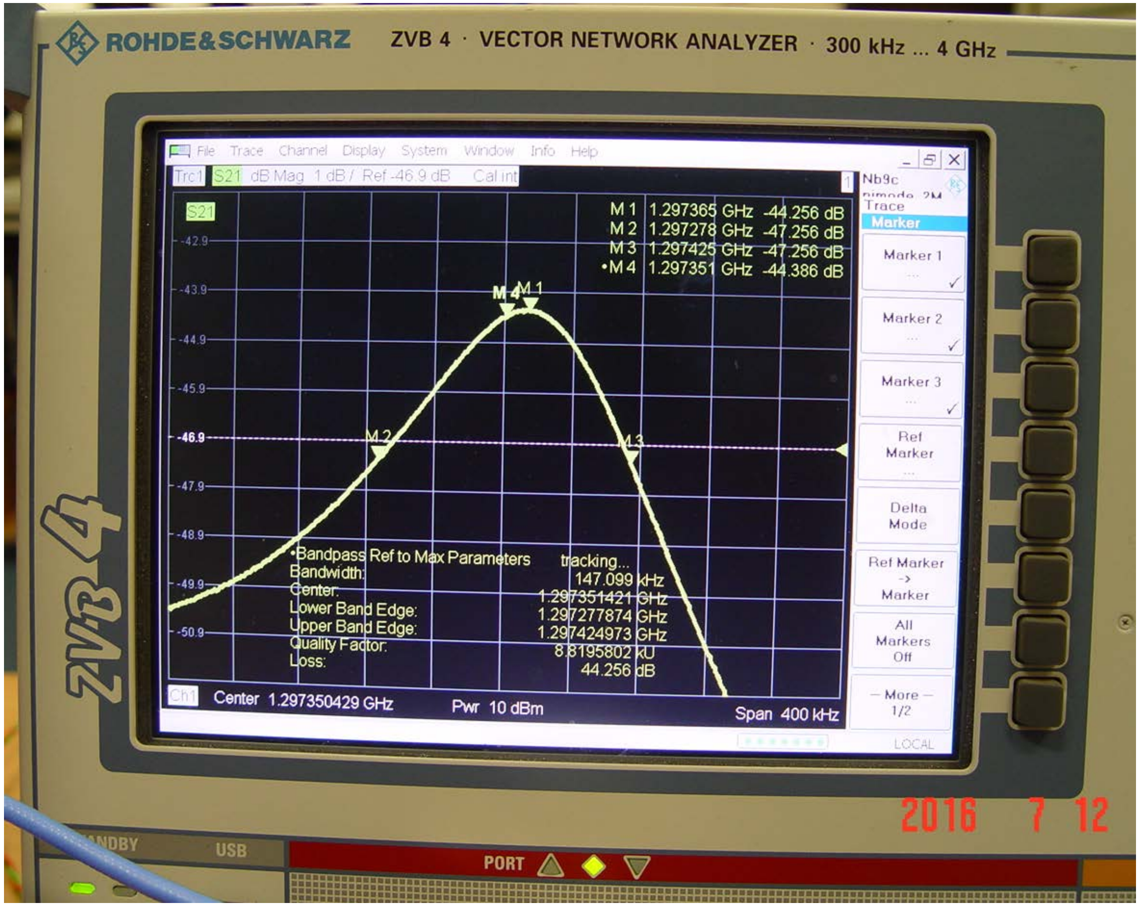


Measurement of tuning parameters of a multi-cell Cavity

Frequency measurement

Record π mode frequency of a multi-cell SCRF cavity

π mode frequency of a multi-cell SCRF cavity should be equal to the design / target frequency of a multi-cell cavity



Screen of VNA

Measurement of tuning parameters of a multi-cell Cavity

Field Flatness Measurement

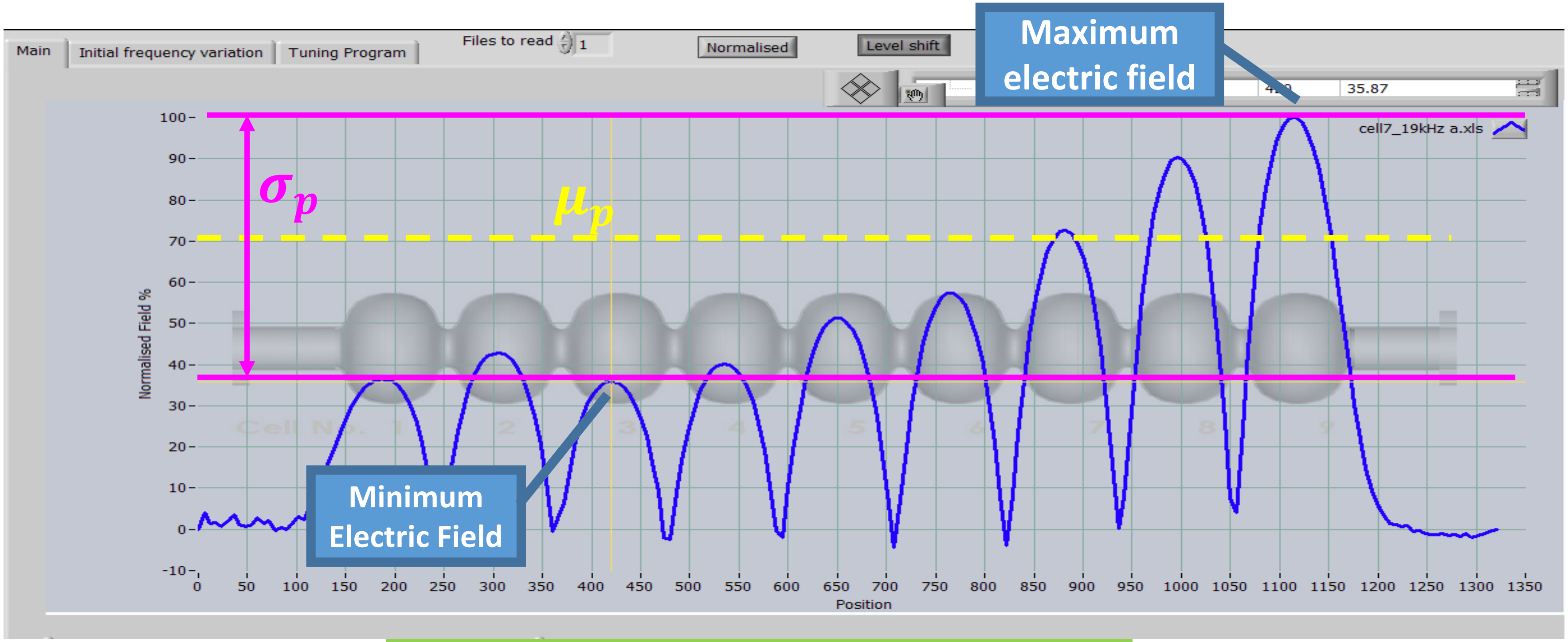
$$Field\ Flatness\ \% = \frac{E_{min}}{E_{max}} \times 100$$

$$Field\ Flatness\ \% = \frac{(E_{max} - E_{min})}{\frac{1}{N}\sum_{i=1}^{N} E_i} \times 100$$

$$Field\ Flatness\ \% = \frac{\mu_p - \sigma_p}{\mu_p} \times 100$$

σ_p – Standard Deviation of peak fields

μ_p – Average value of peak fields



Relative electric field v/s cavity length

Measurement of tuning parameters of a multi-cell Cavity

Field Flatness Measurement

Field measurement is based on ***Slater perturbation theory***

When a resonant cavity is perturbed, (a foreign object is introduced into the cavity) electromagnetic fields inside the cavity changes accordingly.

Small change in volume makes small change in stored energy and frequency

The frequency shift is proportional to the relative electric and magnetic fields at the location of object

Measurement of tuning parameters of a multi-cell Cavity

Field Flatness Measurement

Slater perturbation theory

$$\frac{\Delta f}{f_0} = -\frac{\pi r^3}{U}\left[\frac{\varepsilon_r - 1}{\varepsilon_r + 2}\varepsilon_0 {E_0}^2 + \frac{\mu_r - 1}{\mu_r + 2}\mu_0 {H_0}^2\right]$$

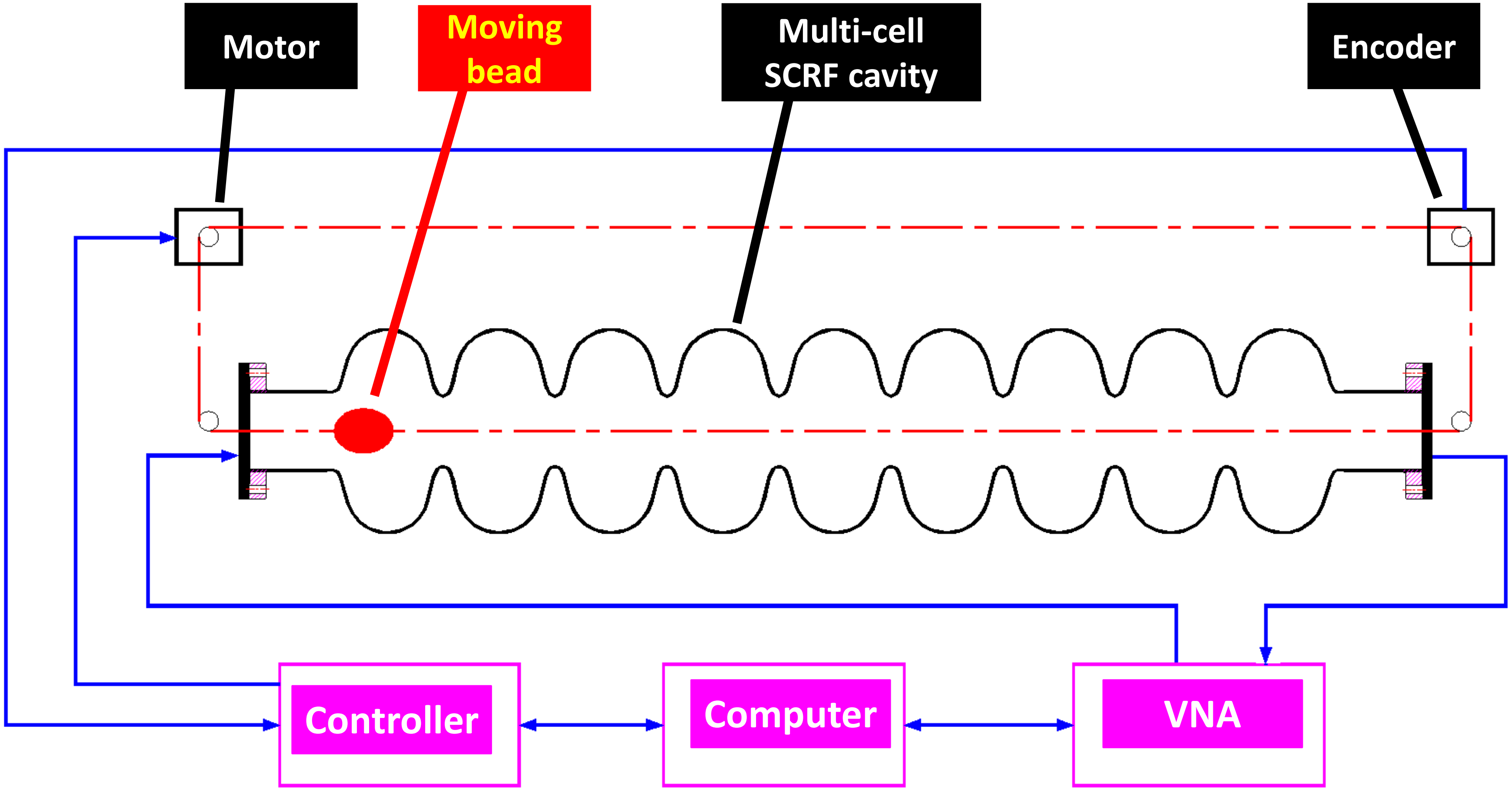
Δf -- frequency shift; Hz
f_0 -- unperturbed frequency; Hz
E_0 -- amplitude of electric field v/m
ε_r -- dielectric constant of the dielectric sphere
ε_0 -- permittivity of vacuum (~ 8 x 10-12 v/m
μ_r -- relative permeability of the bead
μ_0 -- permeability of vacuum
U -- power stored in cavity; watt
k -- constant

$$\frac{\Delta f}{f_0} = k{E_0}^2$$

Small shift in π mode frequency of a multi-cell cavity is used to plot electric field along cavity axis

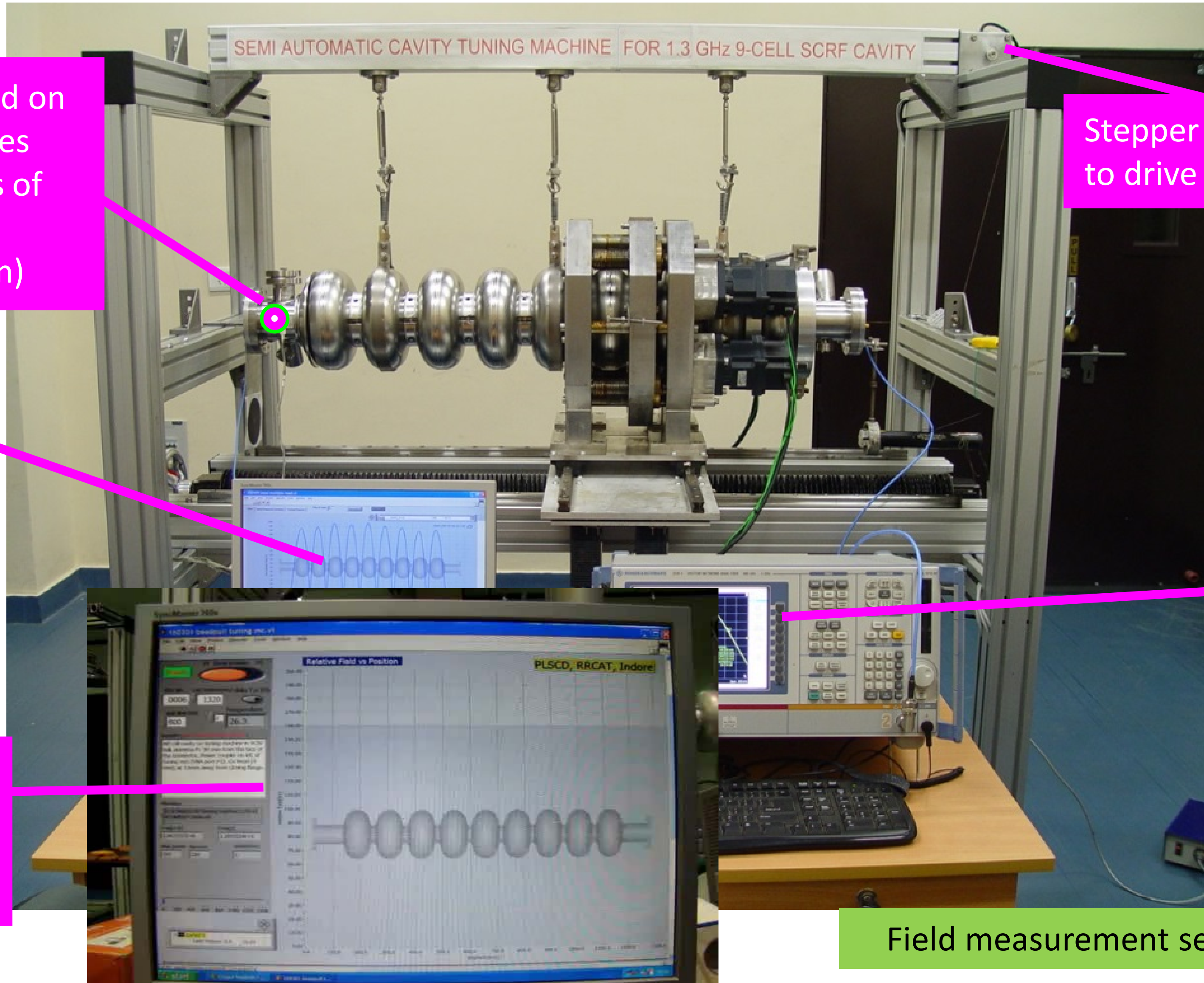
Measurement of tuning parameters of a multi-cell Cavity

Field Flatness Measurement



Schematic Layout of bead pull test setup

Cavity tuning using semi-automatic tuning machine



Bead mounted on a thread moves along the axis of the cavity (for animation)

Stepper Motor to drive bead

PC setup

VNA

Recorded movie of bead pull run

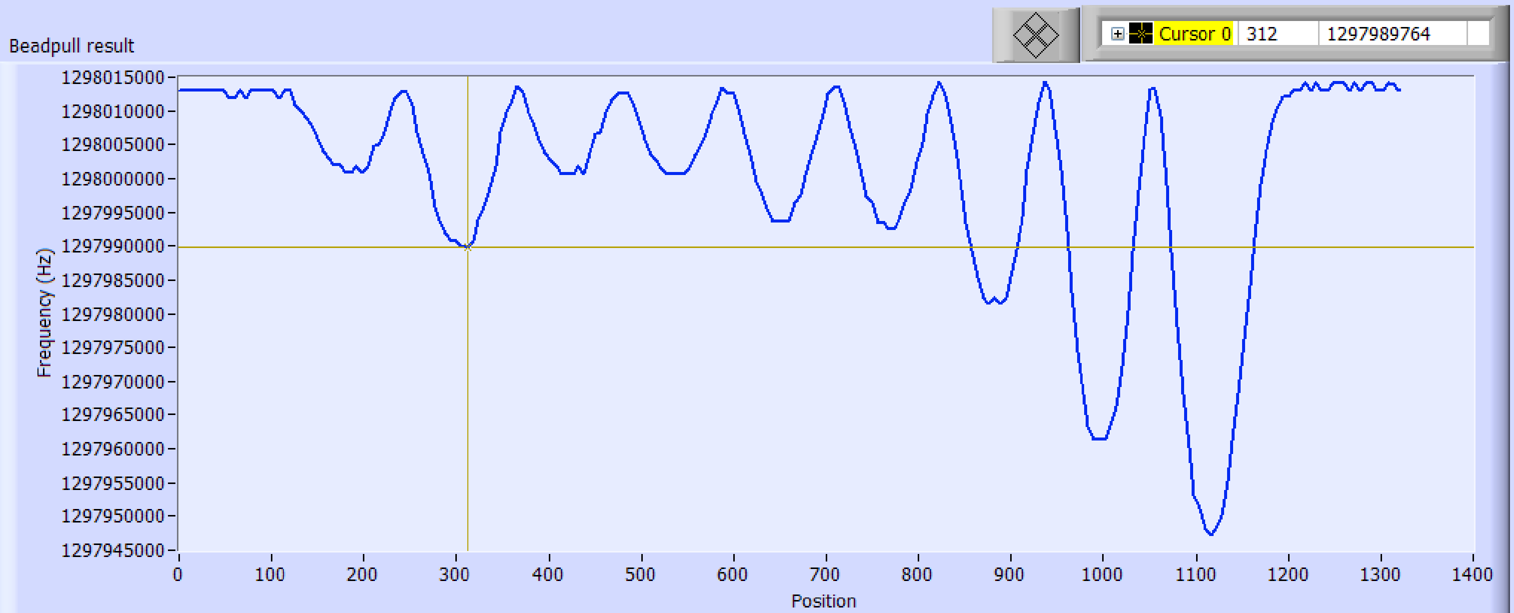
Field measurement setup

Measurement of tuning parameters of a multi-cell Cavity

Field Flatness Measurement

Beadpull result (location and Minimum frequency value for each cell)

198	312	438	546	660	774	888	1002	1116
1298000850	1297989760	1298000670	1298000590	1297993500	1297992410	1297981330	1297961240	1297947150

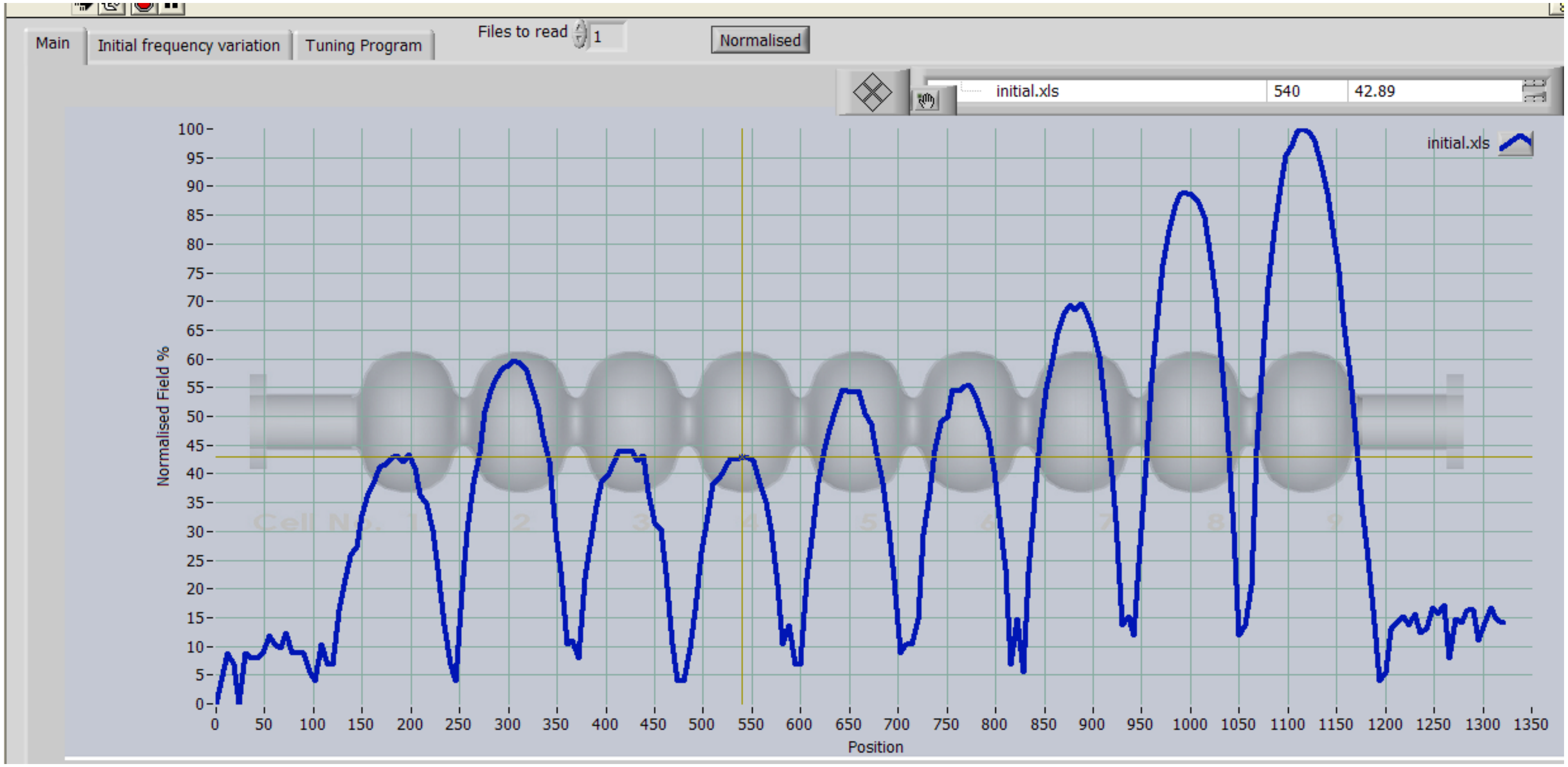


Frequency v/s bead position

A frequency plot is generated after bead pull run

Measurement of tuning parameters of a multi-cell Cavity

Field Flatness Measurement



Relative field v/s bead position

A program has been developed in LabVIEW to plot a graph between relative electric field and bead position

How to tune a multi-cell SCRF Cavity?

Inputs

Values of $\frac{\pi}{n}$ and π mode frequencies of cavity

Field profile of the cavity

Desired / target frequency

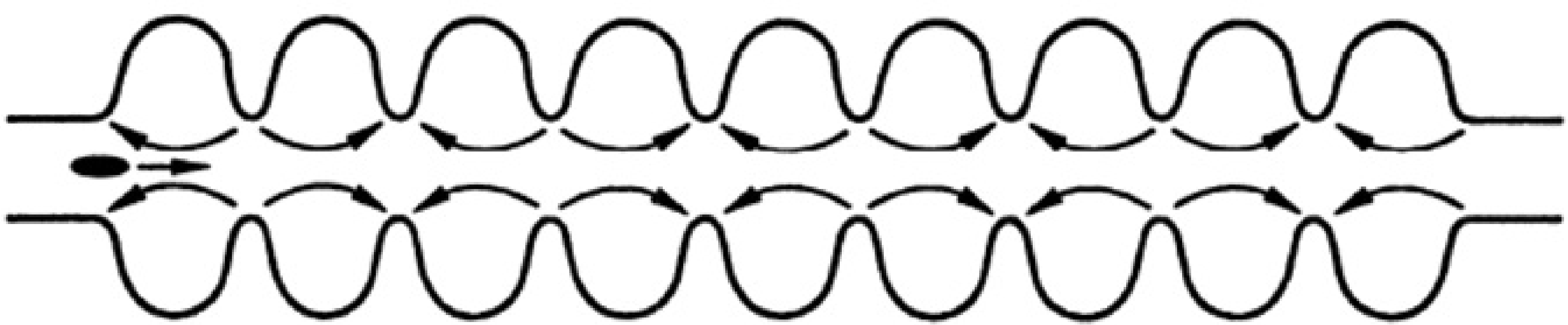
Tuning Sensitivity

Cavity temperature

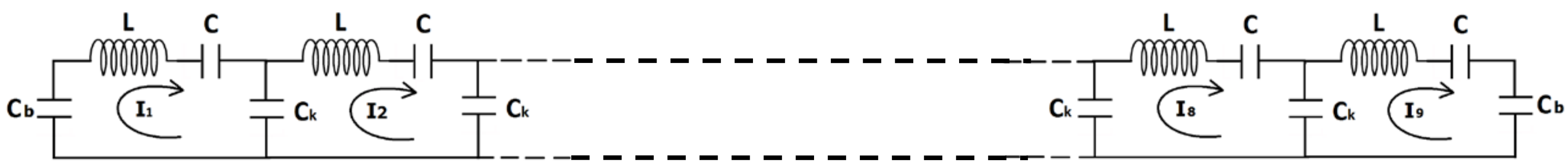
Output

Amount of frequency correction for each cell

Understanding Tuning Methodology



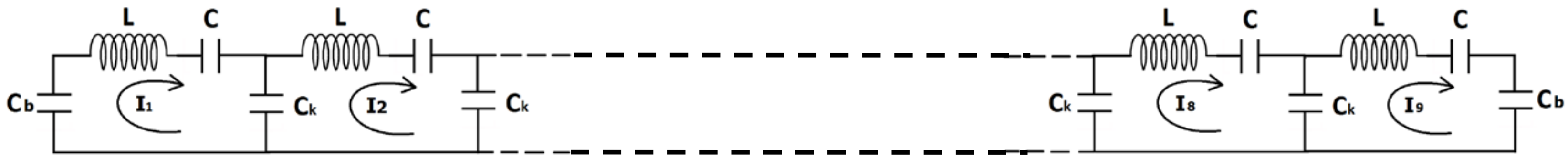
Sketch of electric field lines of the π mode of a 9-cell SCRF cavity



Equivalent circuit of a 9-cell SCRF cavity

I -- Inductance of cell
C -- Capacitance of cell
Cb -- Capacitance, beam tube
Ck – Capacitance, cell to cell coupling
I1, I2, … I9 – Loop current

Understanding Tuning Methodology



Equivalent circuit of a 9-cell SCRF cavity

By applying Kirchhoff's voltage summation rule to each current loop we get the following equations

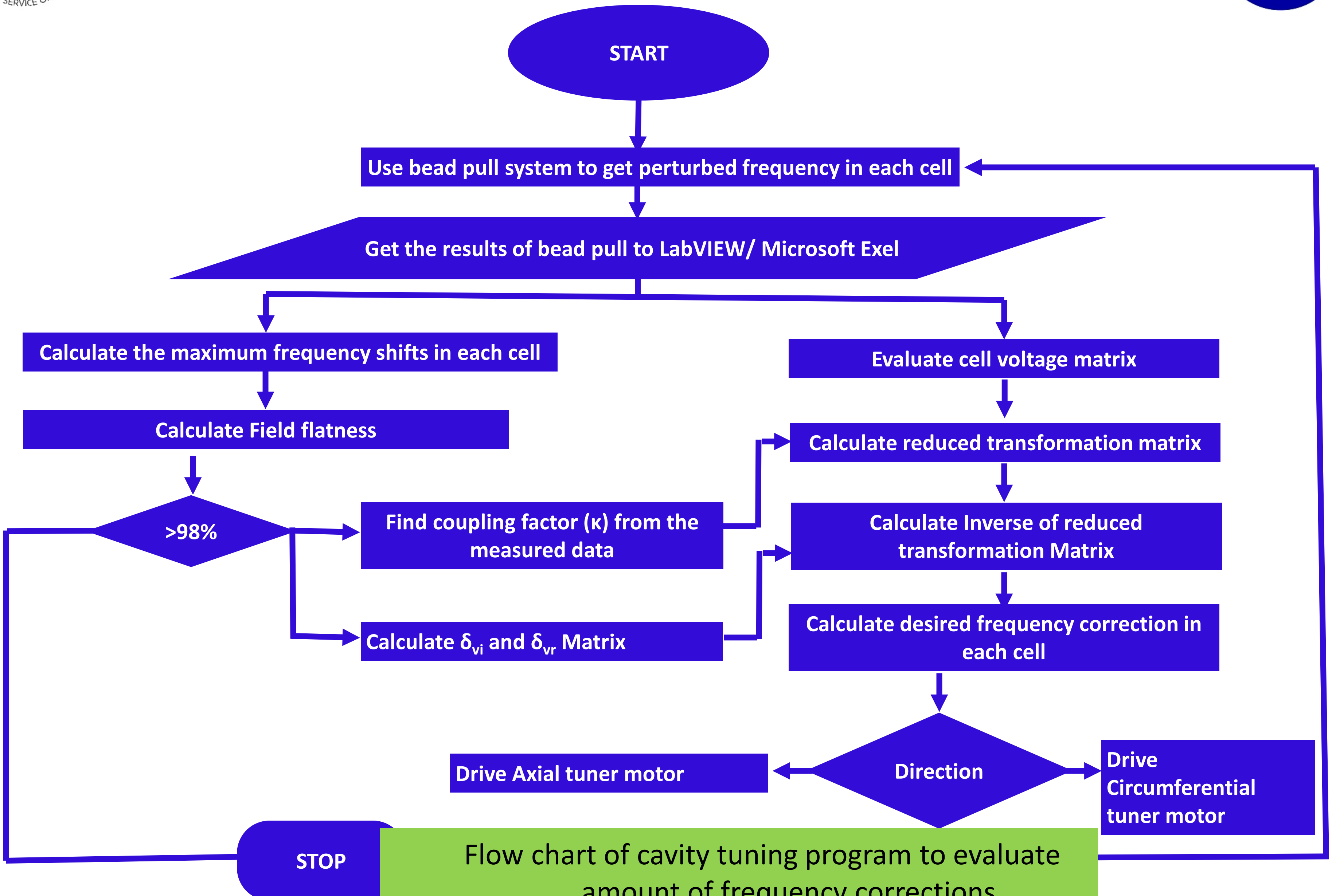
$$\left(\frac{1}{i\omega C_b} + i\omega L\right) I_1 + \left(\frac{1}{i\omega C}\right) I_1 + \left(\frac{1}{i\omega C_k}\right)(I_1 - I_2) = 0$$

$$\frac{1}{i\omega C_k}(I_1 - I_{j-1}) + \left(i\omega L + \frac{1}{i\omega C}\right) I_j + \left(\frac{1}{i\omega C_k}\right)(I_j - I_{j+1}) = 0 \qquad 1 < j < 9$$

$$\left(\frac{1}{i\omega C_k}\right)(I_9 - I_8) + \left(i\omega L + \frac{1}{i\omega C}\right) I_9 + \left(\frac{1}{i\omega C_b}\right) I_9 = 0$$

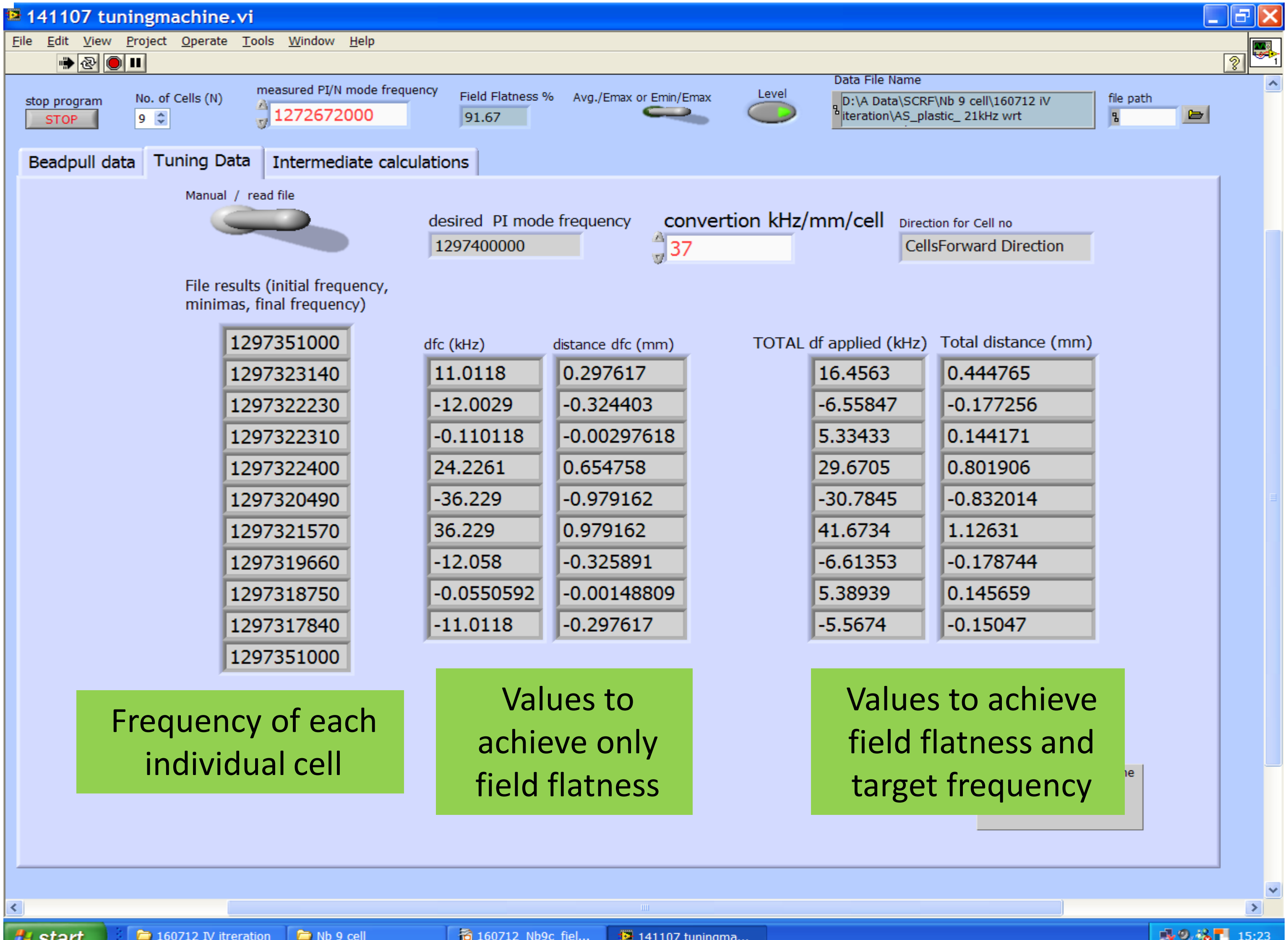
Detailed procedure to solve the equations is given in the book titled 'RF Superconductivity for Accelerators' by Hasan Padamsee et al

Understanding Tuning Methodology



Flow chart of cavity tuning program to evaluate amount of frequency corrections

Understanding Tuning Methodology



Frequency of each individual cell

Values to achieve only field flatness

Values to achieve field flatness and target frequency

Out put of cavity tuning program

Understanding Tuning Methodology

Cell no.	Required Frequency Change (kHz)
1	16
2	-6
3	5
4	29
5	-30
6	41
7	-6
8	5
9	-5

Maximum reduction of frequency

Maximum increase of frequency

Tuning program output

How cavity tuning is carried out?

Cavity tuning is carried out by permanent deformation of individual cells to get

- Target frequency and
- Required field flatness

Types of tuners

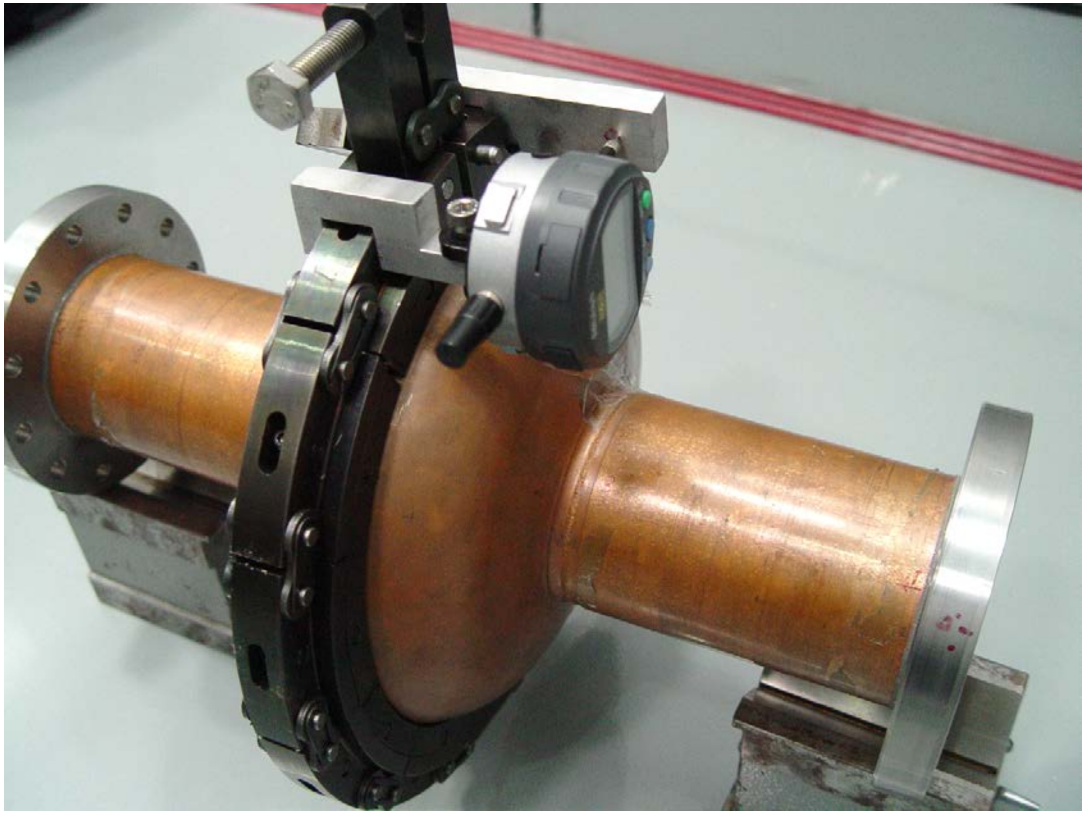
1. Circumferential tuners and

2. Axial Tuners

Circumferential Tuner

Chain Link Tuner

Circumferential Tuner



Chain Link Tuner mounted on single cell cavity

Circumferential Tuner

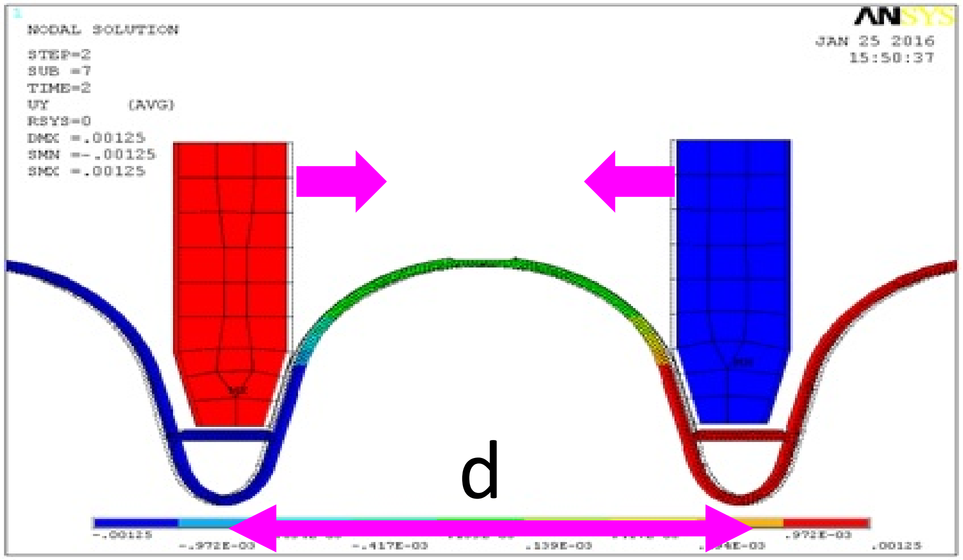
Tuning sensitivity measurement setup

Tuning sensitivity - ~ 170 kHz/mm

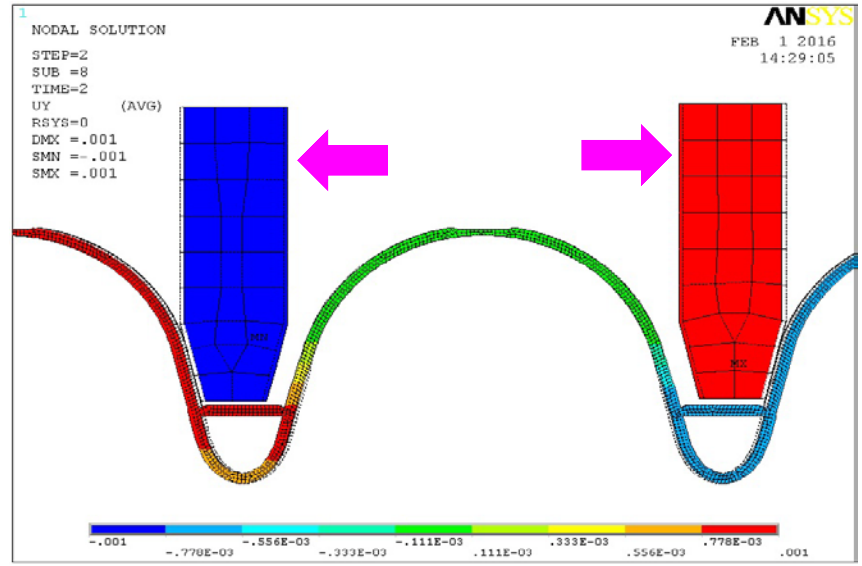
Disadvantages

- **Large tightening torque needs to be applied to get permanent deformations**
- **It can not be used to decreases the cavity frequency.**

Axial Tuner



Compression of a cell
(Jaws move inwards)



Expansion of a cell
(Jaws move outwards)

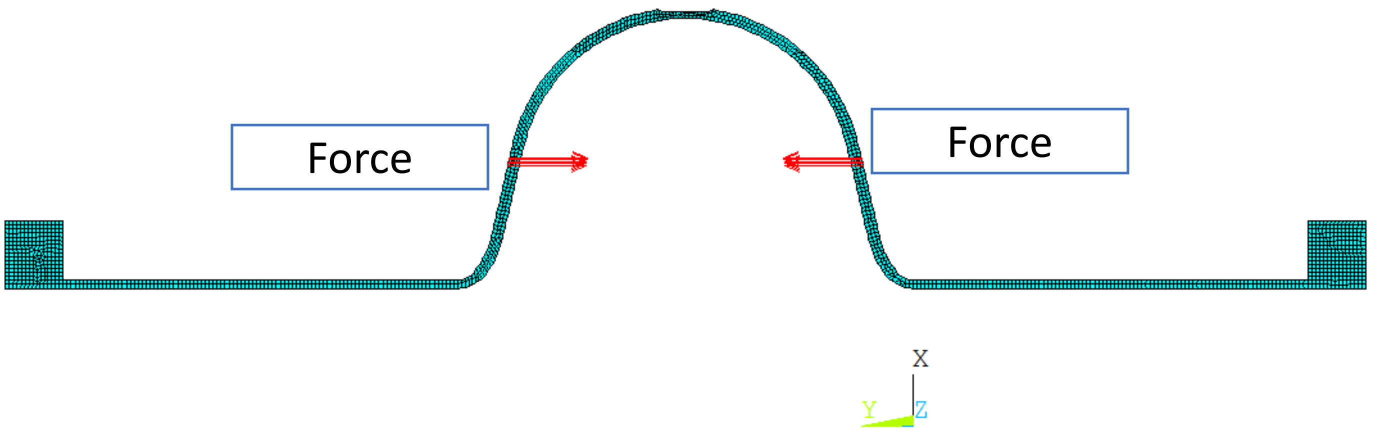
$$Capacitance\ C \propto \frac{A}{d}$$

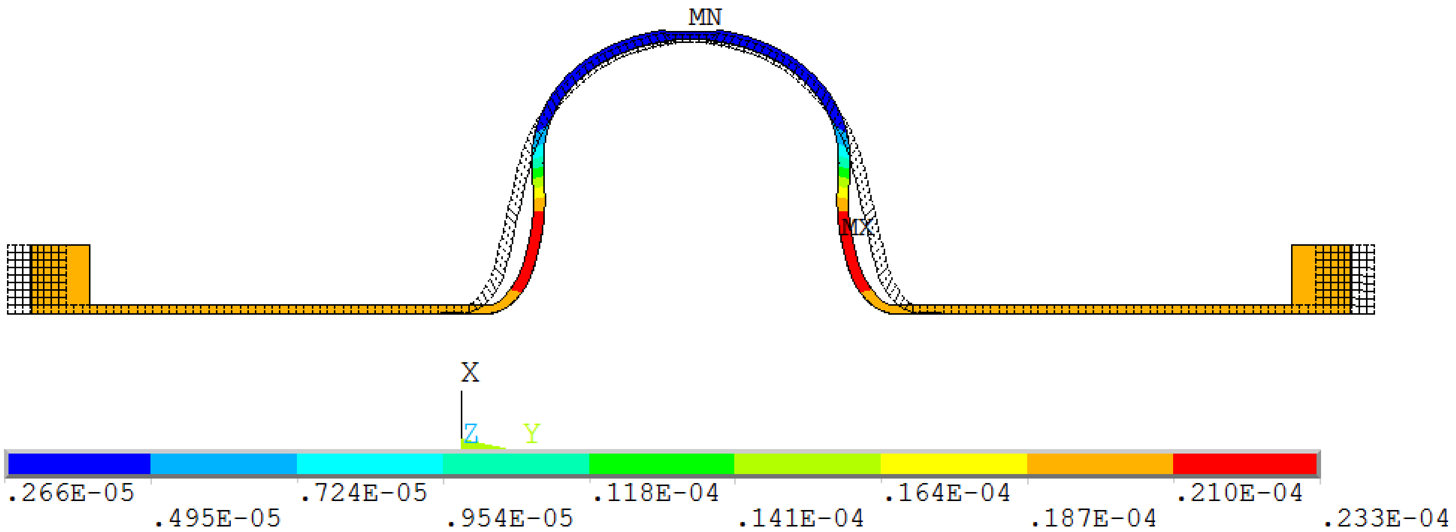
d- cell length

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

Reduction in cell length increases capacitance and hence reduces frequency and vice a versa

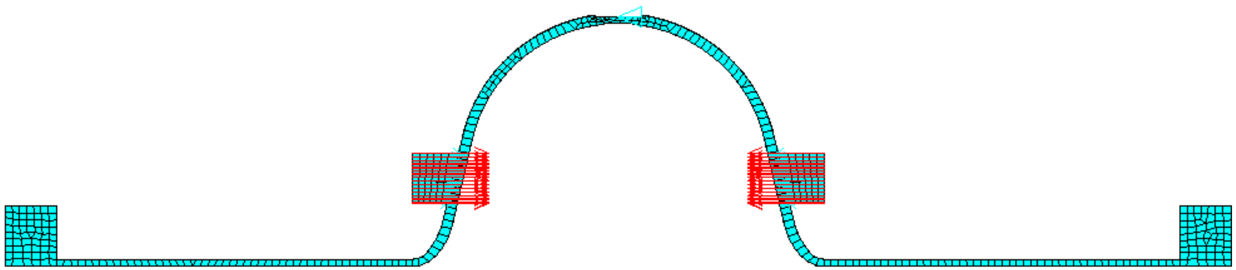
Structural analysis of cavity cell subjected to tuning forces

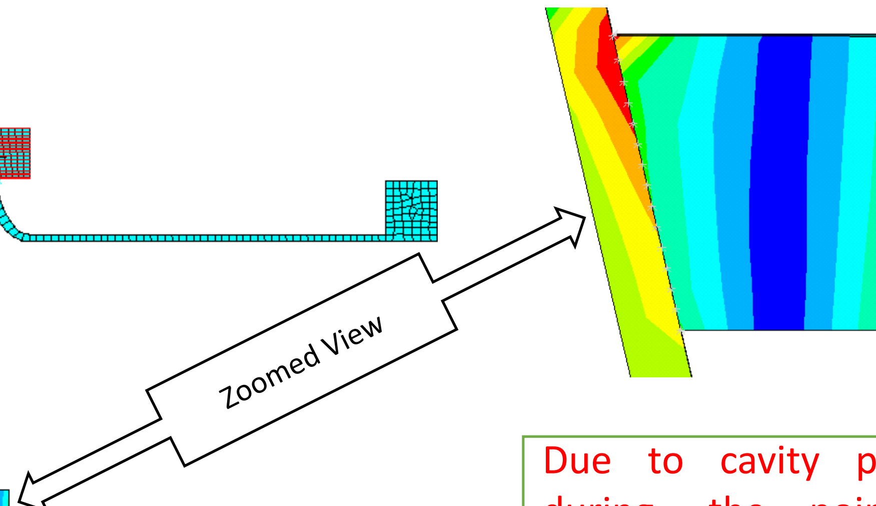


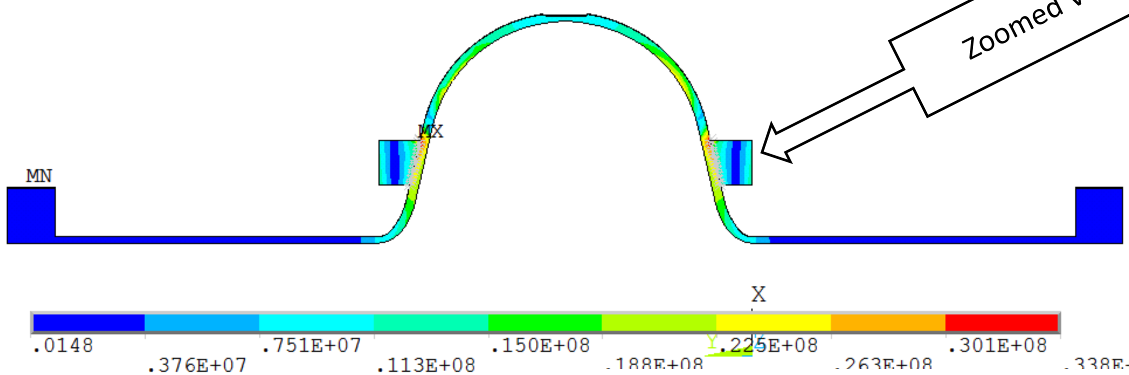


Cell deformation plot on application of tuning force

Structural analysis of cavity cell subjected to tuning forces



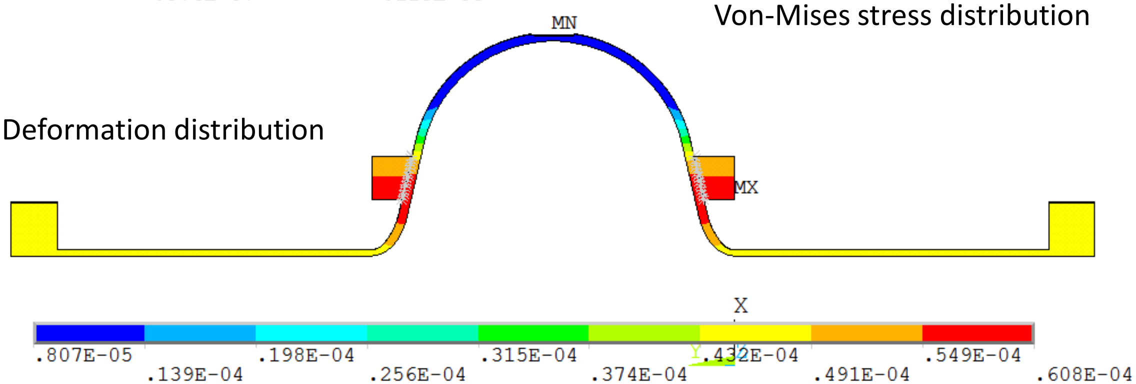




Von-Mises stress distribution

Due to cavity profile, during, the point of application of force shifts. Tuning force varies due to difference in stiffness of the cavity at different radius location

Deformation distribution



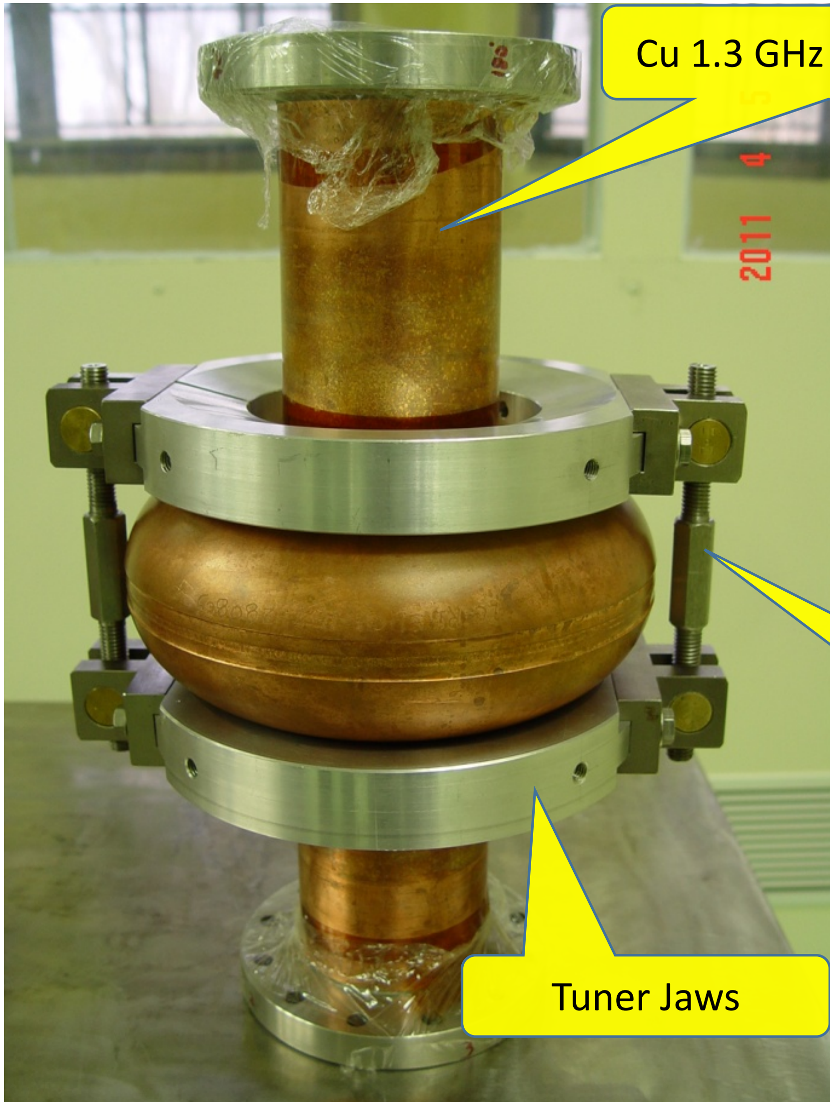
Contact analysis for cell deformation due to application of tuning force

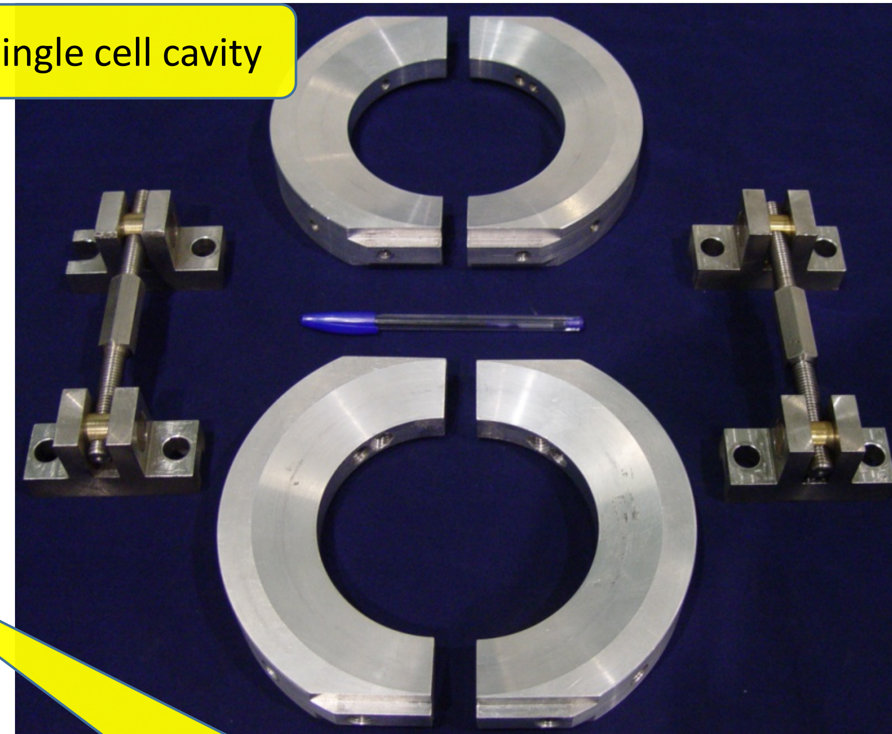
Structural analysis of cavity cell subjected to tuning forces

TUNING FORCE (kN)	DEFORMATION (µm)	STRESS (MPa)	Δf (kHz)	PERMANENT DEFORMATION (µm)	Δf (kHz)
1	13.38	4.75	-12.295	0.00	0
5	67.00	23.80	-58.042	0.00	-0.008
10	134.80	40.40	-108.944	0.21	-0.147
15	218.00	47.40	-161.559	16.98	-12.083
16	240.00	49.40	-173.048	23.80	-17.406
17	262.00	51.10	-185.345	33.40	-24.448
18	288.00	52.80	-198.335	45.40	-32.708
19	318.00	54.30	-212.577	61.60	-44.133
20	352.00	56.00	-227.853	80.80	-57.151
25	752.00	64.90	-357.786	390.00	-230.28
29	2080.00	80.90	-518.348	1574.00	-472.99

Estimation of tuning force to get permanent deformation in cell

Axial Tuner

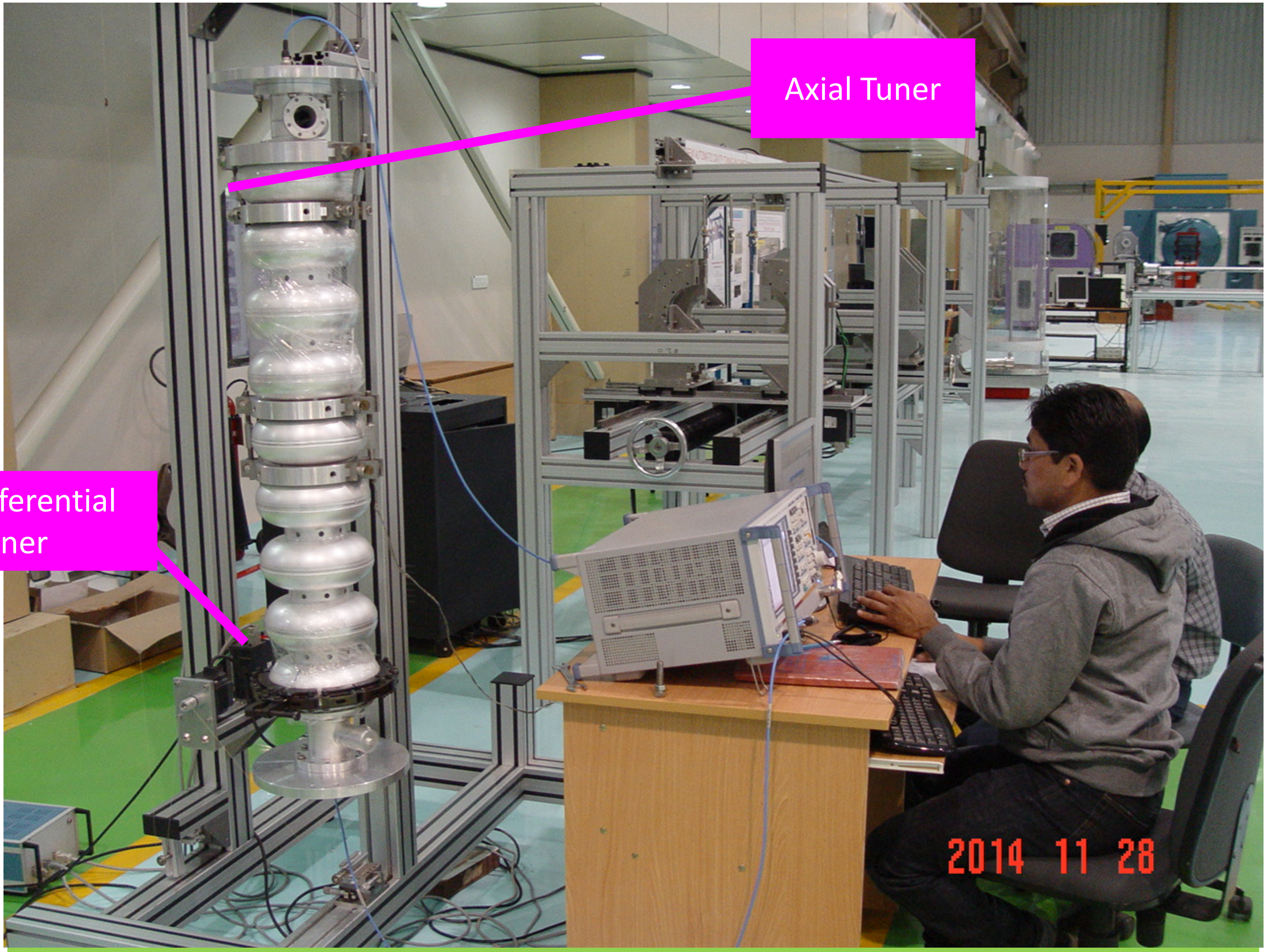




- **Can compress as well as stretch the cavity cell.**
- **Cavity bending is also possible.**

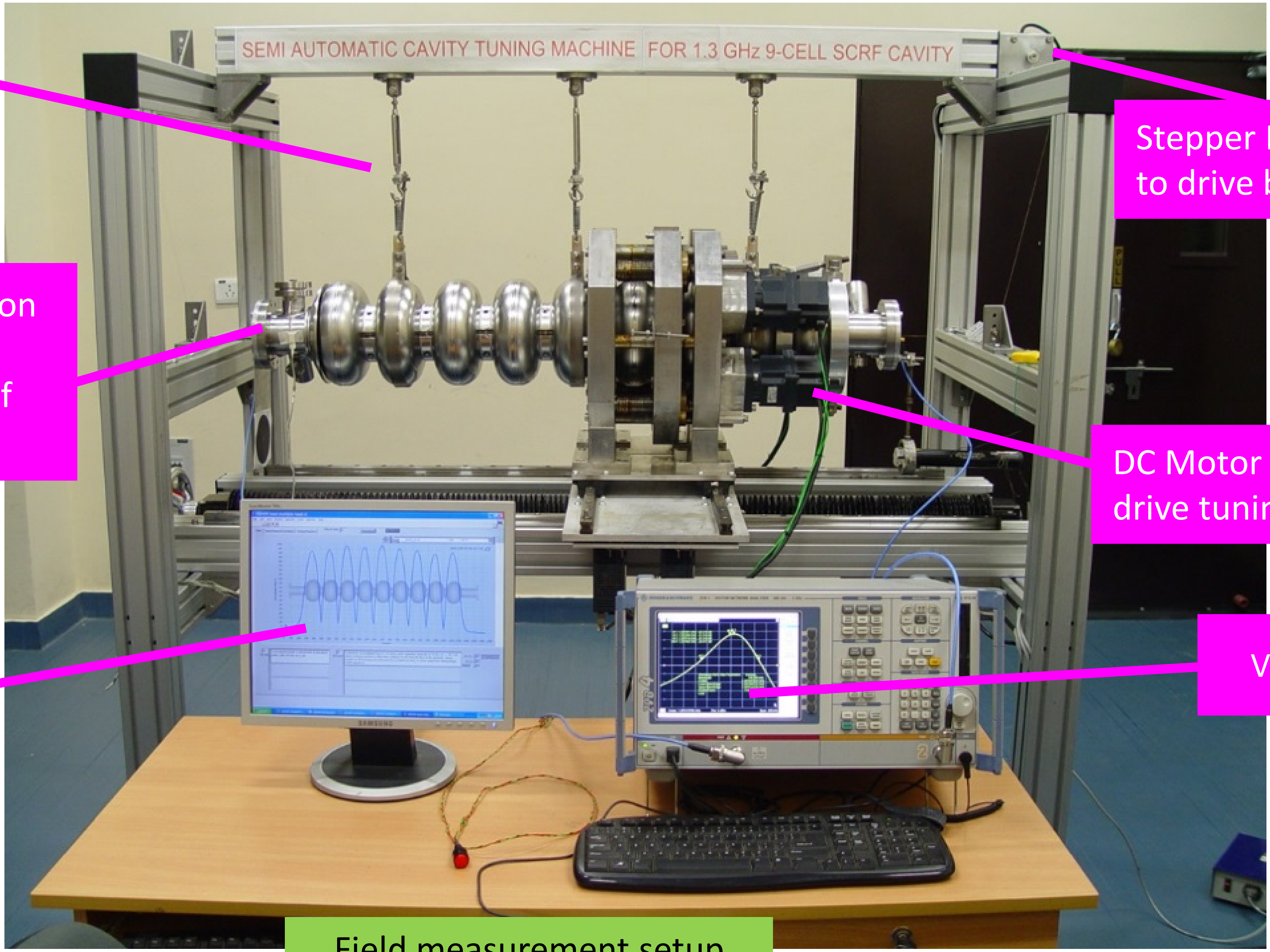
Manual Tuner

Axial Tuner



Vertical bead pull test setup with circumferential and axial tuners mounted on a multi-cell cavity

Cavity tuning using semi-automatic tuning machine



Cavity Suspension System

Stepper Motor to drive bead

Bead mounted on a thread moves along the axis of the cavity

DC Motor to drive tuning jaws

PC setup

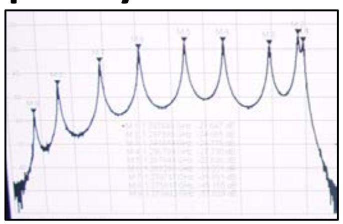
VNA

Field measurement setup

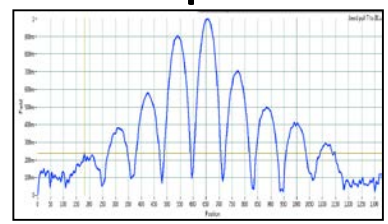
Cavity tuning using semi-automatic tuning machine

Mount cavity on Tuning machine

Frequency Measurement



Perform Bead pull at π-mode



Tuning Program

Desired π-mode frequency

Out put:- Frequency correction for each cell

Tuning is performed

Designed parameter achieved ?

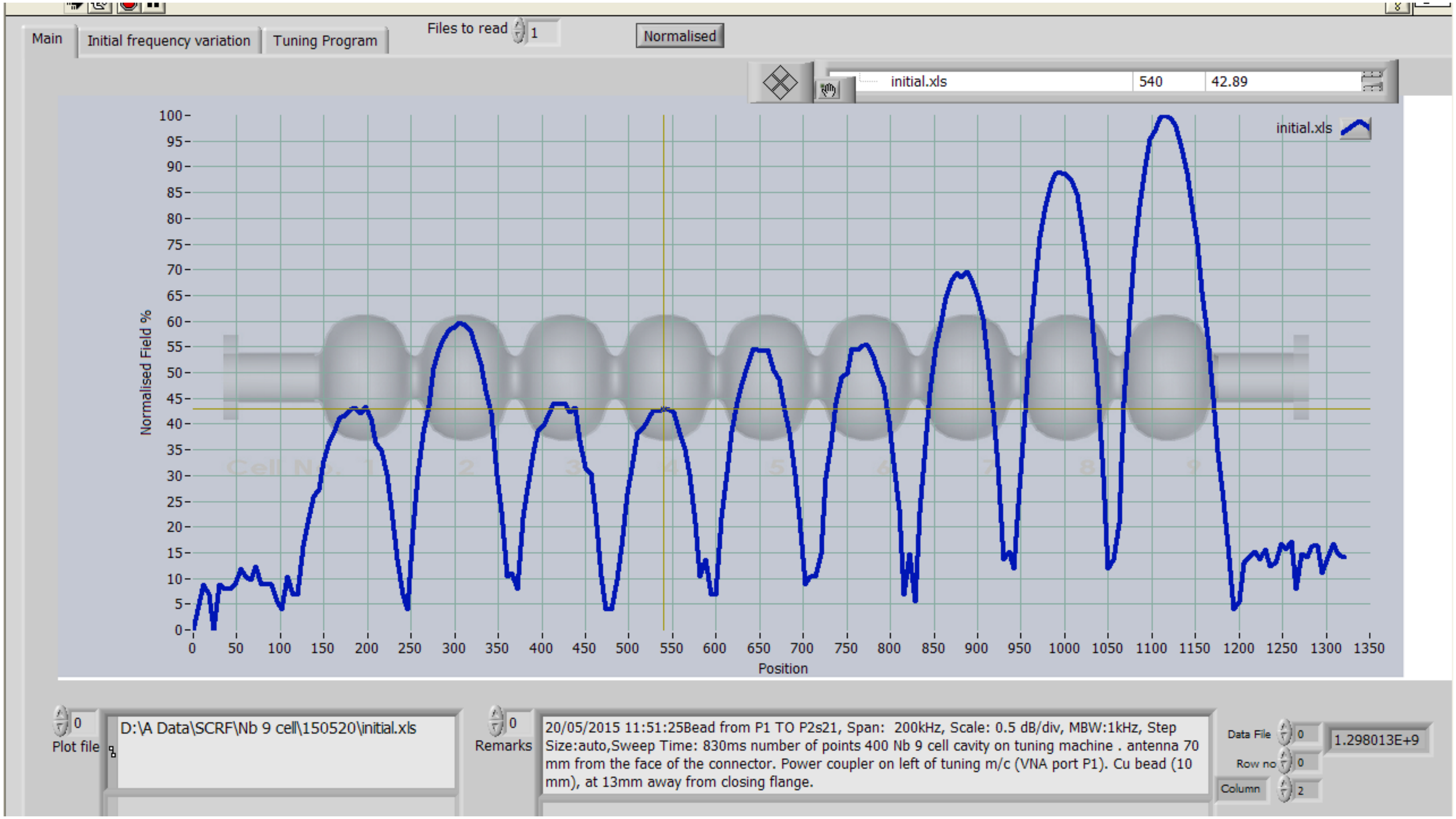
If, No

If Yes, Then stop Tuning

Flow chart of cavity tuning

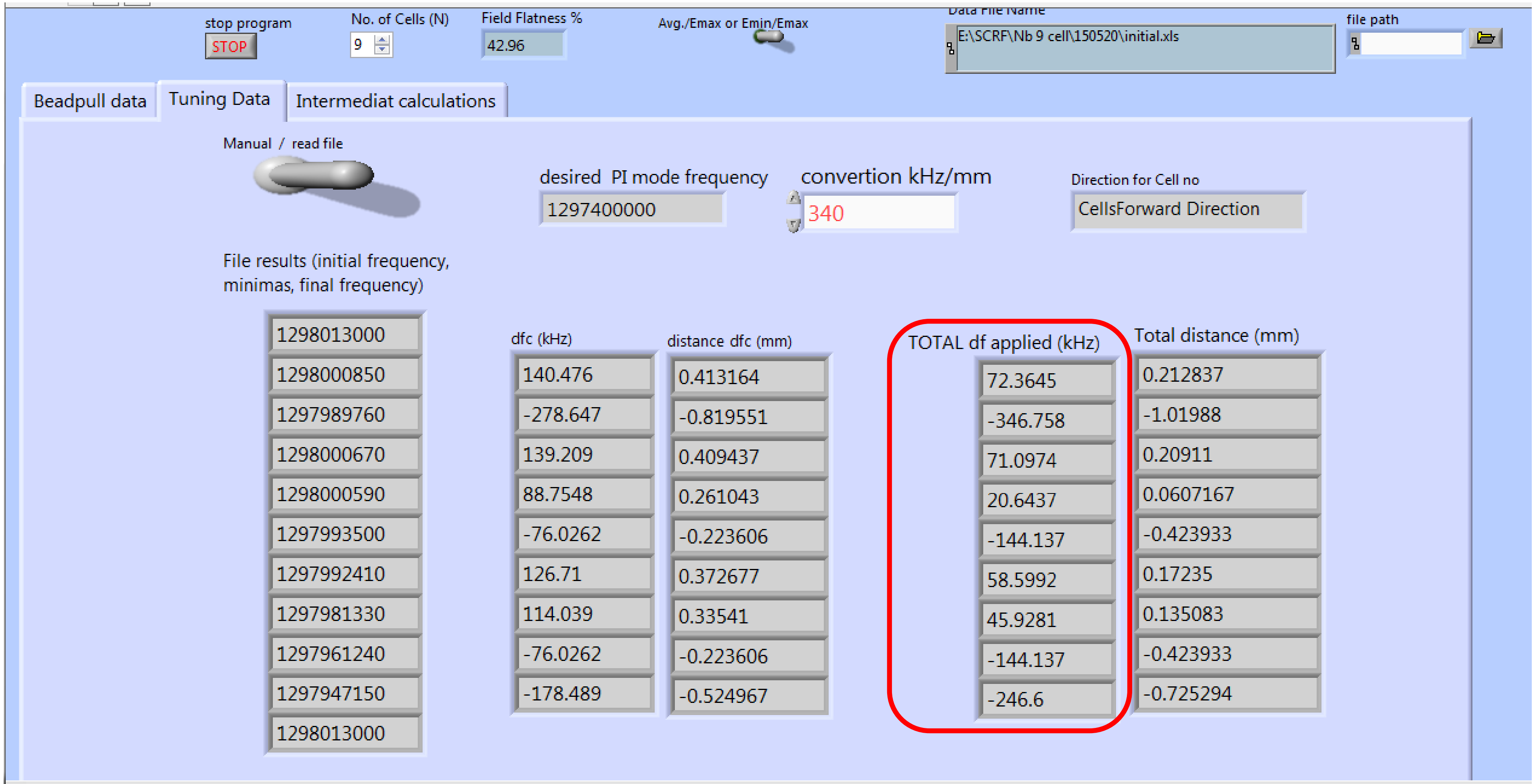
Cavity tuning using semi-automatic tuning machine

Pi mode frequency: 1298 MHz, Field flatness: 43 %



Relative electric field plot of as received cavity (after welding)

Cavity tuning using semi-automatic tuning machine



Amount of frequency corrections per cell calculated by tuning program

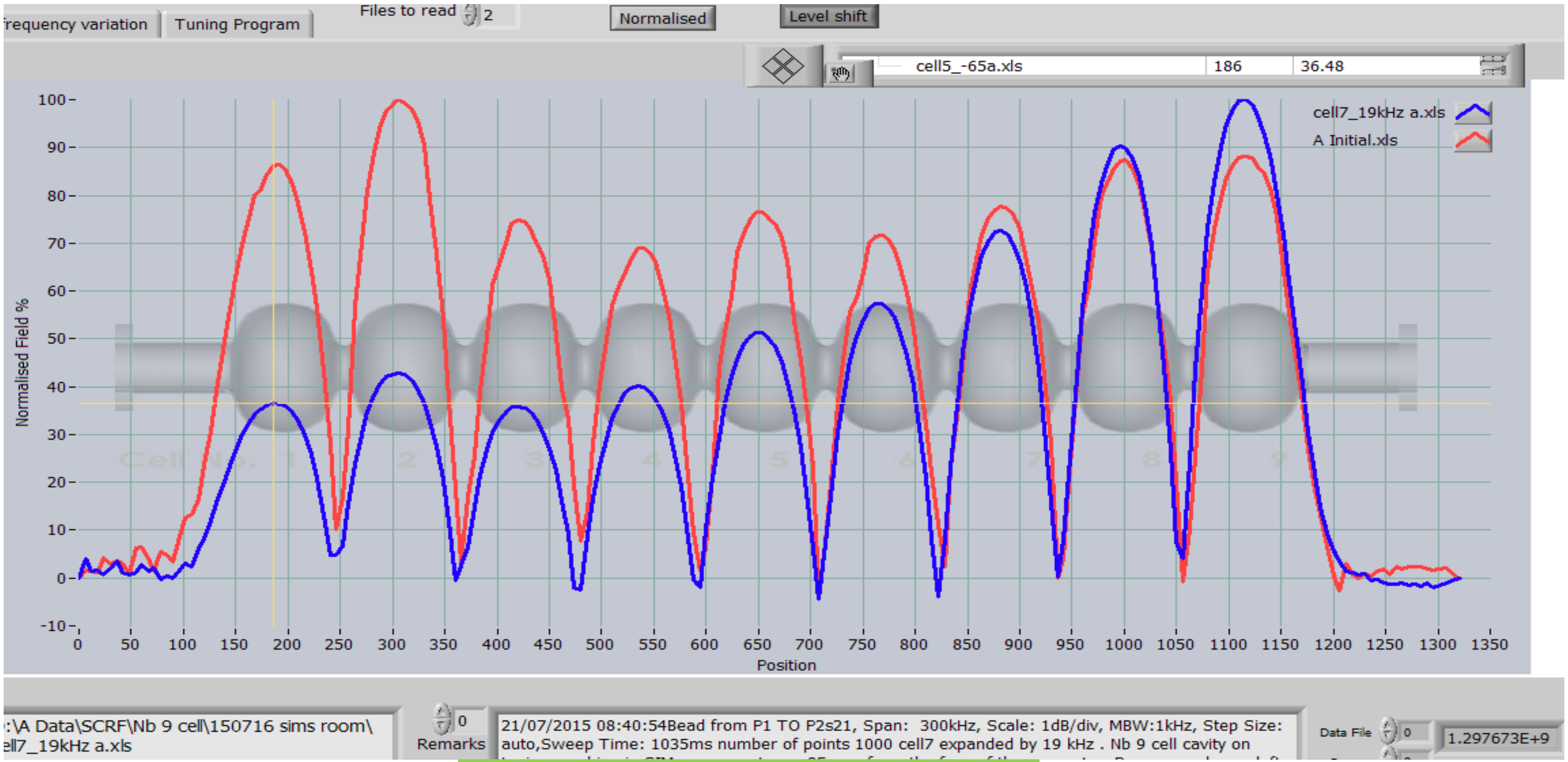
Compression correction: -881.632 kHz

Expansion correction: 268.6329 kHz

Net correction:-612.999 kHz

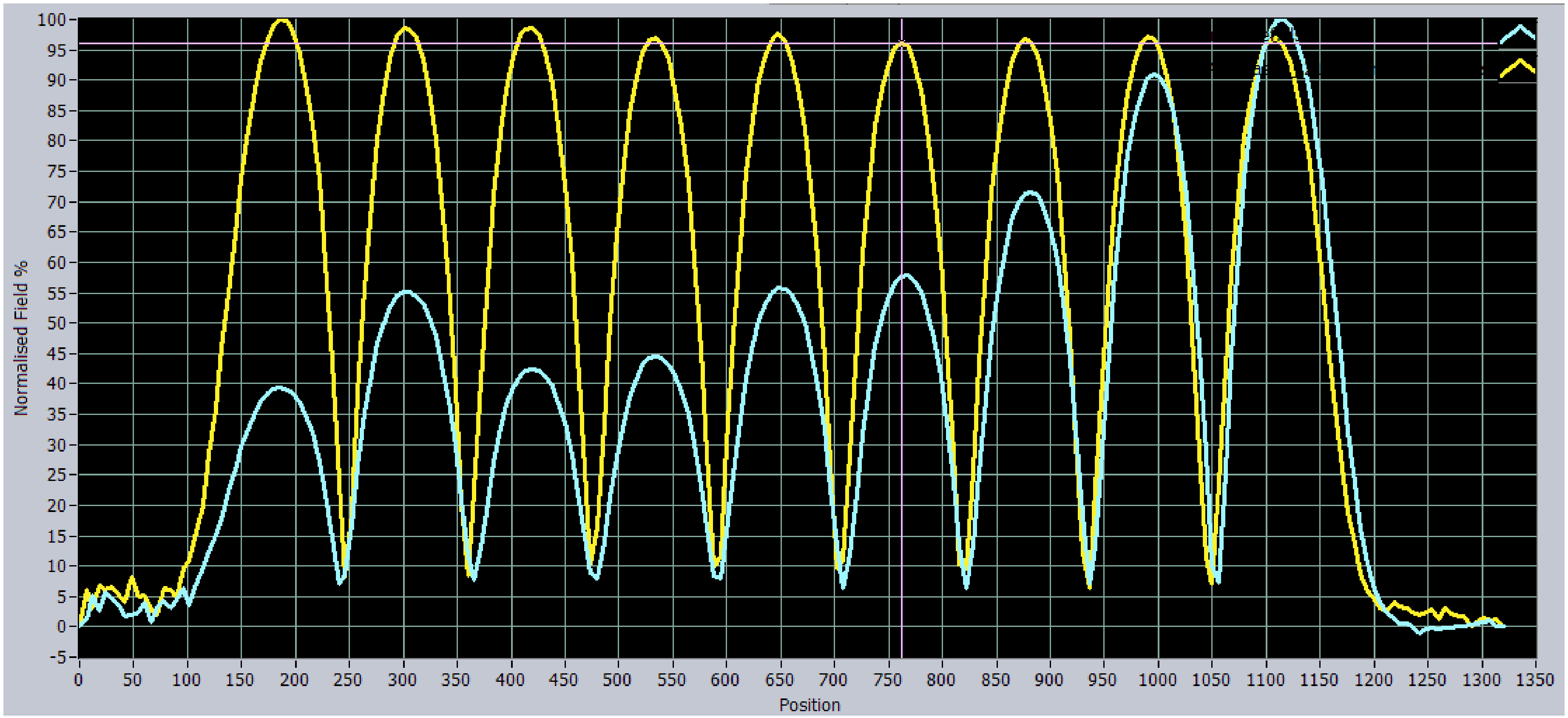
Cavity tuning using semi-automatic tuning machine

Initial Field flatness: 43% Intermediate Stage Field flatness: 70%



Relative electric field plot
(Intermediate Stage of iteration)

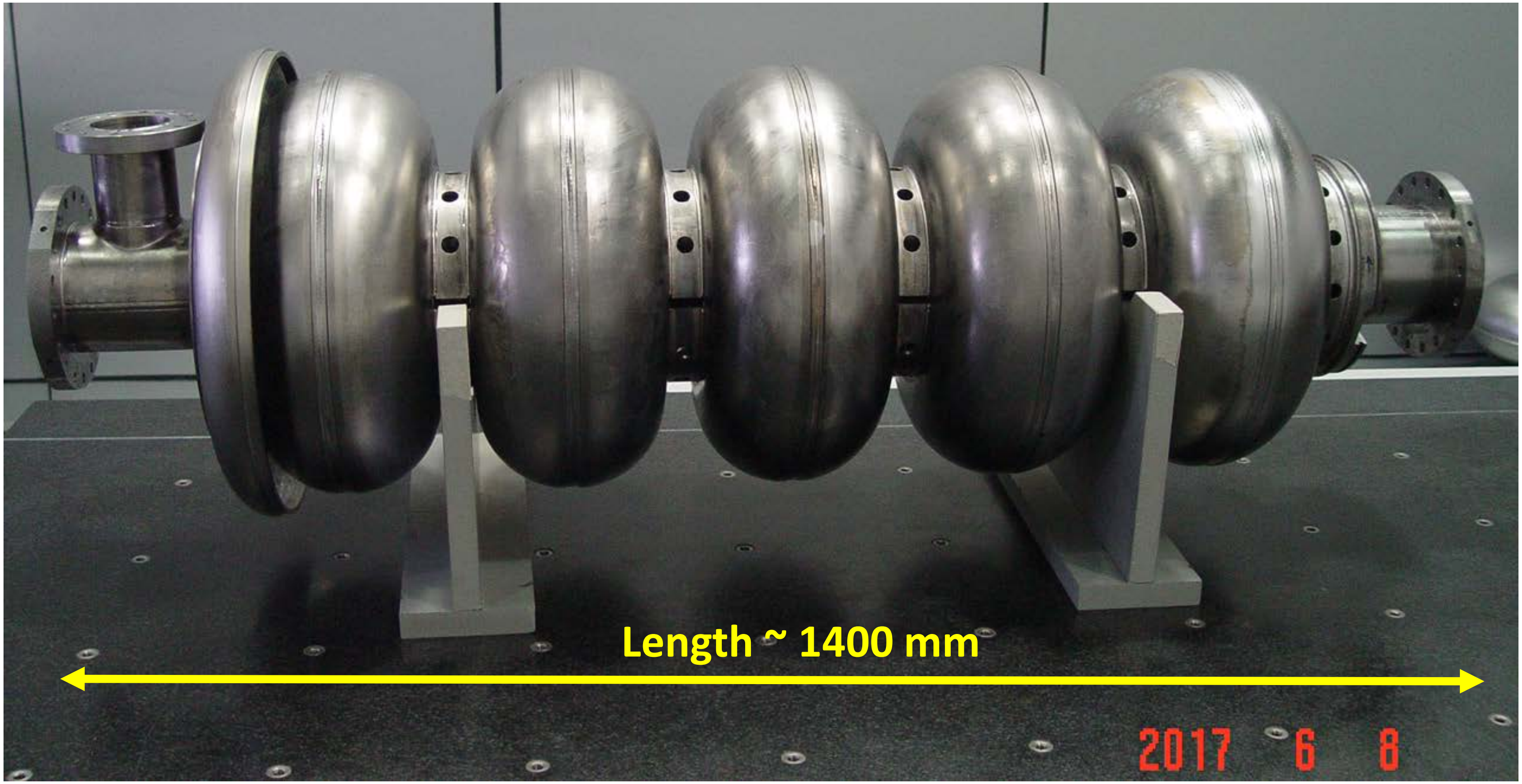
Cavity tuning using semi-automatic tuning machine



Relative electric field plot (After Final Stage of iteration)

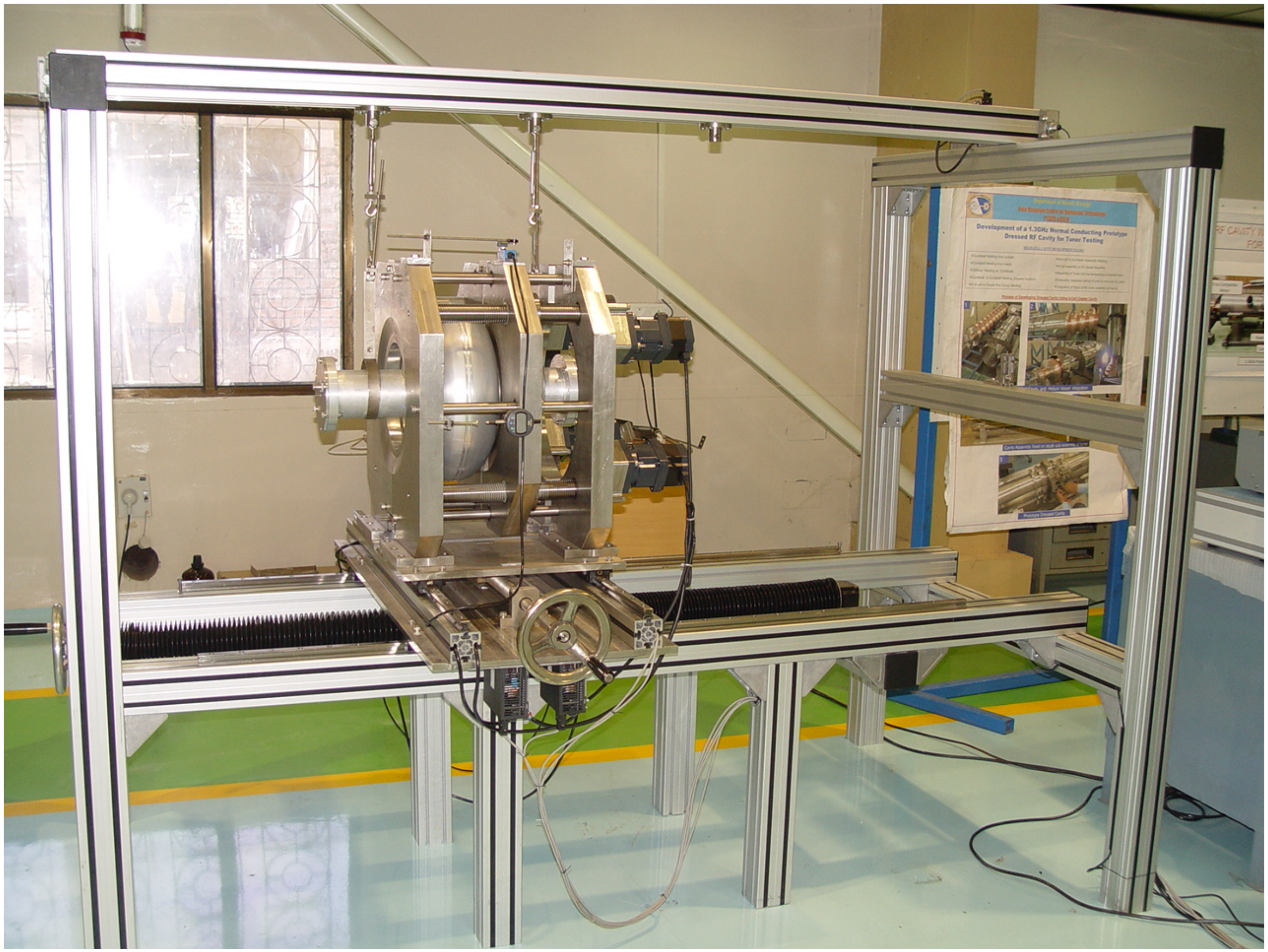
RF parameter	Initial	Final	Desired
Frequency (GHz)	1.2969	1.29738	1.29740
Field Flatness (%)	23.8	97	≥ 95

Cavity tuning using semi-automatic tuning machine



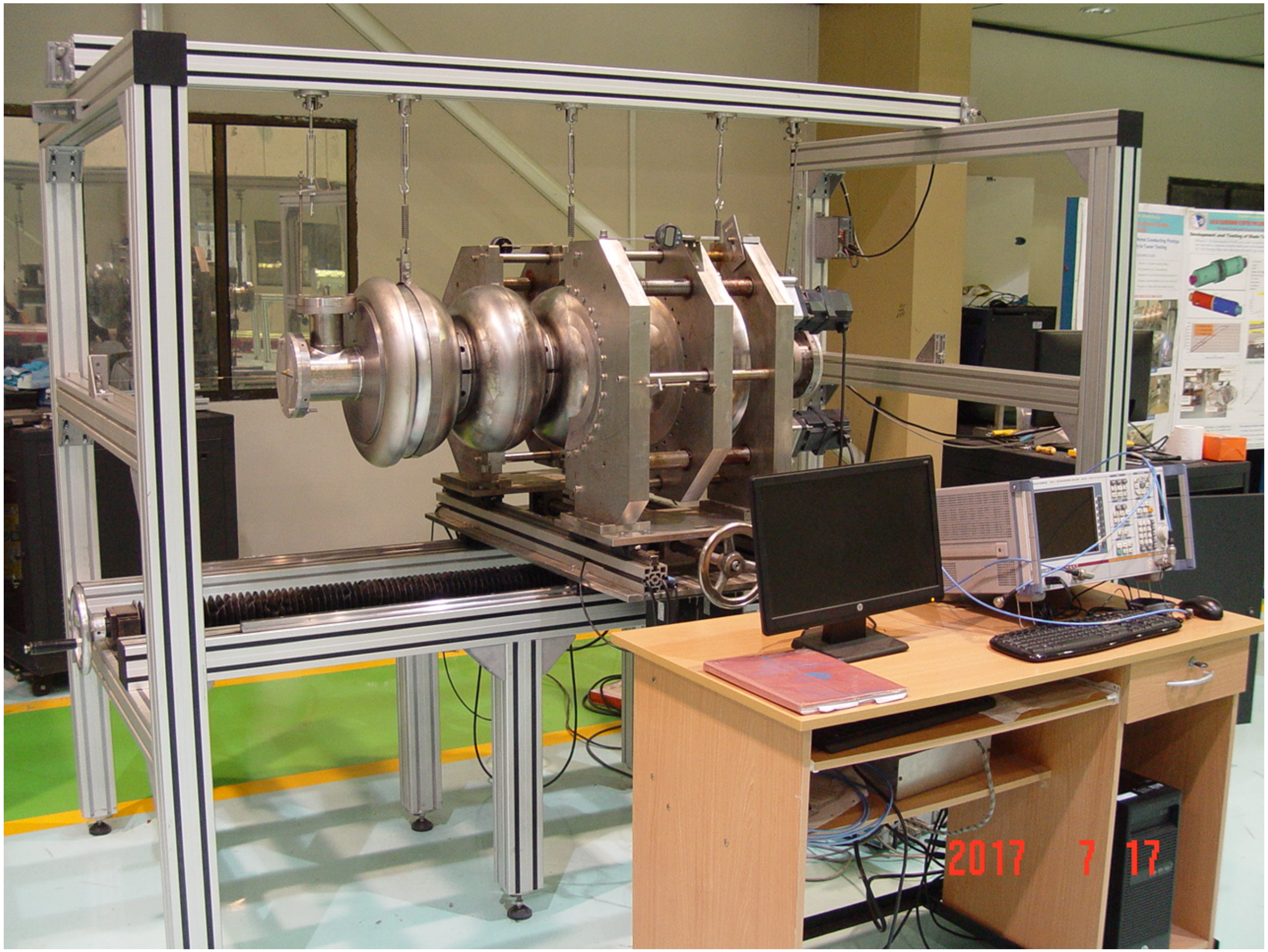
650 MHz β0.92 Five Cell SCRF cavity

Cavity tuning using semi-automatic tuning machine



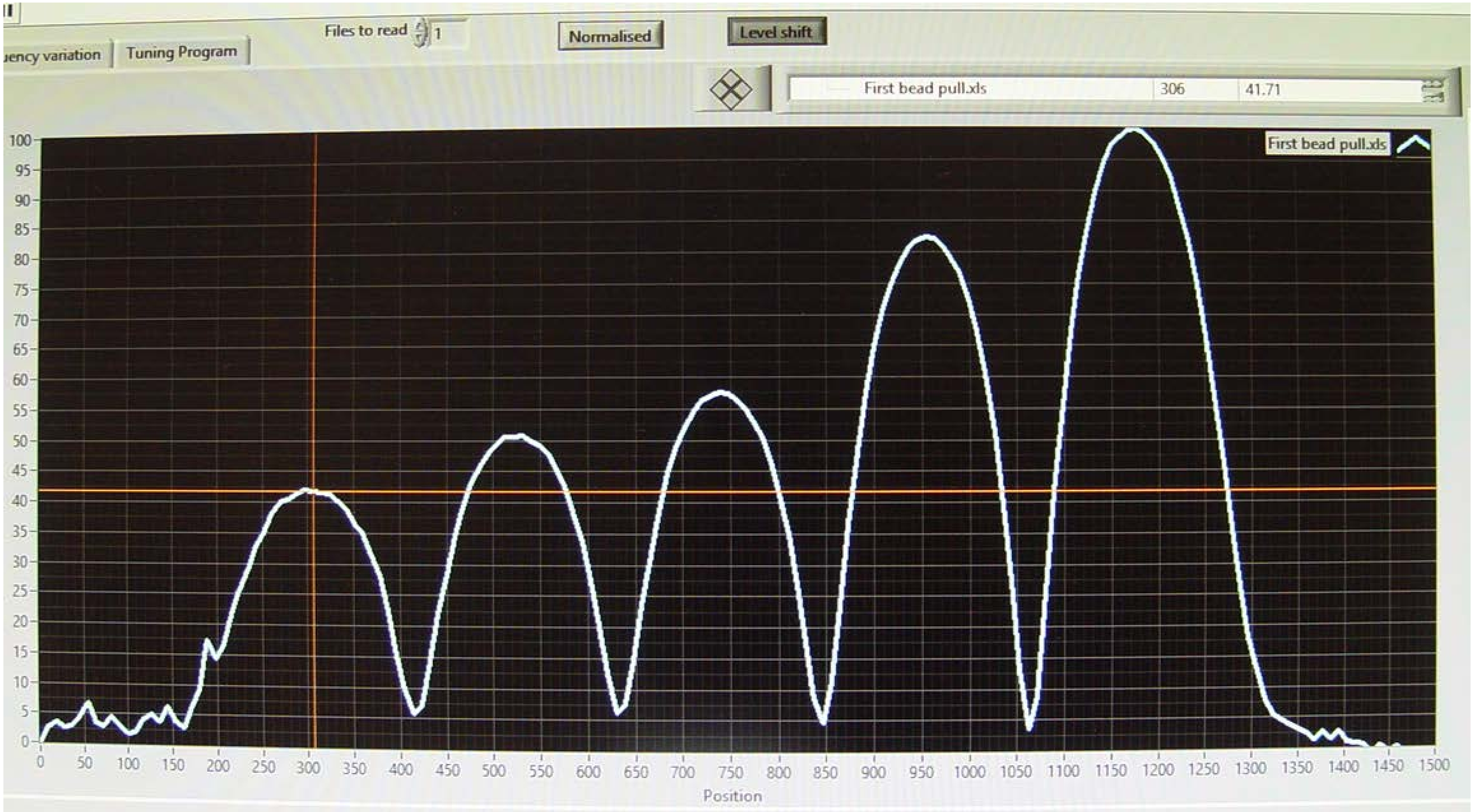
Single cell 650 MHz aluminium cavity mounted for system trials

Cavity tuning using semi-automatic tuning machine



650 MHz β0.92 Five Cell SCRF cavity mounted machine for tuning operation

Cavity tuning using semi-automatic tuning machine



Relative electric field plot of as received 650 MHz β0.92 five cell cavity (after welding)

RF parameter	Initial	Desired
Field Flatness (%)	~ 40	≥ 90

Cavity tuning using semi-automatic tuning machine

DAE Group Achievement Award

Title :- Development of a tuning machine for 1.3 GHz nine cell superconducting RF cavity

Year :- 2015

Group Leader – Shri S. C. Joshi, OS & Head PLSCD, RRCAT, Indore

Thank You