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Balloon Tuning Technique for SRF Cavities

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Final Report

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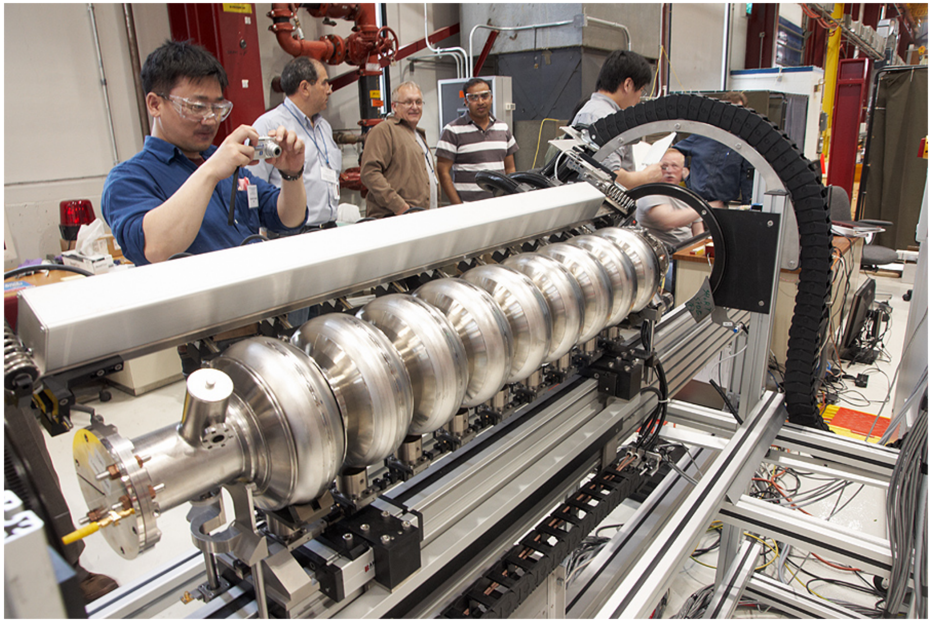
Introduction

- An SRF Cavity is a niobium resonating structure that contains an electromagnetic field.
  - At low temperatures niobium behaves like a superconductor and exhibits ultra low losses (Resistance ~ $10^{-9}\,\Omega$).

- The Cavity is formed to a specific **size** and **shape**.
  - Electromagnetic wave become **resonant** in different modes and build up inside.

Frequency of resonance

Keeping an SRF cavity at the exact **frequency of resonance** is crucial for the particle accelerator.

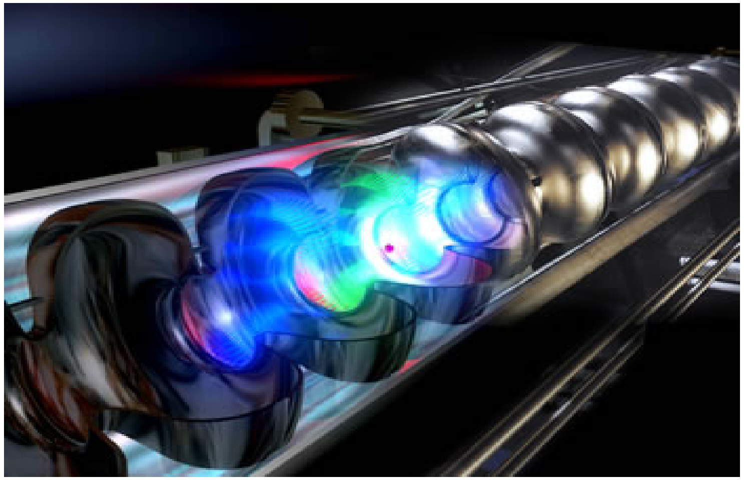


- The control of an operating cavity resonance frequency is achieved by **elastically** deforming the structure through a tuning mechanism.
- When the cavity is not under operation, an **inelastic** tuning may be performed, as shown in the Figure.

Field Flatness

- Having equal electromagnetic **field amplitudes** in the cells is needed to achieve the desired accelerating gradient values.

  - **Field Flatness** (FF): ratio between the lowest and the highest on axis electric field amplitude in all the cavity cells.
  - FF > 0.9 needed for an appropriate cavity operation.
  - FF adjustments made by deforming the niobium structure: **plastic cavity tuning**.



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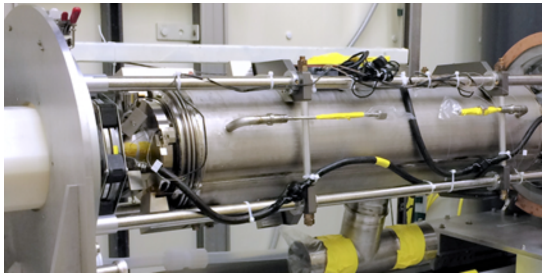
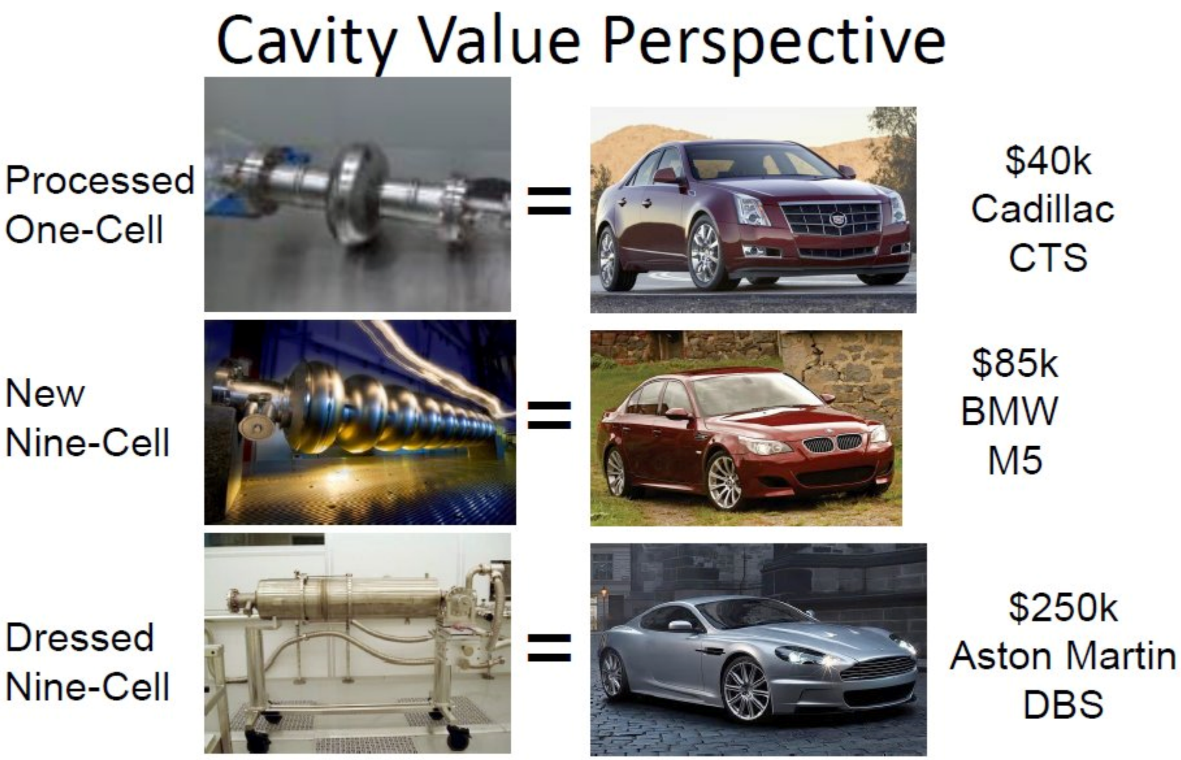
Adjustments

- Actual manufacturing process cannot guarantee a sufficient grade of precision for both frequency and field flatness.
- Cavity preparation steps cause **frequency shifts** and **FF deterioration**.
- Adjustments techniques are mature for bare cavity, but inefficient and expensive for dressed ones.



LCLS-II: Dressed cavity FF issues

- In LCLS-II experiment, a **dressed** cavity accidentally suffered a plastic deformation during the insertion in the cryomodule.
  - Significant FF deterioration: cavity **not usable** anymore.



- Cavities are **expensive** structures.
- Dressed cavity FF adjustment is almost as expensive as the cavity is.

Dressed cavity adjustments

- When a dressed cavity shows FF issues, the current solution consists of:
  - Removing the outermost vessel
  - Fixing frequency and FF by the tuning machine
    - Cells deformation
  - Welding a new helium tank around the cavity

- The procedure is delicate, full of risks and **expensive** (~$200k).

- **Innovative** tuning techniques should be investigated to have an easy way for a dressed cavity retuning and field correction.

Balloon Tuning Technique (BTT)

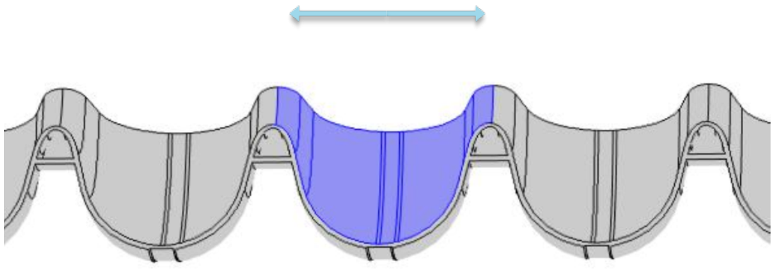
- **Balloon Tuning Technique**: a **novel** possible tuning solution for dressed multi-cell cavities, using pressurized balloons.

- Features:
  - Control the **deformation** of each single cell →
    - Compression
    - Extension
  - Improve the FF (above 90%)
  - Inexpensive

- Significance: minimize the impact of a production failure in a large-scale leading project, such as PIP-II and LCLS-II.

BTT: Cell deformation effects

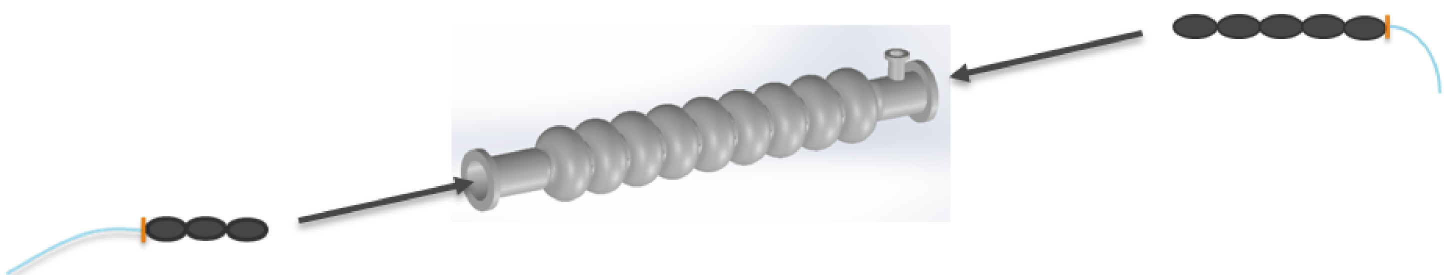
- Goal:
  - Permanent change in the **iris-to-iris** distance of a targeted cell.
    - Resonance frequency retuning
    - Cell field amplitude adjustment



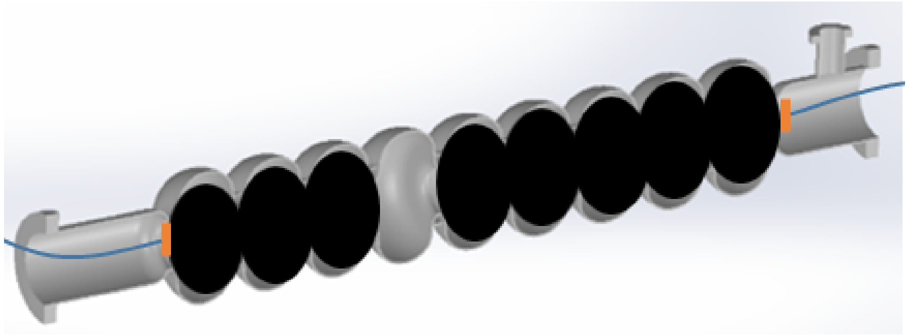
- Compression produces a decrease in both frequency and field amplitude, whereas expansion produces an increase.

Balloon Tuning Concept, Targeted Cell Compression

- Suppose Cell 4 must be **compressed**, in order to decrease the resonance frequency and the field amplitude.
- Deflated balloons are folded and placed in <u>all the other cells</u>.

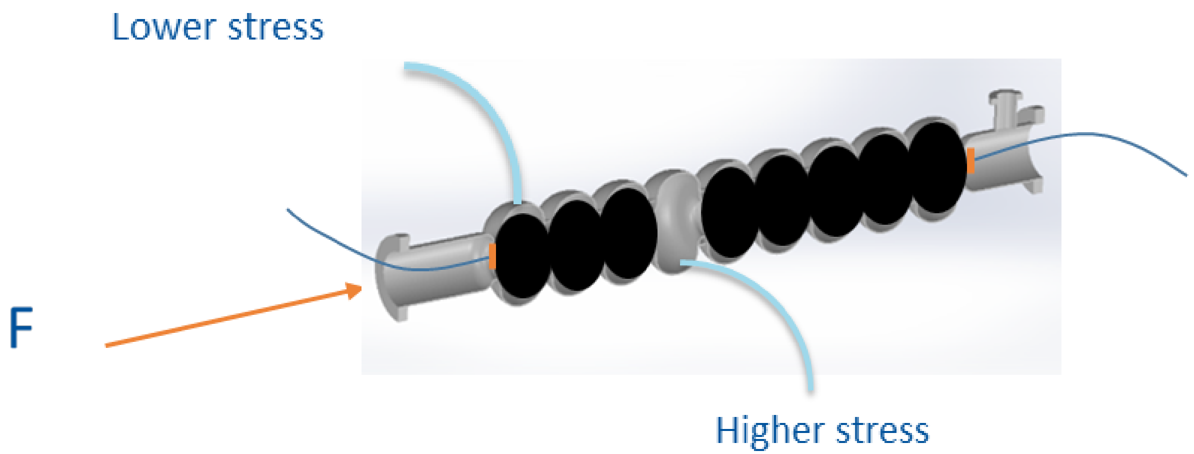


- Once inside, balloons get **pressurized**.



Balloon Tuning Concept, Targeted Cell Compression

- A compression **force** is applied by the tuner to the first end flange, whereas the other flange remains fixed.

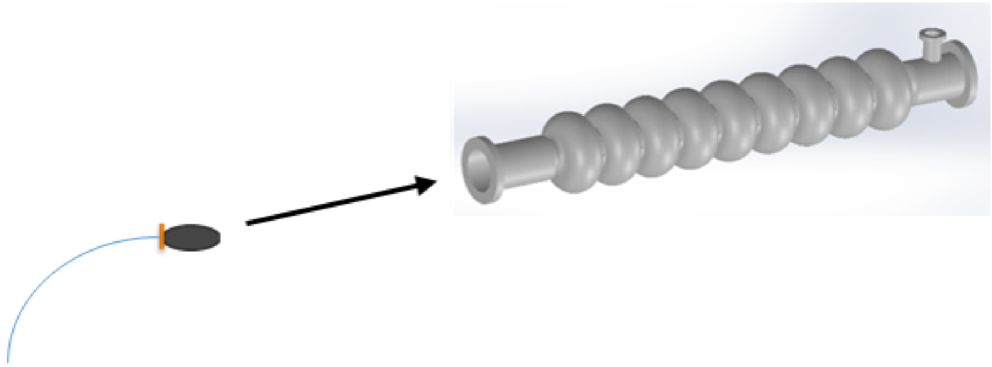


- The targeted cell gets **plastically** deformed.

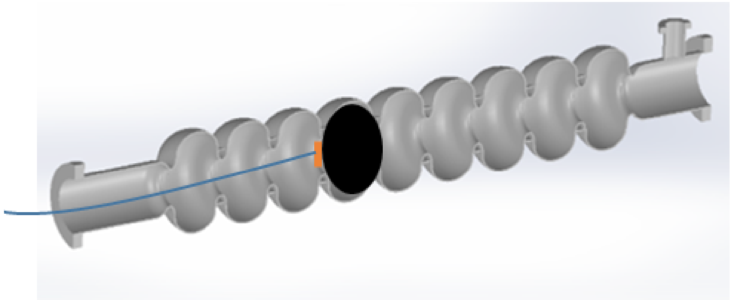
- All the other cells remain in the linear **elastic** region because of a lower stress state.

Balloon Tuning Concept, Targeted Cell Expansion

- Suppose Cell 4 must be **expanded,** in order to increase the resonance frequency and the field amplitude.
- A deflated balloon is placed just in Cell 4.

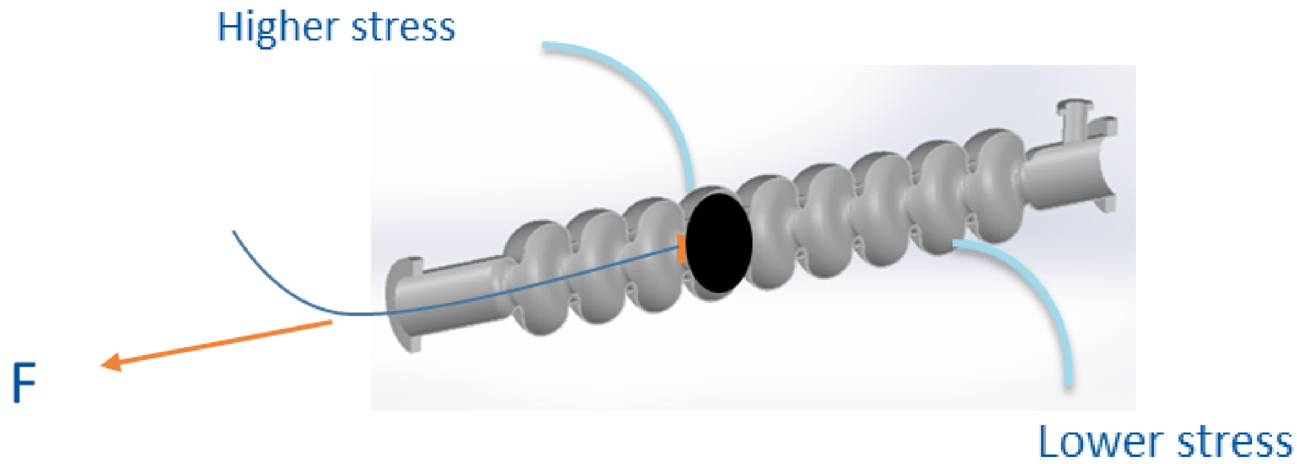


- Once inside, the balloon gets pressurized.



Balloon Tuning Concept, Targeted Cell Expansion

- A traction **force** is applied by the tuner to the first end flange, whereas the other flange remains fixed.



- The targeted cell gets **plastically** deformed.

- All the other cells remain in the linear **elastic** region because of a lower stress state.

FE Analysis: validation of the concept

- FE analysis has been performed in order to validate the Balloon Tuning Concept.
  - Verify the existence of a **differential stress** between the targeted cell and all the other ones.

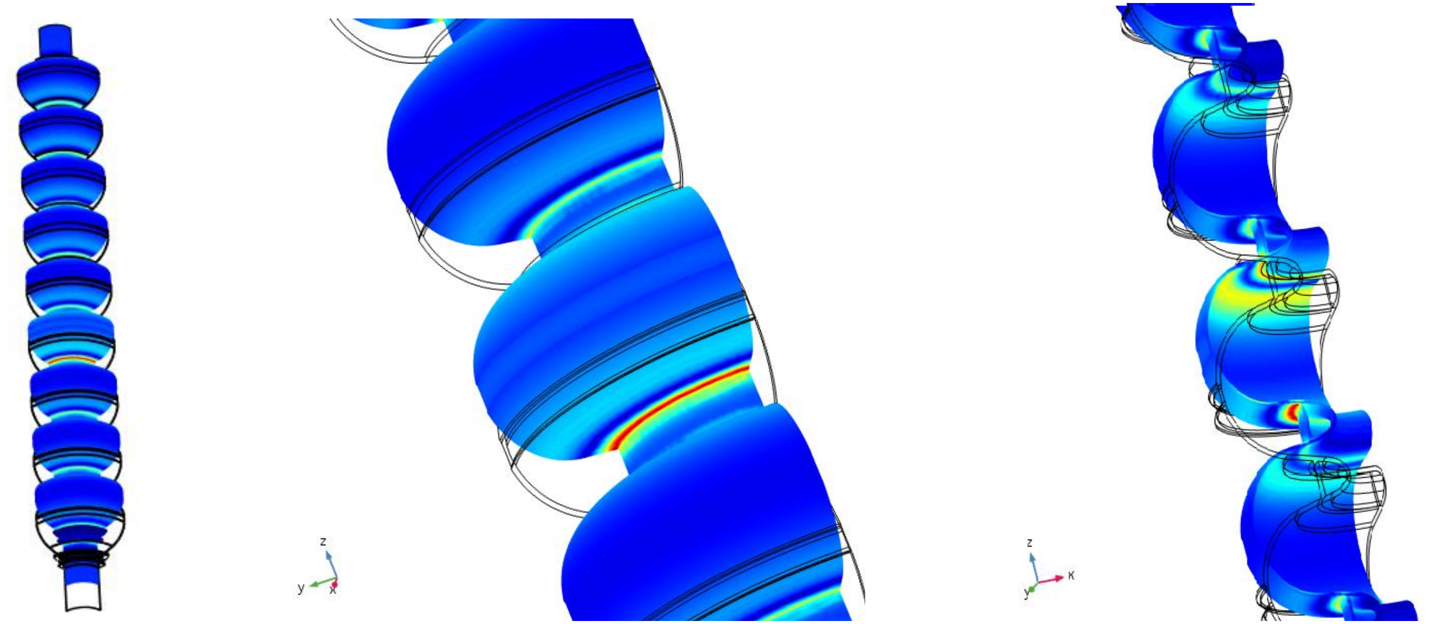
- Simulations made for each single cell separately, in both compression and extension.
  - Parametric Sweep over
    - **Balloon Pressure**, P → {1.5, 2, 2.5} bar
    - Compression/Traction **Force**, F → {2, 3, 4, 5, 6, 7, 8} kN

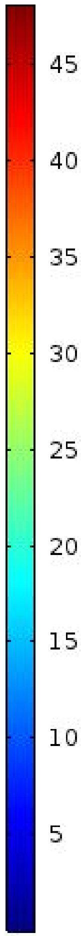
- We expect:
  - Similar results for **Middle Cells** (2-8)
  - Slightly different results for **End Cells** (1 and 9)

Compression Case, Results – Middle Cells

For example, Cell 4 Compression

- 3D Plot of von Mises Stress along the cavity [MPa], P = 2 bar and F = 4 kN



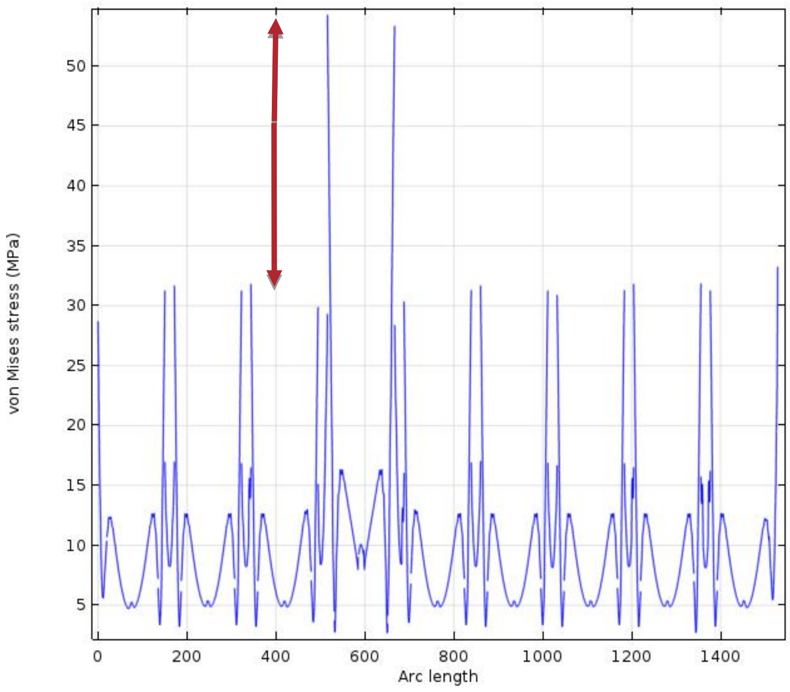


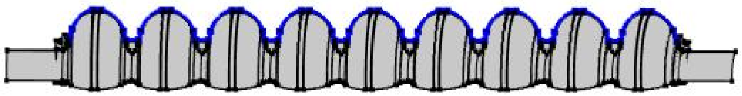
- Higher stress values appear in Cell 4, as expected.

Compression Case, Results – Middle Cells

Cell 4 Compression

- 2D Plot of von Mises Stress along the profile [MPa]
  - P = 2.5 bar and F = 4kN





- **Stress Spikes** localized on cell iris.
- The mechanism is based on the differential stress between Cell 4 and Other Cells.

- Equal results obtained for the other middle cells.

Working Point (F, P) Selection

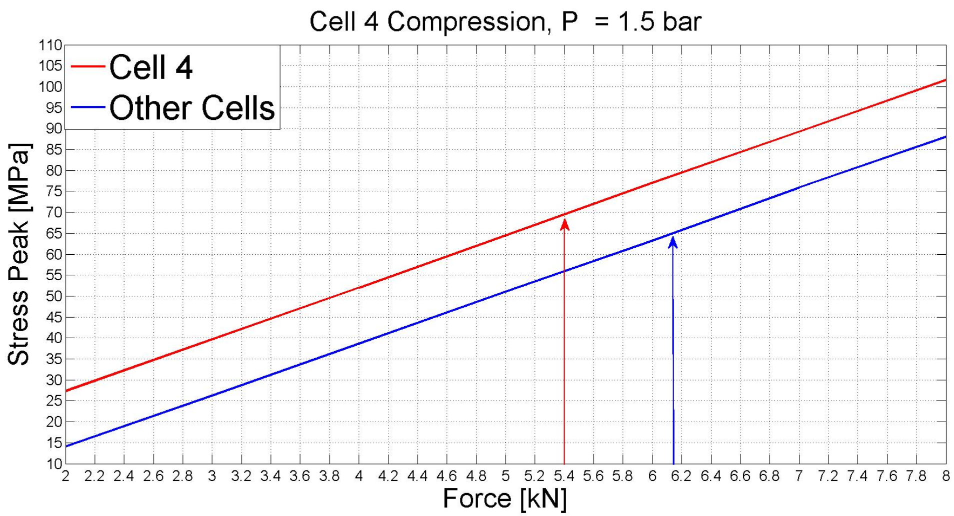
- Niobium **Yield Stress** is approximately 70 MPa

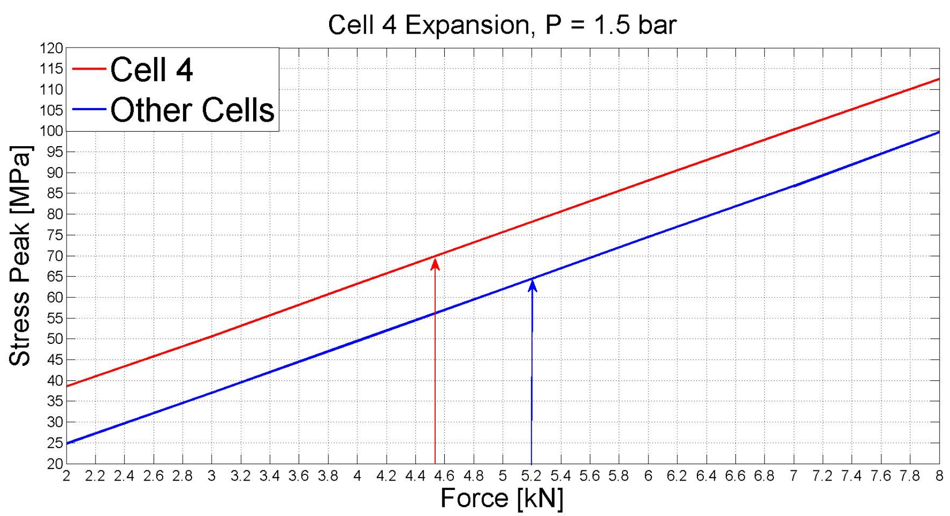
- Our goal is to produce
  - Plastic deformation in the Targeted Cell
  - Elastic deformation in all the Other Cells

- So, for each Cell, we have to select a suitable combination of applied force and balloon pressure in order to have:
  - Peak Stress Value on the Targeted Cell > 70 MPa
  - Peak Stress Value on the Other Cells < 65 MPa

- In the following section this study is reported for Middle and End Cells, in both compression and extension cases.

P = 1.5 bar, Middle Cell





- Red arrows indicate the **minimum** Force needed for targeted cell plastic deformation.
- Blue arrows indicate the **maximum** Force we can apply to avoid plastic deformation of the other cells.
- We can choose a working point in the region **between** arrows.

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Working Point Selection, Tables

Pressure (bar)	Working Region (kN) Compression	
	Middle Cell	End Cell
1.5	5.40 – 6.15	5.55 – 6.10
2	5.35 – 6.40	5.48 – 6.40
2.5	5.30 – 6.70	5.40 – 6.70

Pressure (bar)	Working Region (kN) Expansion	
	Middle Cell	End Cell
1.5	4.52 – 5.20	4.65 – 5.20
2	4.20 – 5.20	4.30 – 5.20
2.5	3.80 – 5.20	3.90 – 5.20

FE Analysis: Multiphysics Simulation

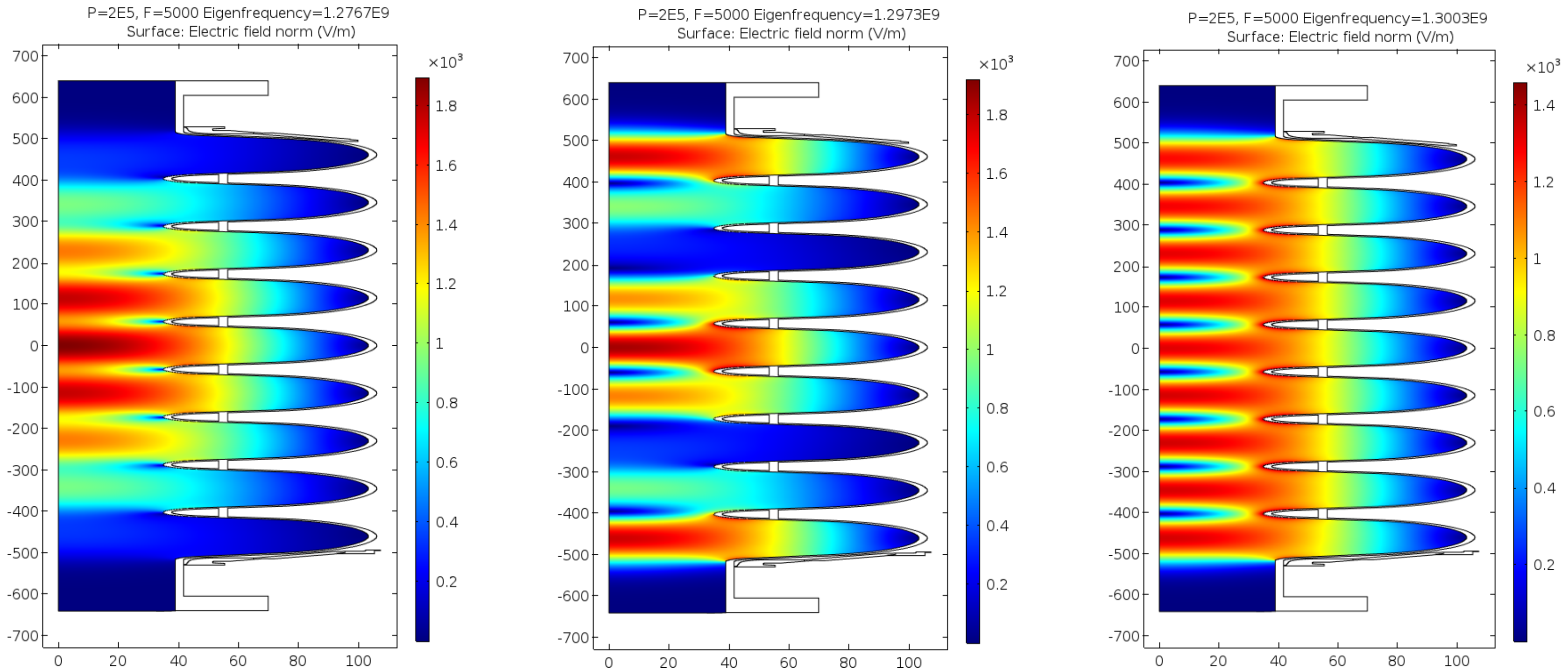
- The **loading** process has been studied by means of a Multiphysics Analysis (COMSOL):
  - Solid Mechanics → Stationary Study
  - Electromagnetic Waves → Eigenfrequency Study
  - Moving Mesh

- Understand how the resonance frequency would change during a targeted cell expansion and compression.

- Simulations were made for a Mid Cell and End Cell, in both compression and expansion cases.

Pi-Mode Selection

- Electromagnetic field may resonate in 9 <u>different modes</u>.
- **Pi-mode** selection: fields in adjacent cells must be π radians out of phase with each other so as to produce acceleration.



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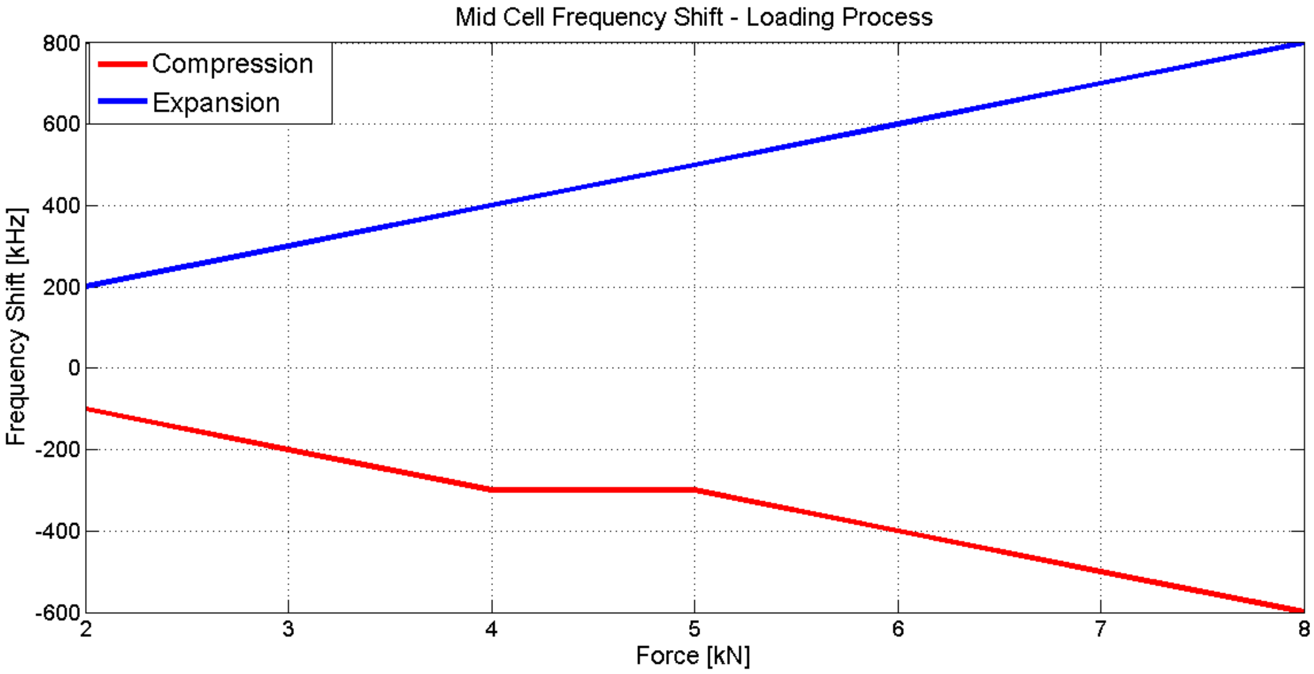
Loading Process Frequency Shift

- Cavity Pi-Mode Eigenfrequency at rest is 1.3006 GHz.
- The Pi-mode Eigenfrequency variation is represented for a Mid Cell loading process.



- Such a result does not represent a permanent frequency shift, since an **elastic recovery** should be taken into account.

Experimental Tests

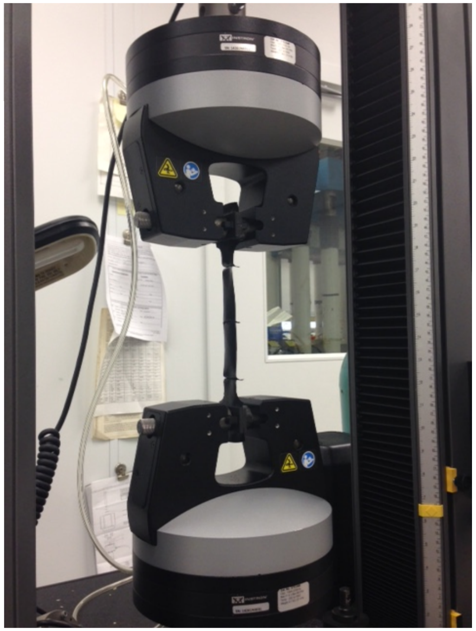
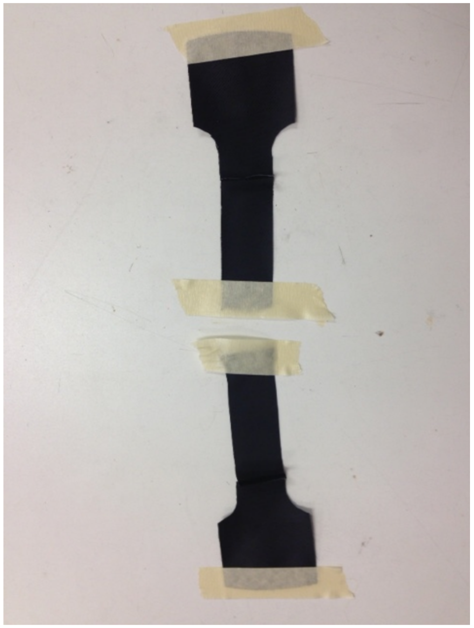
- A set of experimental tests were performed so as to start the BTT validation process.

- **Preliminary** steps:
  1. Tensile test on balloon material samples
  2. Pressure test on a 1-cell balloon

- **Final** steps:
  1. Cavity field profile and resonant frequency measurement before tuning
  2. Expansion test on a Mid Cell
  3. Modified field profile and resonance frequency analysis after tuning

Material Tests – Balloon material

- A tensile test was performed on three samples of the balloon material, i.e. **rubberized nylon**.
  - Room temperature
  - Tensile Elongation velocity: 2 mm/min

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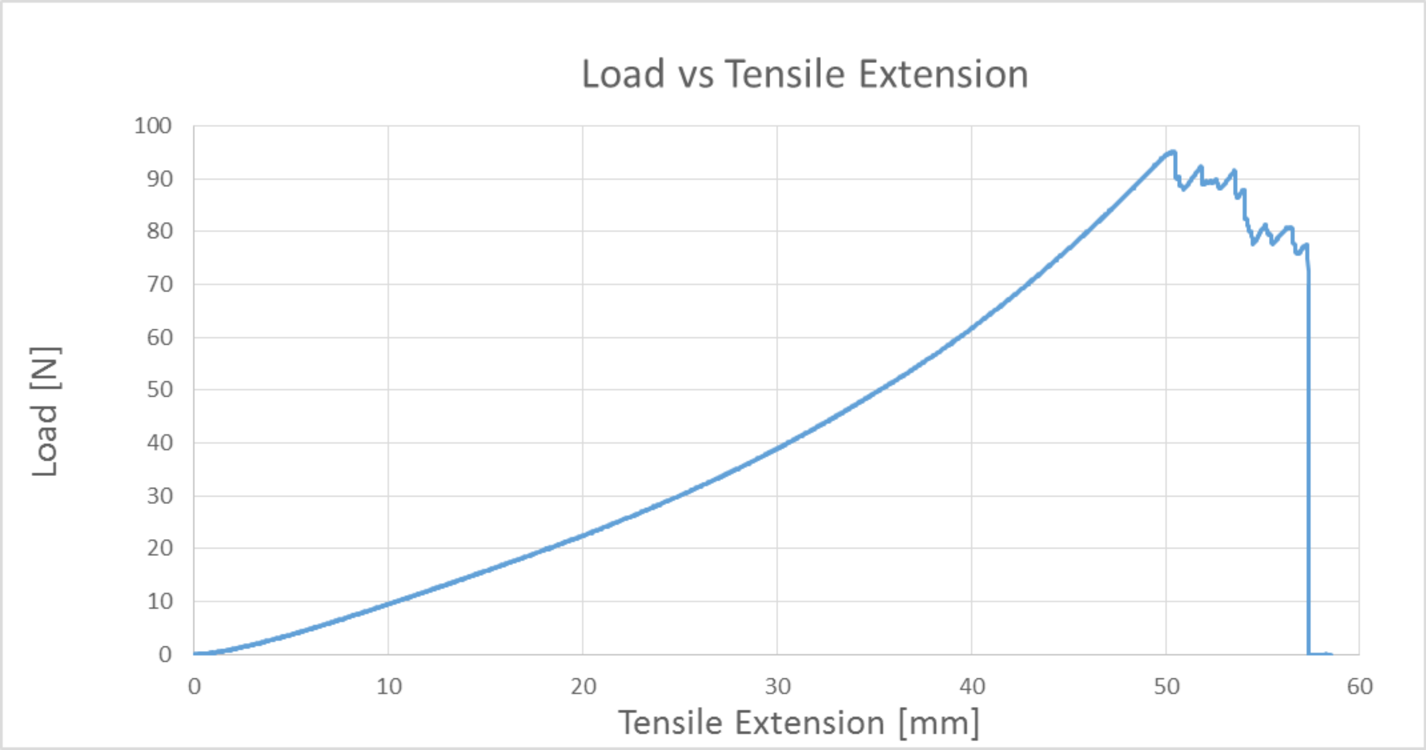
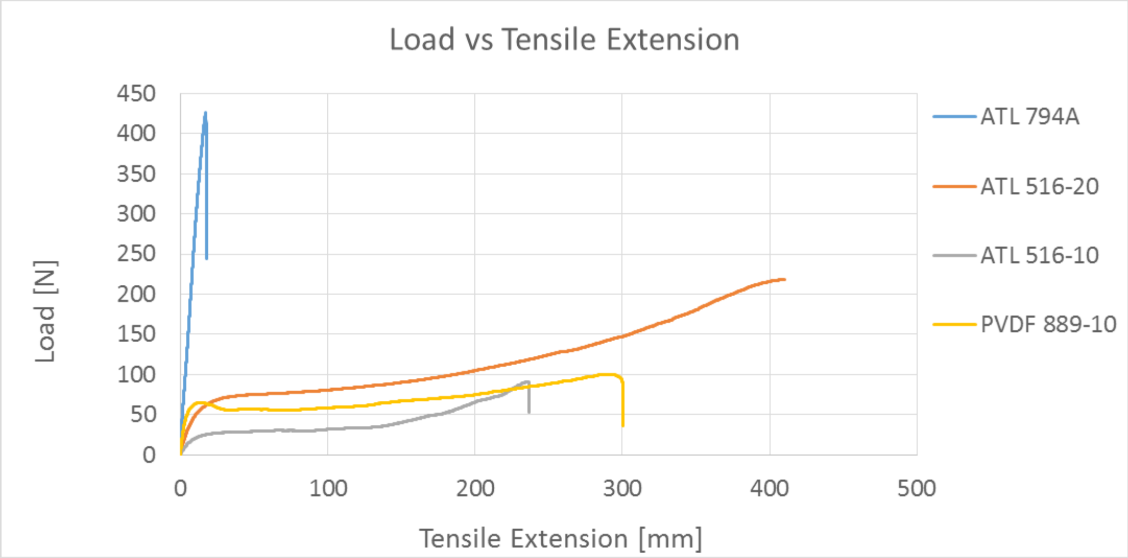
Tensile Test Results – Balloon material



Test results		
Maximum Load [N]	Maximum Tensile Extension [mm]	Percent Elongation at Break
95.12	58.50	38.74%

Tensile Test Results – Alternative materials



- **ATL 516-20** and **PVDF 889-10** show an amazing **ductility** and could represent an interesting alternative.

	Initial geometrical values [mm]			Test results		
	Length	Width	Thickness	Max. Load [N]	Max. Tensile Extension [mm]	% Break Elong.
ATL-794A	89	25	0.31	425.80	17.49	20.34%
ATL 516-20	85	25	0.56	217.84	410.18	482.57%
ATL 516-10	73	25	0.28	90.80	236.83	324.42%
PVDF 889-10	72	25	0.23	99.80	300.736	417.69%

1-Cell Balloon Pressure Test – Lab 2

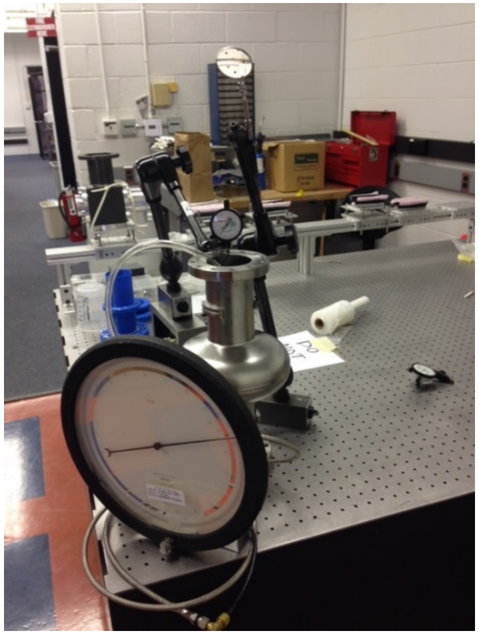
- The balloon has been designed at Fermilab and produced by an external vendor.

- When inflated, the balloon
  - reproduces the cell shape
  - is slightly **bigger** than a cell.

- After the balloon material qualification, a **pressure test** was performed on the constrained 1-Cell balloon.
  - Verify the balloon is able to bear a **2 bar** internal pressure.

1-Cell Balloon Pressure Test – Lab 2

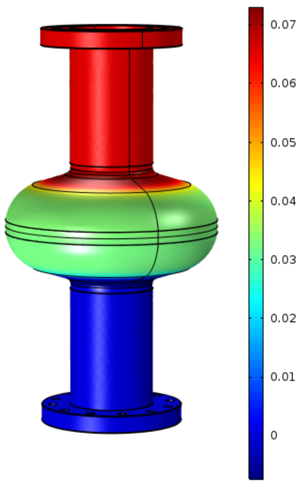
- Deflated balloon placed into a 1.3 GHz one-cell Niobium cavity (NR005).
- Balloon pressurized up to 2 bar, with a step of 0.1 bar.
- A strain gauge was placed on the cavity top flange, so as to measure the **axial displacement**.

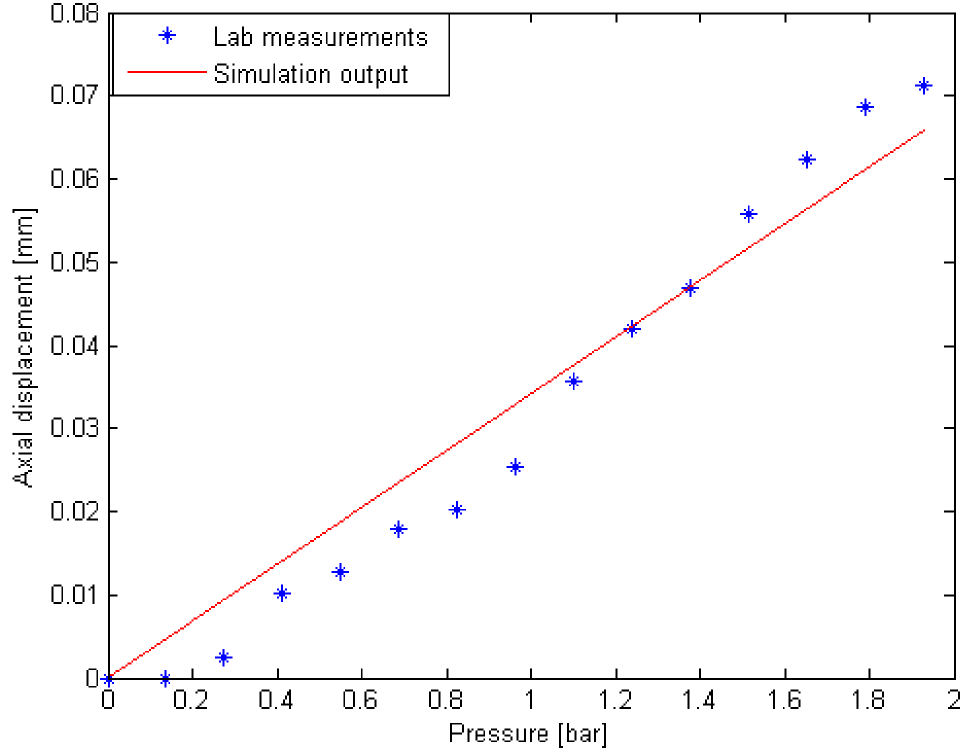


1-Cell Balloon Pressure Test – Results

- The balloon was **qualified** for a pressure of 2 bar.
    - A 2 bar pressure is sufficient for a Working Point existence.

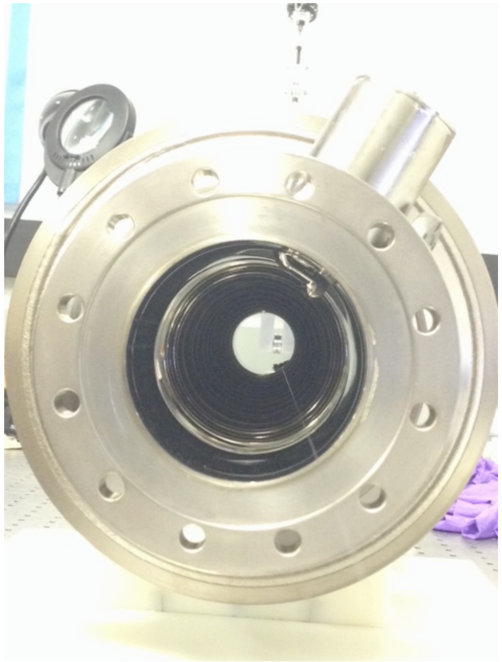
- **Matching** between axial displacement measurements and simulation results.



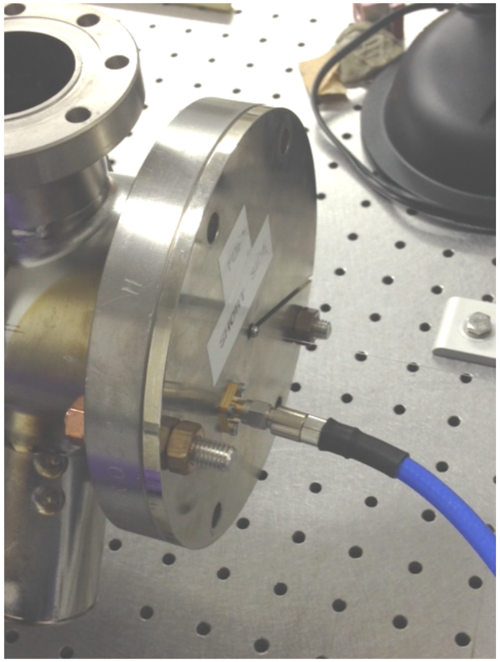


9-Cell Cavity Preliminary Measurements

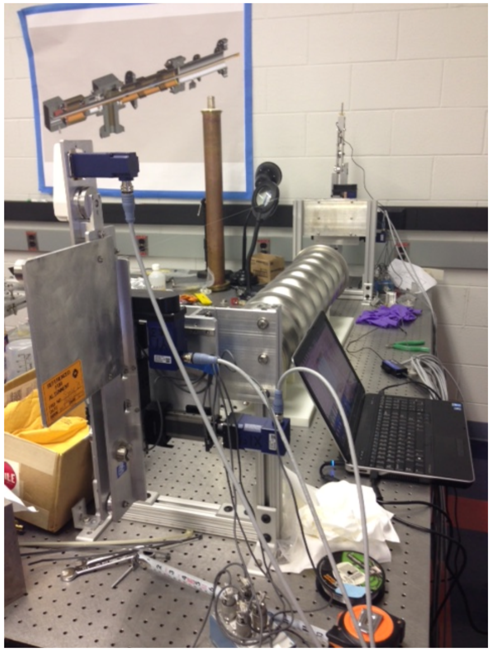
- A **Bead Pulling Measurement** was performed three times on a 9-Cell 1.3 GHz cavity (NR002)



Perturbing bead **alignment** to cavity axes



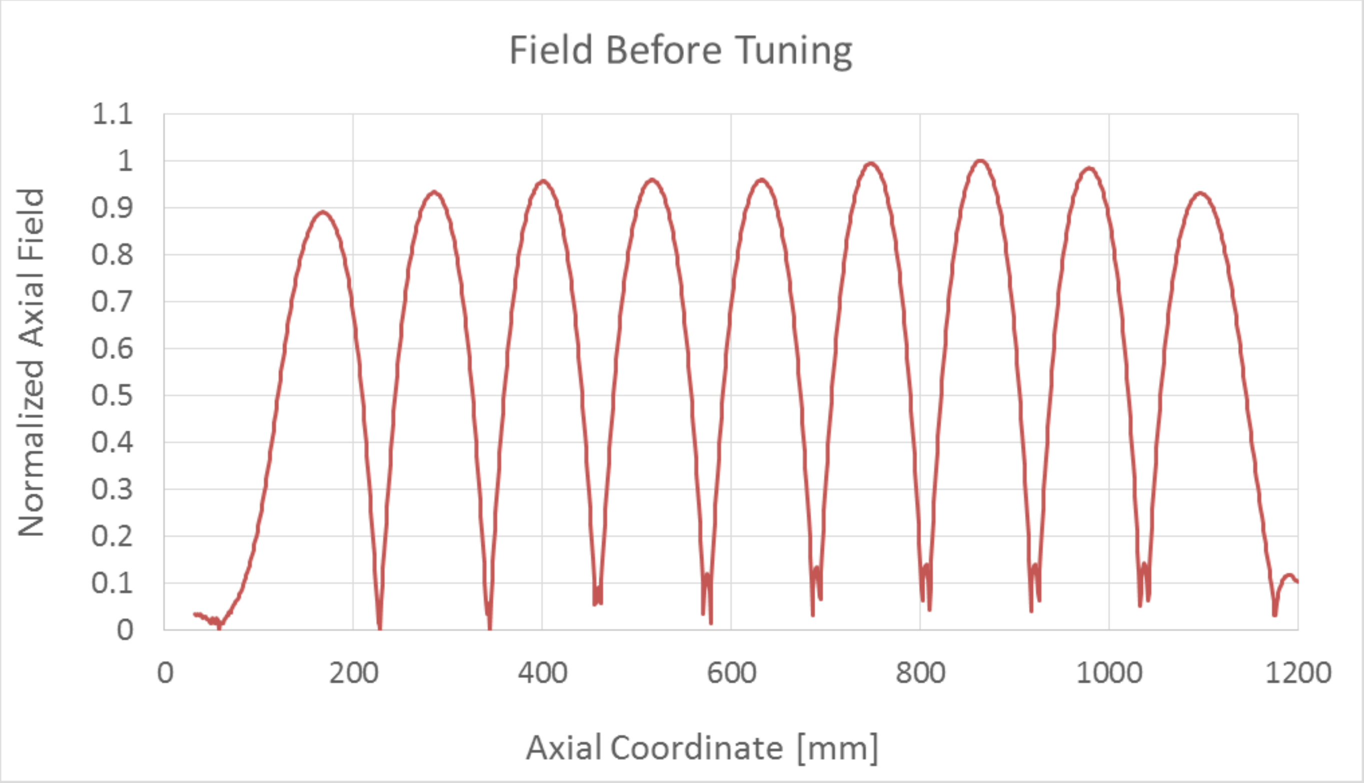
RF power injection and bead access



Real time data acquisition

9-Cell Cavity Preliminary Measurements

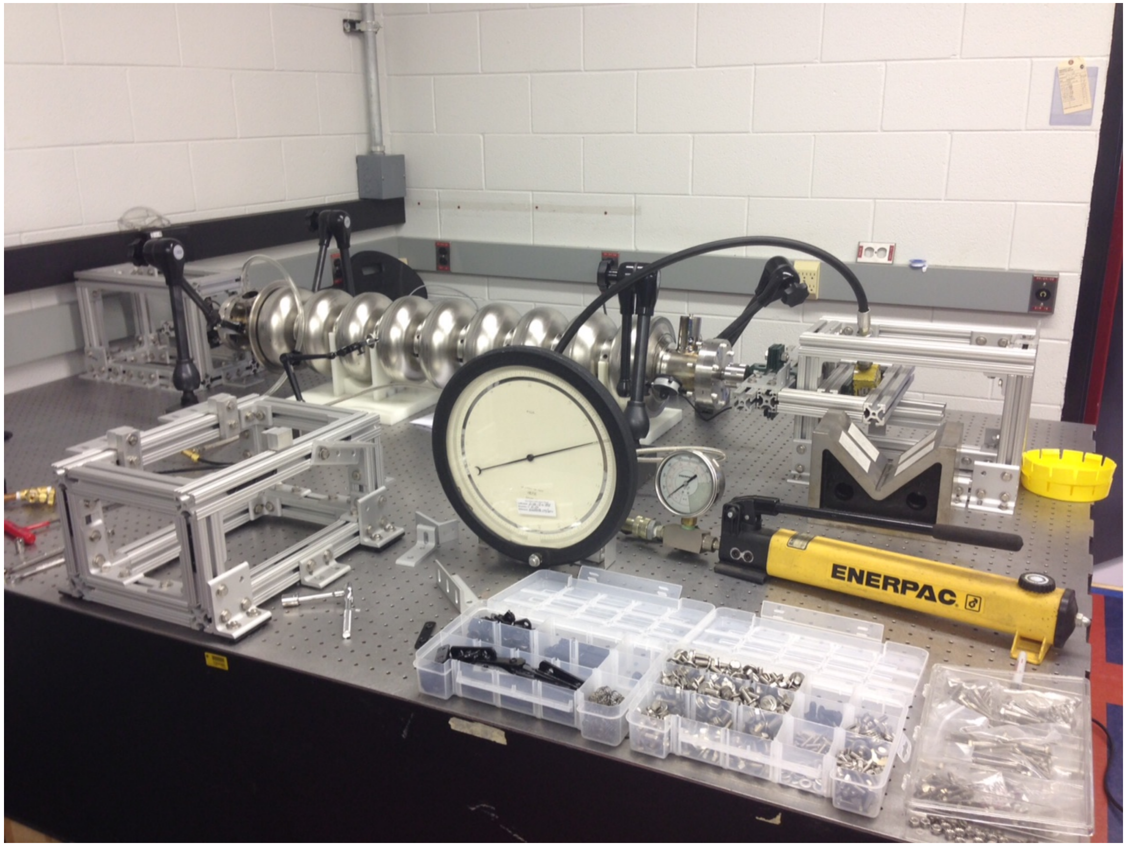
- Cavity resonant **frequency** before tuning is equal to 1297.338 MHz.



- **FF** measured value is 0.88.

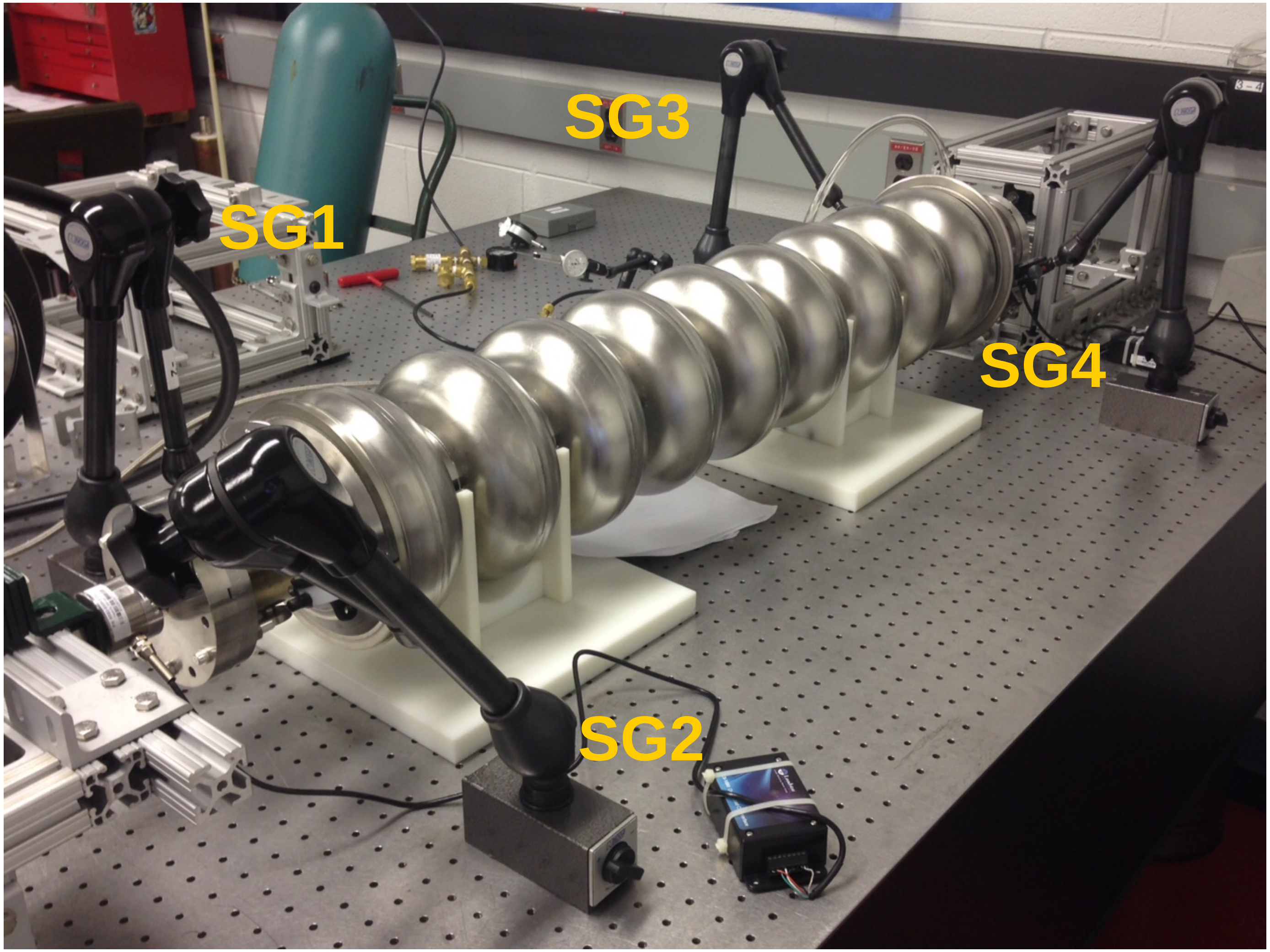
Expansion Test, Lab 2

- An expansion test was attempted on our 9-cell 1.3 GHz cavity, Cell 2.



- Balloon pressurized at 2 bar in Cell 2.
- Traction **force** applied by an hydraulic actuator on one flange.
- Two load cells used for
  - load control
  - **friction** evaluation.

Expansion Test, Strain Gauge Positioning



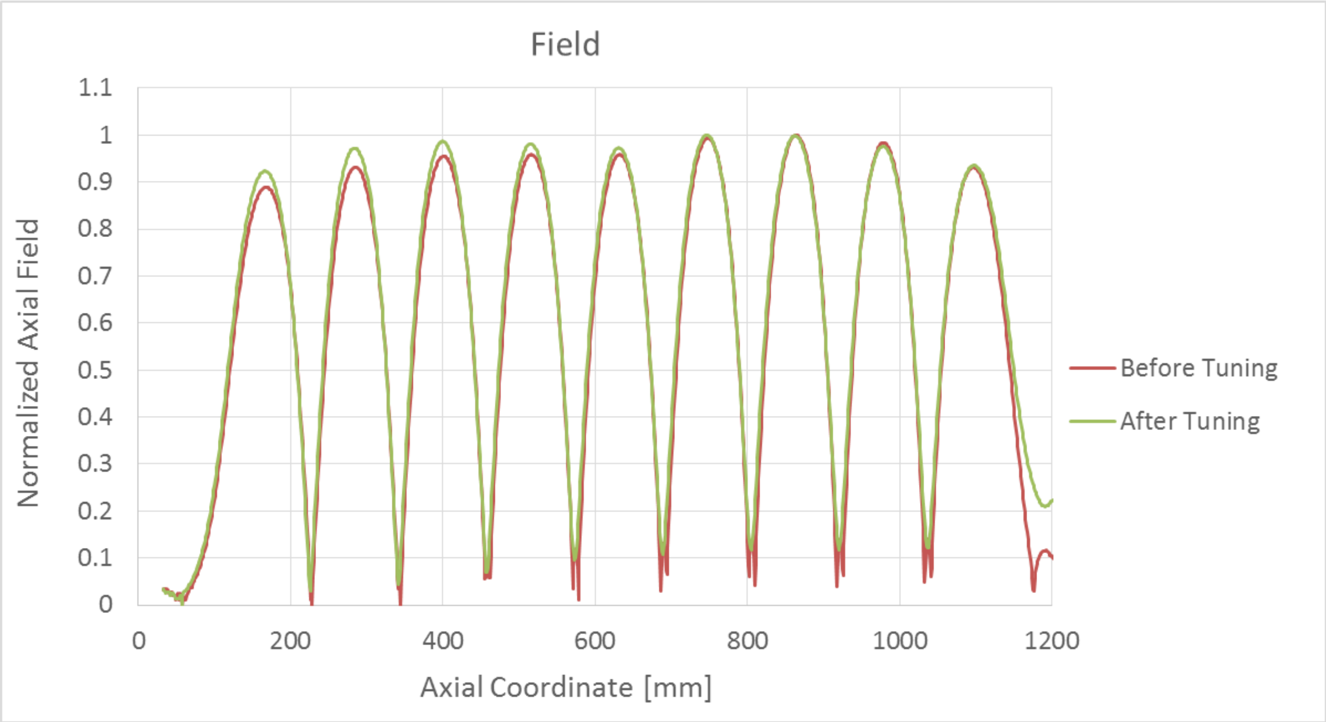
Expansion Test Results

- Axial displacement measured along the cavity axis.
- The loading process has produced a **permanent** elongation equal to 480 µm.

Traction Force [kN]	Measured displacement [mm]			
	SG1	**SG2**	**SG3**	**SG4**
0.222	0	0	0	0
0.663	5.283	4.953	2.794	3.658
1.334	11.176	14.224	6.096	7.874
2.064	18.085	15.621	9.119	9.017
4.180	Out of range	Out of range	18.669	17.907
0.222	5.436	3.397	4.572	3.302

Frequency and Field Profile after BTT

- Cavity resonant frequency after tuning is equal to 1297.379 MHz → **40 kHz** frequency shift.
  - A higher value was expected → Measurement affected by **humidity**
- Normalized Axial Field after tuning analysis.



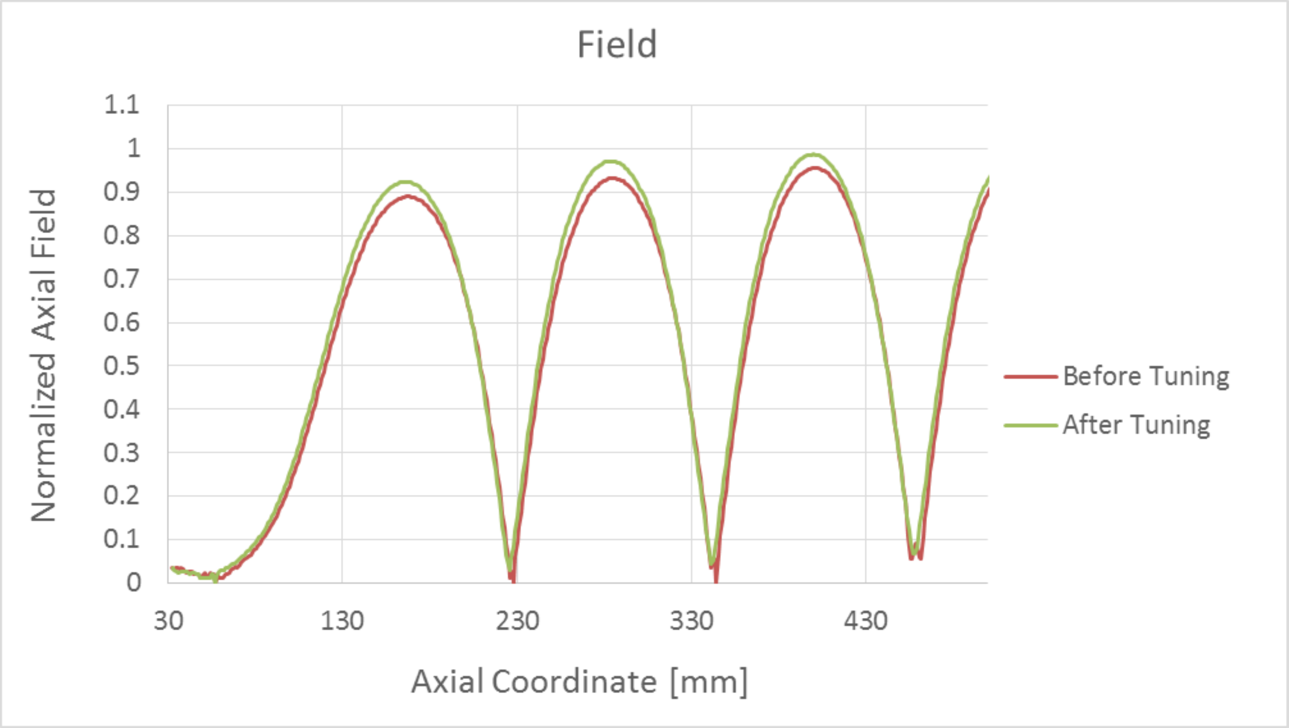
- FF after tuning equal to 0.93.

↓

+ 5%

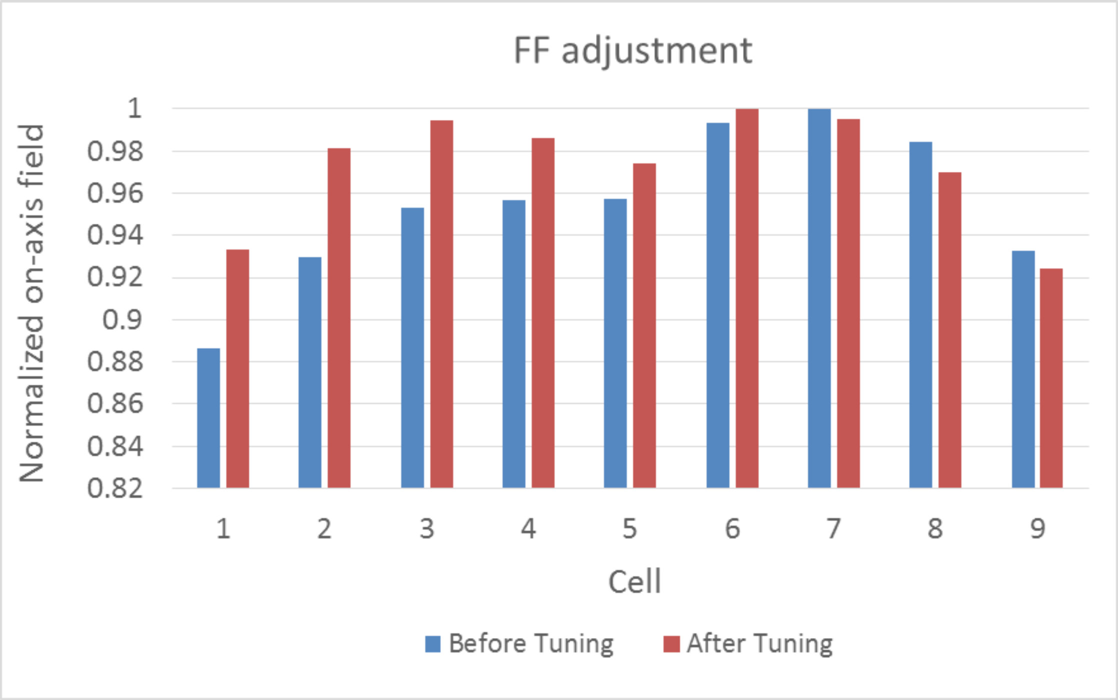
Field in adjacent cells

- **5% increase** in Cell 2 normalized on axis field.



- Also **adjacent** cells (1 and 3) experience a similar increase, as shown in Figure.
    - It is a side effect usually produced also in classic tuning.

Field Flatness Overall Analysis



Increase in normalized on axis field:

- Cells 1-3: + 5%
- Cells 4-5: + 1.5%.
- Cells 6-9: - 0.06%

Problem: a slight plastic deformation seems to have occurred also in some non targeted cells (such as 4 and 5).

- The force used in the test was 4.2 kN, probably too high.
  - Difference between real cavity and nominal model.

Future Studies

- A first BTT concept validation has been achieved, but further steps are needed:
  - The loading process should be studied by means of a **non linear** and **time dependent** multiphysics simulation.
    - Accurate estimation of the permanent effect produced by the tuning.
  - A new **working point** analysis should be made considering the real cavity features instead of the nominal ones:
    - Niobium elastic modulus correction ~ 80 GPa
    - Measurement of real cavity thickness
      - Nominal thickness usually modified by preliminary chemical treatments made on the cavity.
  - An efficient way for balloon **insertion** and **removal** should be found, with related cavity polluting issues.