# Design of alternative β=0.92 cavity for Project X

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# Motivations for the alternative design of HE section

- The DOE approval for the CD-0 or “Mission Need” phase of Project X is still ongoing and the extension of the Project X applications is quite important.
- The Accelerator-Driven Subcritical systems (ADS) for energy generation and the transmutation of waste are under development in many countries (China, EU, Japan, India). The alternative designs for Project X that is consistent directly with the needs of ADS could potentially strengthen the Fermilab international collaboration and give us the opportunity to take a leading role in that area.
- DoE may consider US ADS program in the future. If Project-X technique may be used directly for ADS, it may strengthen our position also.
- Project X is a good candidate as a muon source for a future Neutrino Factory and/or a Muon Collider.
- All the above mentioned projects need the CW proton beam with

**4-12 MWt** of beam power & **4-10 mA** average current.

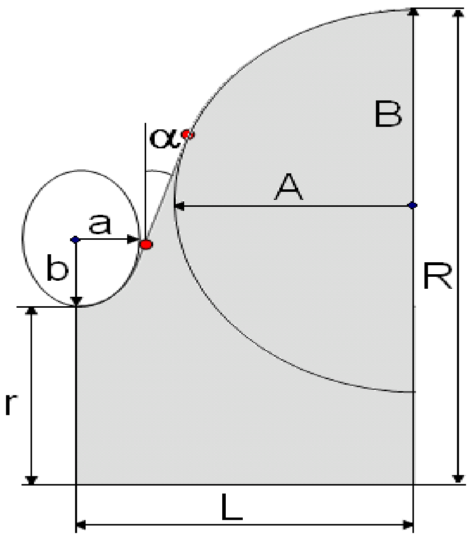
The Project X capability for a future upgrade is critical !

# Outline

- Current Design of b=0.90 Cavity for Project X
- HOM problems
- Reasons and necessity for the alternative cavity design
- The strategy of the cavity shape optimization
- Design of the Regular cell
- Design of the End cell
- Full 5-cell cavity simulation
- Potential problems and future simulations
- Conclusions

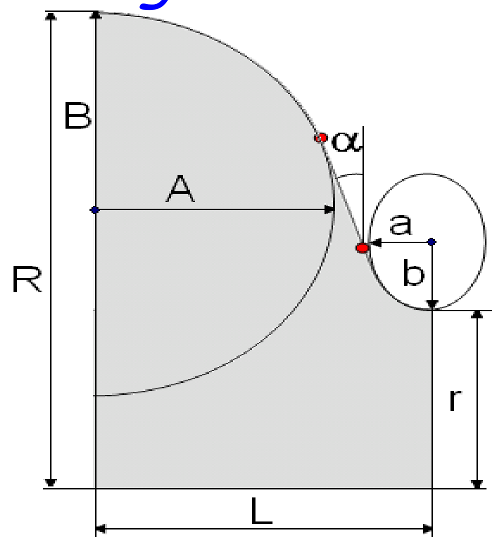
# β= 0.90 Cavity for Project X Overview

| End cell* | |
|---|---|




| | |
|---|---|
| r | 50 |
| R | 200.277 |
| L | 106.971 |
| A | 82.5 |
| B | 84.5 |
| a | 20 |
| b | 39.5 |
| α | 7.02 |

Regular cell*




| | |
|---|---|
| r | 50 |
| R | 200.277 |
| L | 103.75 |
| A | 82.5 |
| B | 84 |
| a | 18 |
| b | 38 |
| α | 5.2° |

*All dimensions are in mm.

The cavity design was optimized for the Project X parameters:

CW, 1 mA current

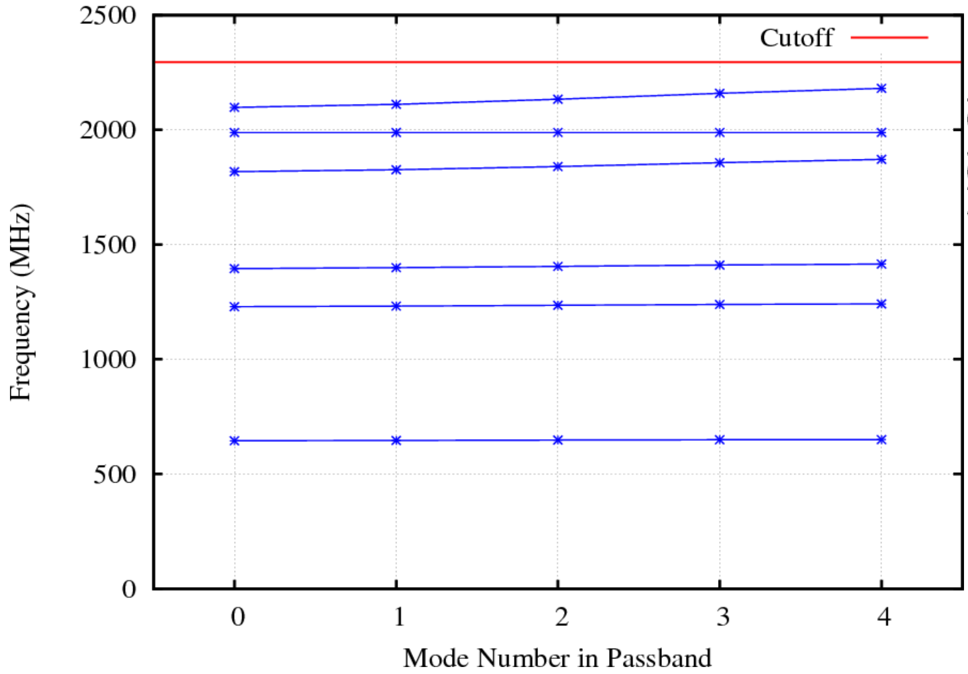
and has a conservative

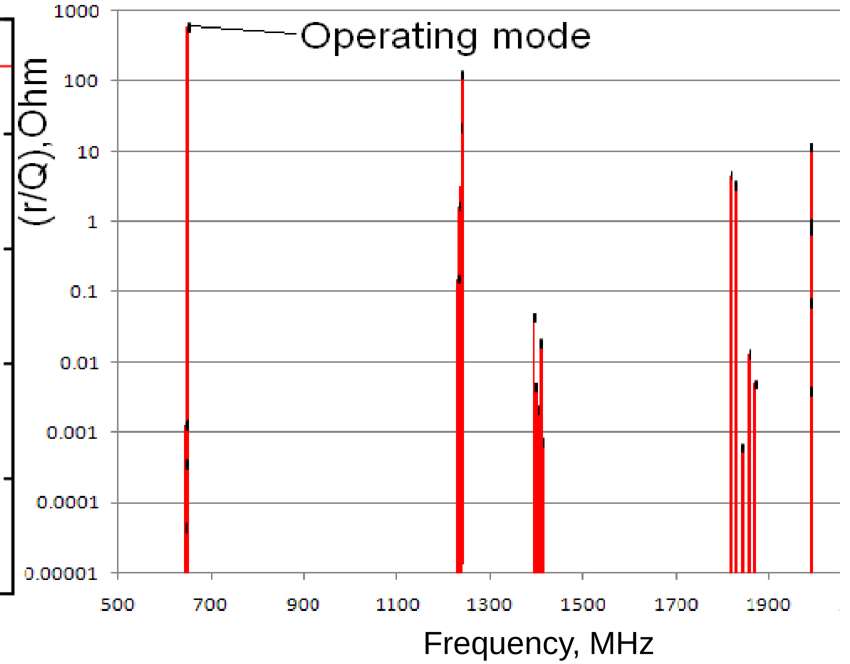
5 degree walls

based on the surface processing requirements

# Monopole High Order Modes (HOM) in the HE section

Dispersion curves and monopole HOM spectrum for the HE 650 MHz cavity




- For *β* = 0.90:
  - two modes have (*r/Q*) ~10 Ohm: F=1988 (*df*=11 MHz)
  - one mode has (*r/Q*) = 22 Ohm: F=1238.6 MHz (*df*=7 MHz) , and
  - one mode has (*r/Q*) = 130 Ohm: F=1241 MHz (*df*=5 MHz)

*df* is the difference between the HOM frequency and nearest main beam spectrum line.

# Effect of the HOMs of the 5th passband in the HE section

## ❖Resonance excitation.

Monopole modes should not increase the beam longitudinal emittance $\varepsilon_z$ ($\varepsilon_z$ = 1.6 keV*nsec):

$$\hat{U}_{HOM}\sigma_t << \varepsilon_z$$

$\hat{U}_{HOM}$ - an average energy gain caused by HOM,

$\sigma_t$ - a bunch length.

For high-Q resonances:

$$\hat{U}_{HOM} \approx \frac{\tilde{I}(R/Q)}{4\sqrt{2}\ \delta f/f}$$ and thus, $$\delta f \approx f\frac{\tilde{I}(R/Q)\sigma_t}{4\sqrt{2}\ \varepsilon_z}$$

$\delta f$ - the difference between the HOM frequency and the beam spectrum line frequency ($\delta f/f << 1/Q$)

$\tilde{I}$ - a beam spectrum line amplitude.

# Effect of the HOMs of the 5th passband in the HE section

The worst case, beginning of the 650 MHz HE section:

$\sigma_t$ = 2.1e-3 nsec (or 0.5 deg).

For $\tilde{I}$ = 1 mA and (R/Q)= 6 Ohm (HOM of the 5th passband with the frequency of 1988 MHz) one has:

$\delta f$ >> 3 Hz!

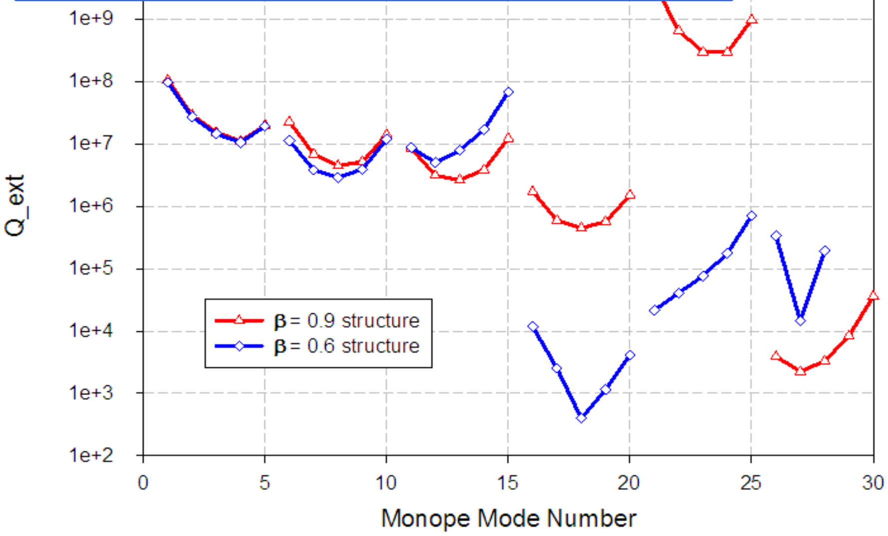
- When the distance between the beam spectrum lines is 1 MHz, the probability that the cavity has the resonant frequency close enough to the beam spectrum line is ~ 3e-6.

- The gain amplitude caused by the HOM is < 250 keV, that is small compared to the operating mode gain, ~18 MeV, and does not contribute to the cryogenic losses : $P_{losses}$ < 1.8 W for $Q_0$ ~ 5e9.

- If the HOM mode is in resonance, it's $Q_{loaded}$ << 2e8.

# Effect of the HOMs of the 5$^{th}$ passband in the HE section

HOM damping through the main coupler.




MODES Number vs. dF/dP (Hz/torr) for β=0.91 cavity*

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | -1.1 | 6 | 59.3 | 11 | 115.9 | 16 | 46.3 | 21 | -87.9 | 26 | 54.4 |
| 2 | 5.5 | 7 | 26.1 | 12 | 93.9 | 17 | 42.9 | 22 | -75.3 | 27 | 21.1 |
| 3 | 13.3 | 8 | -0.8 | 13 | 89.9 | 18 | 42.2 | 23 | 85.0 | 28 | 52.8 |
| 4 | 17.7 | 9 | 4.0 | 14 | 103.2 | 19 | 54.6 | 24 | 92.5 | 29 | 109.8 |
| 5 | 5.2 | 10 | 35.3 | 15 | 118.5 | 20 | 80.7 | 25 | 91.5 | 30 | 155.5 |

Operating mode

5$^{th}$ passband

* courtesy to M. Hassan and I .Gonin, Fermilab

Microphonics for the 5$^{th}$ passband are significantly higher than for the operating mode and, thus, one can expect its frequency stability below 10 Hz or the effective $Q_{loaded} < 10^8$

Monopole HOMs are not a problem for the current Project X parameters (CW, 1 mA ) !

**BUT…WHAT ABOUT CW and 10 mA !?**

# Reasons for the alternative design of HE section

- The cryogenic losses in the SC cavity are proportional to the average beam current in square:

$$P_{cryo} \sim \tilde{I}^2$$

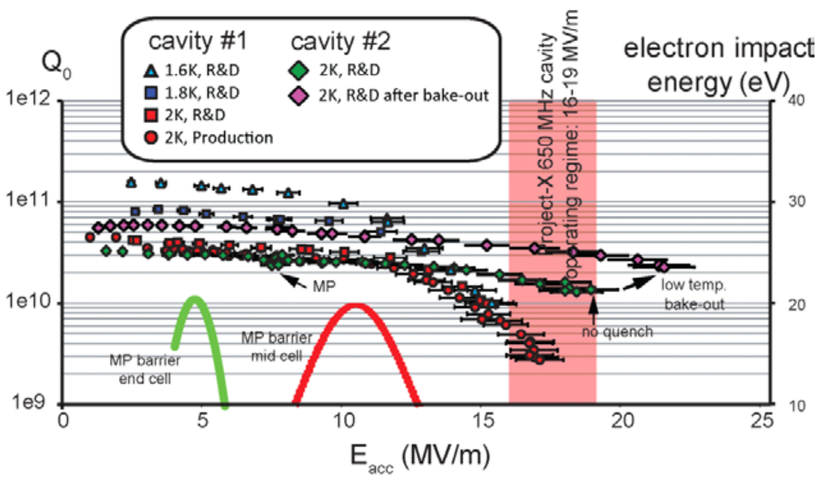
- The potential problem of the current HE structure with the 5$^{th}$ monopole passband could rise up the cryo losses from

1 Wt to 100 Wt (!) for the 10 mA proton beam.

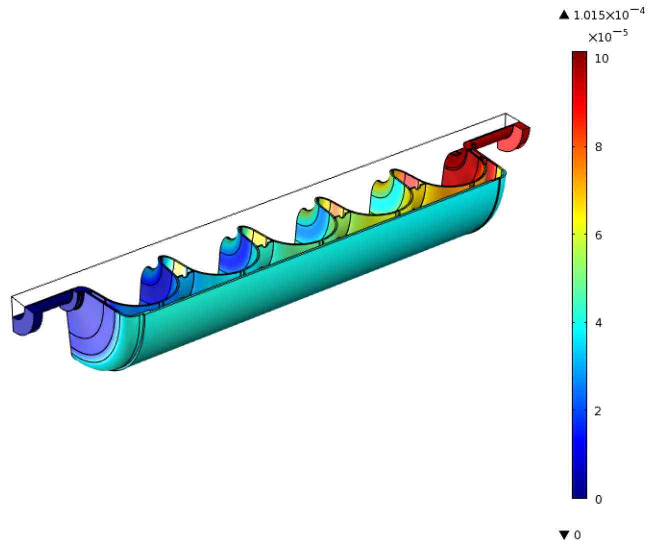
**We consider the alternative design of the accelerating structure for the HE section of Project X, suitable for the high current operations and thus for ADS applications.**

# The premise for SC cavity design

- The recent JLAB experiment with b=0.61 650 MHz single cavity has shown a very good result even the cavity has a flat (“0” degree) walls (F. Marhauser, etc., “Preliminary Test Results from 650 MHz Single Cell Medium Beta Cavities for Project X”, SRF2011).
- The proper position of the stiffening ring can provide the good mechanical stability even for the cavity with flat walls (M. Hassan, I.Gonin, “Microphonics in 650 MHz-B09”, TD Internal Report).




**650MHz Single Cell beta =0.61 Prototype Cavities for ProjectX**



**Microphonics in 650 MHz, β=0.9 Cavity dF/dP ~ 5.2 Hz/torr**

# Cavity shape optimization for the case of beta<1

- There is a recent publication on the optimal choice of the TESLA cavity shape with beta=1 (V. Shemelin, Phys. Rev. ST Accel. Beams 12, 114701, 2009) but there is no such a full analysis ever been made for the beta<1 cavity. Also the representation of results of the shape optimization has a lack of clarity in our mind.

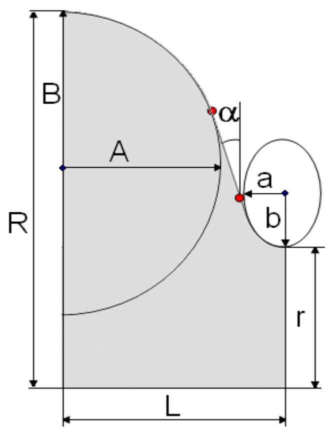
- Optimization of the cavity shape for beta<1 is more challenge than for the case of beta=1 because it has additional degree of freedom – the cell period.

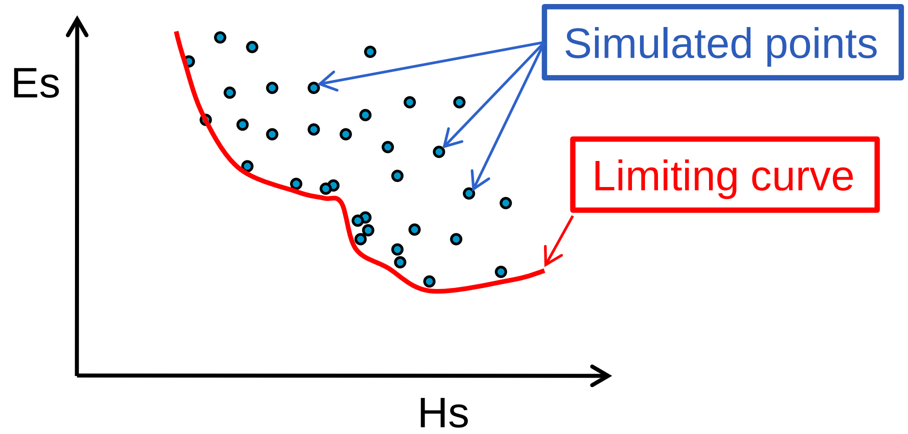
- Modern computers are able to simulate a single variant of the cell geometry in 2D for less than 1 minute with a very good accuracy of eigenfrequency and surface fields.

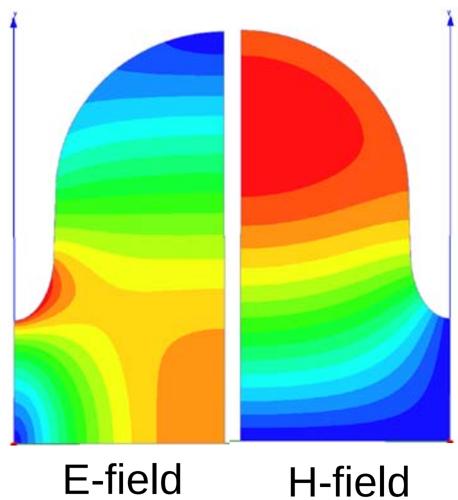
**It is possible to do a full automatic optimization of the low or high betas cavity shape within a reasonable time !**

# Cavity shape optimization for the case of beta<1

- The main goal of the cavity shape optimization is to minimize both surface electric $E_s$ and magnetic $H_s$ fields. Thus, the result is not just a one single point but the series of limiting curves in the $E_s$ vs $H_s$ coordinates. The further choice is a trade-offs between the requirements on cavity mechanical stability and surface processing.
- There are only four independent parameters that can be used for optimization: A, B, a, and b – the radiuses of two conjugated ellipses.
- By a proper choice of the diapasons of optimizing parameters one can limit the total number of points below $10^4$ which corresponds to 3 - 4 days of the computer simulation time.

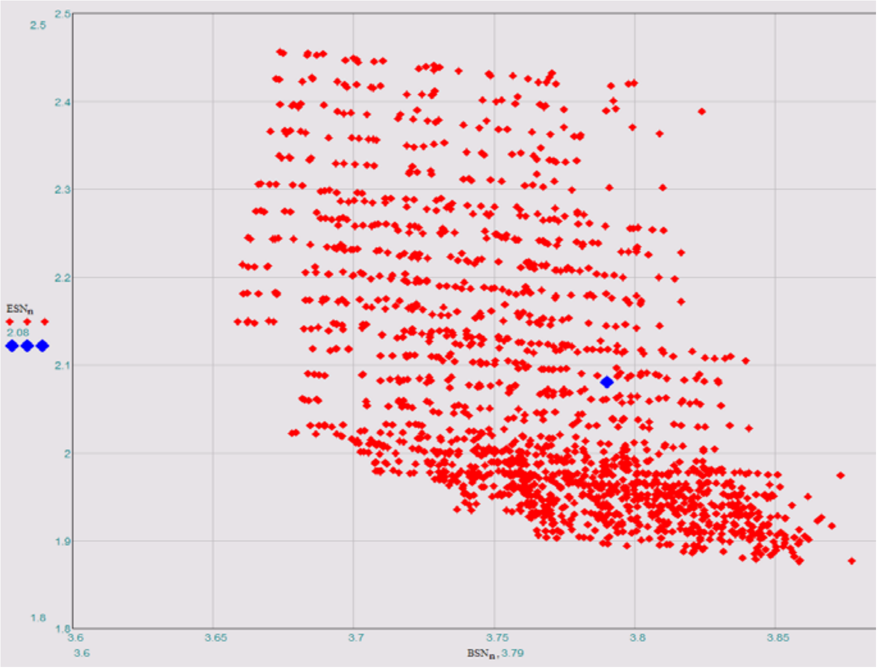


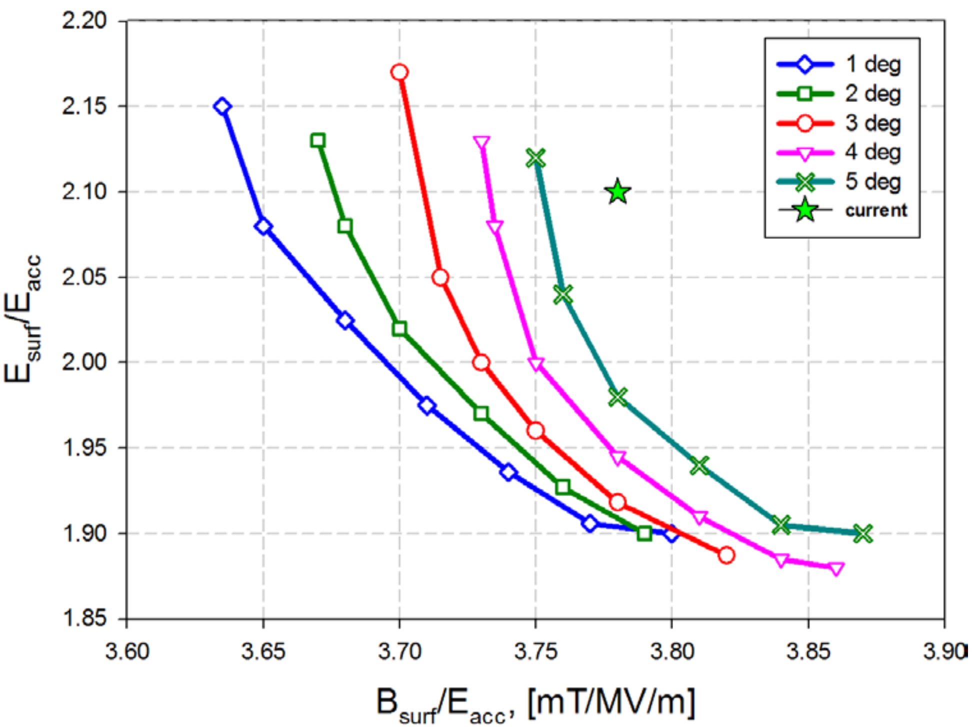



# Regular cell design, R_pipe = 50 mm, beta=0.90

- It is known that the smaller degree of the cavity wall slope (even negative) allows to reduce the surface fields.
- The simulations show that it is possible to lower by 10% the surface electric or by 4% the surface magnetic field in a case of switching from 5 degree to 1 degree slope for the current version of the cell shape.



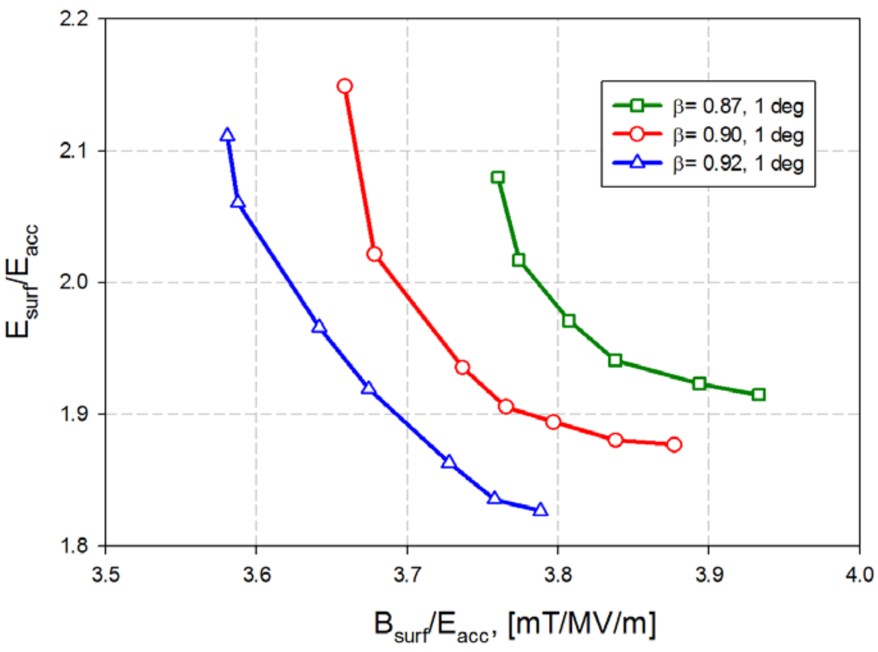
**Enumeration of cell shapes (~2000 points)**



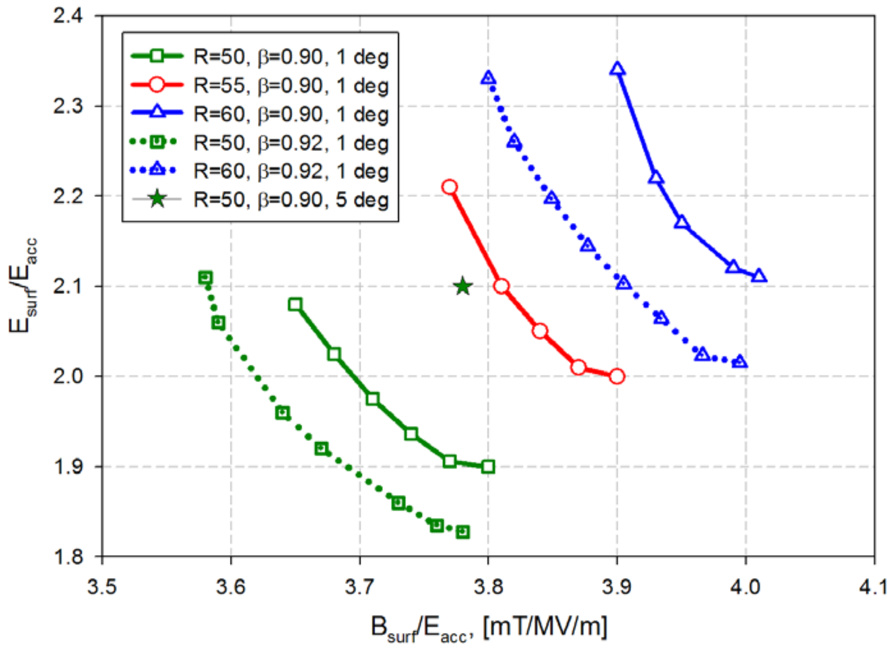

**Surface fields vs cavity wall slope**

# Regular cell design, period and pipe radius variations

- There are two more cavity parameters which we can optimize, the regular cell period (geometrical beta) and the pipe radius.
- The shorter cell period (lower geometrical beta) means thinner diaphragm and higher surface fields.
- Increasing of the pipe radius shows about 5% degradation in the surface electric and 2.5% in magnetic fields per every 5 mm of radius.



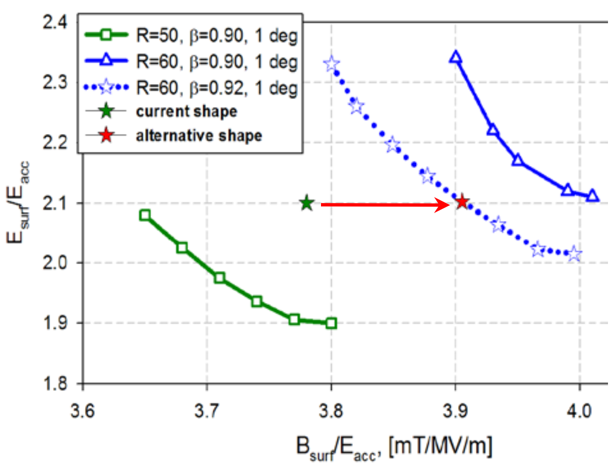

Surface fields vs cell period



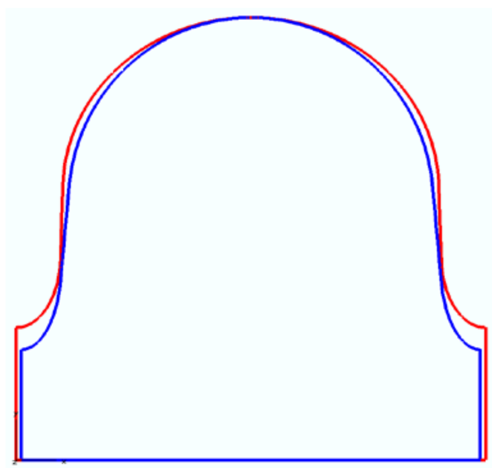

Surface fields vs pipe radius

# Regular cell design, R_pipe = 60 mm, beta=0.92

- Advantages of the larger pipe:
  - ✓ With the same Es and Hs the coupling between the cells is higher, which means a better field flatness and easy cavity tuning.
  - ✓ In a case of high current (10mA), large beam power might create a problem with beam losses. Larger aperture will lower a beam losses.
  - ✓ Larger aperture provides better coupling with the operating mode for the high current case ($Q_{ext} \approx 5 \cdot 10^6$) and reduce the depth of antenna penetration.
  - ✓ The 5th monopole passband is widened and being coupled with the beam pipe which allows to reduce the HOM $Q_{ext}$ and cryogenic loss.



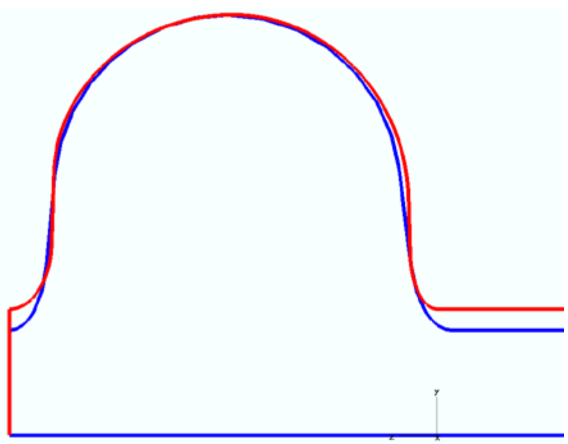

| Quantity | Old | New |
|---|---|---|
| G, Ω | 256 | 261 |
| $R_{sh}/Q_0$, Ω | 607 | 563 |
| $G \cdot R_{sh}/Q_0$, $\Omega^2$ | 1.55E6 | 1.47E6 |
| $E_{surf}/E_{acc}$ | 2.1 | 2.1 |
| $B_{surf}/E_{acc}$ | 3.79 | 3.92 |
| $K_{couple}$, % | 0.75 | 1.42 |



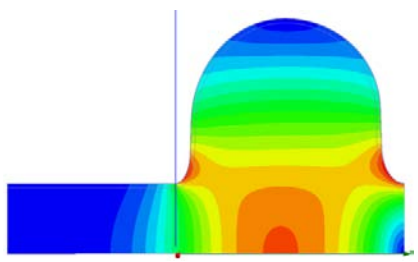
# End cell design, R_pipe = 60 mm, beta=0.92

- Optimization of the End cell is the most challenging part of the cavity design, because it has to fulfill to the different criteria:
  - ✓ The surface fields must not exceed the ones in the regular cell.
  - ✓ The shape of the end cell has to be tuned in order to dump the $Q_{ext}$ of the most dangerous HOMs (particularly it is the 5th monopole passband for the Project X high beta structure).
  - ✓ The length of the End cell needs to provide the optimal beta value for the multi-cell structure.

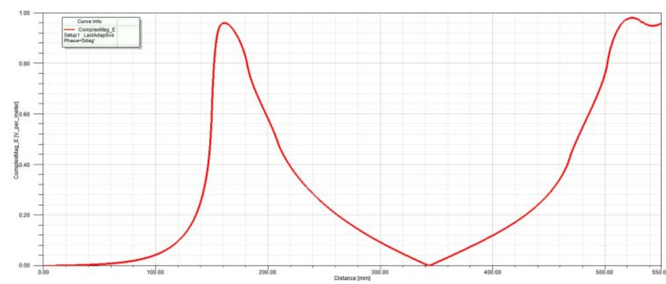
**OLD & NEW End cell shapes***

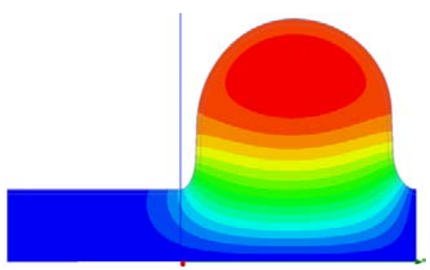


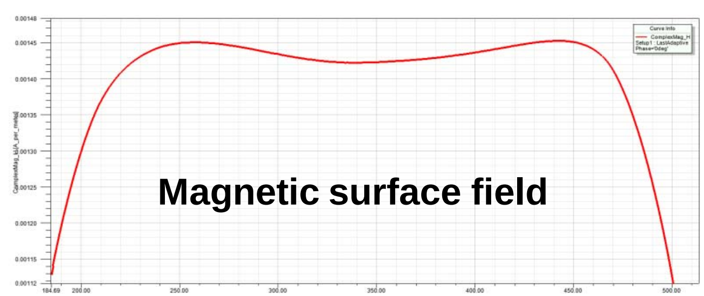
*The optimal beta for a full structure is expected to be the same.



**Electric surface field**



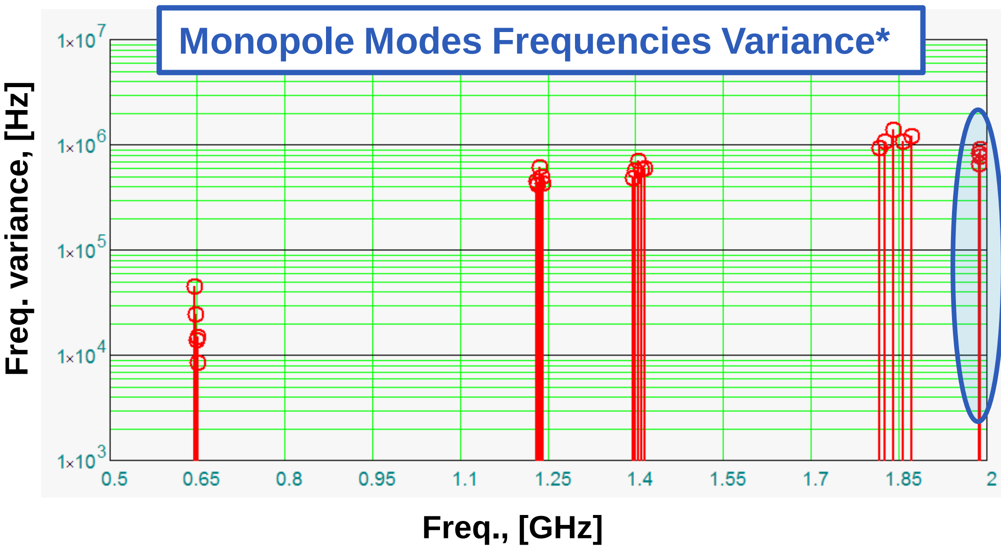


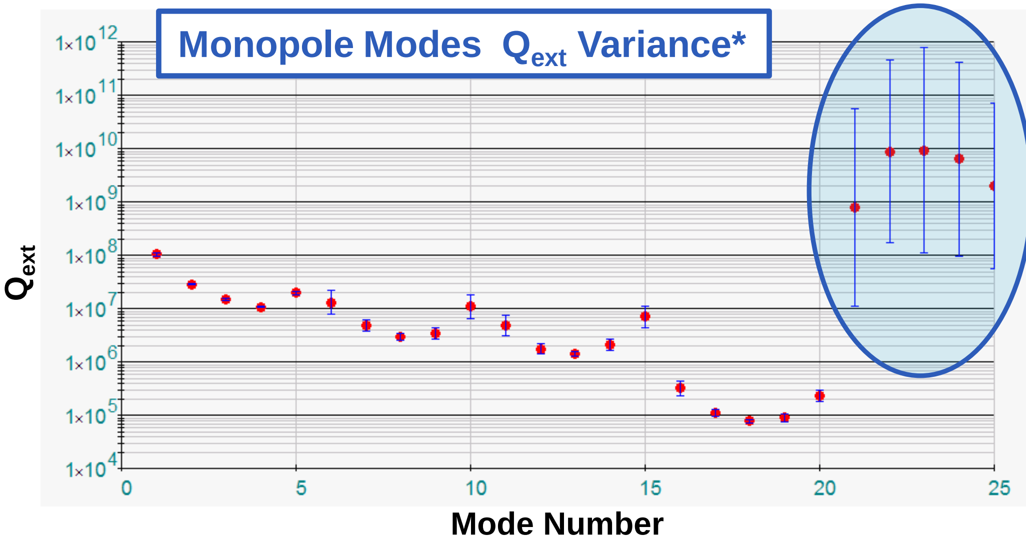


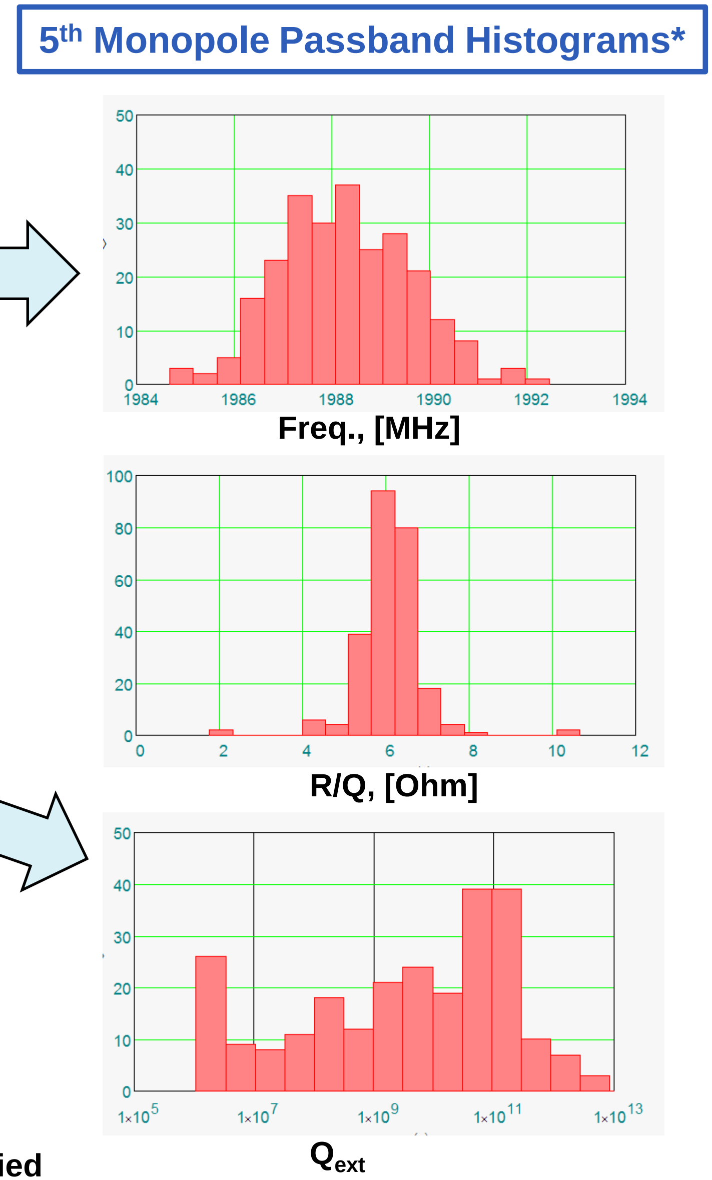
# 5-cell cavity simulation, 5th monopole passband

- The High Order Modes in the accelerating cavity are characterized by its frequencies, R/Q-s and $Q_{ext}$.
- Because of the fabricating tolerances and further surface processing the actual cavity shape never matches with the theoretical shape.
- There are a natural spreads of the HOMs parameters from cavity to cavity. We can reproduce it in the simulations using the following procedure:
  - Apply tolerances to the cell dimensions.
  - Calculating the frequency derivation (for operating mode) of each geometrical dimension for the regular and end cells.
  - Tune the individual cell frequency by changing its period (exactly how the tuning machine is working !) at the stage of the full structure geometry creation.
  - Simulate the derived 5-cell structure (check the operating mode flatness !). Repeat the simulation 30-50 times to get the statistics.
  - Process the HOMs parameters and plot its spreads.

# 5-cell cavity simulation, 5th monopole passband



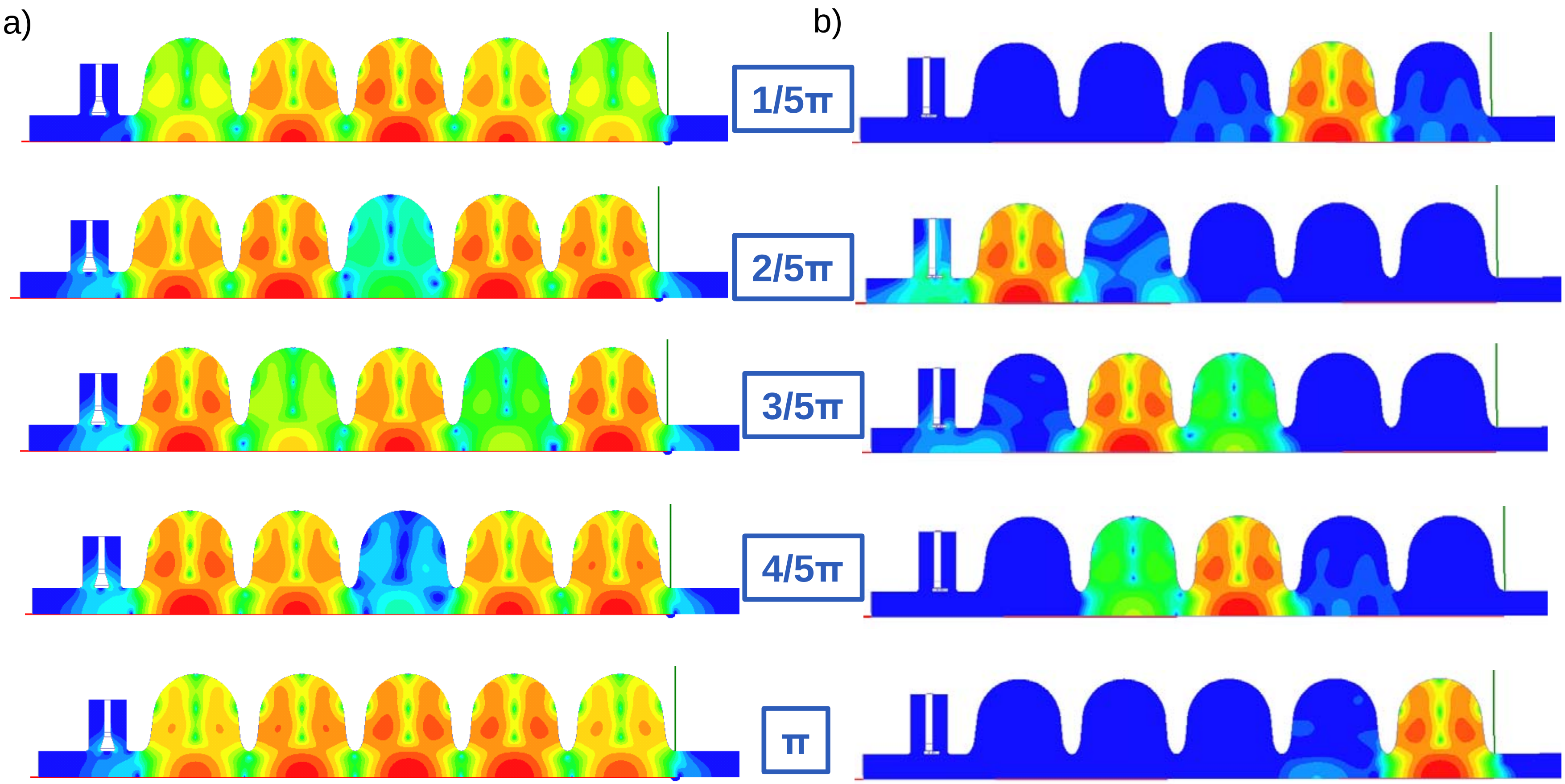




* 650 MHz, beta= 0.90 Project X structure with ± 0.2 mm tolerance applied

# 5-cell cavity simulation, 5th monopole passband

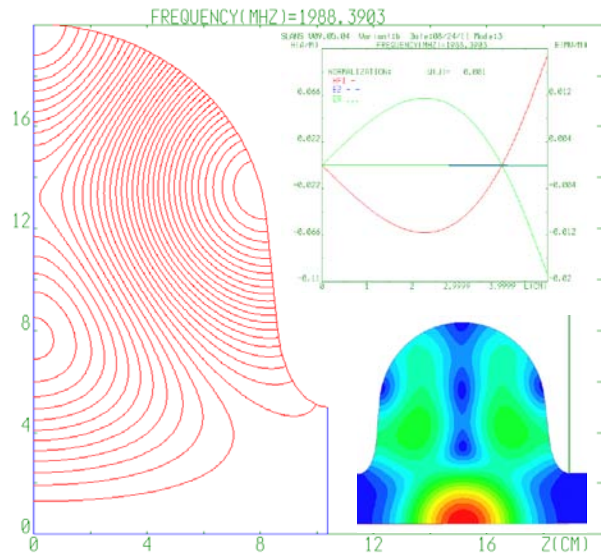
**Maps of Electrical field of the 5th Monopole Passband for the ideal structure (a) and the real structure (b) (± 0.2 mm tolerance applied )**




- **Due to the narrow frequency passband and a high sensitivity to mechanical tolerances, the 5th monopole band dispersion curve splits to the resonances of individual cells.**

## What is wrong with the $5^{th}$ monopole passband ?

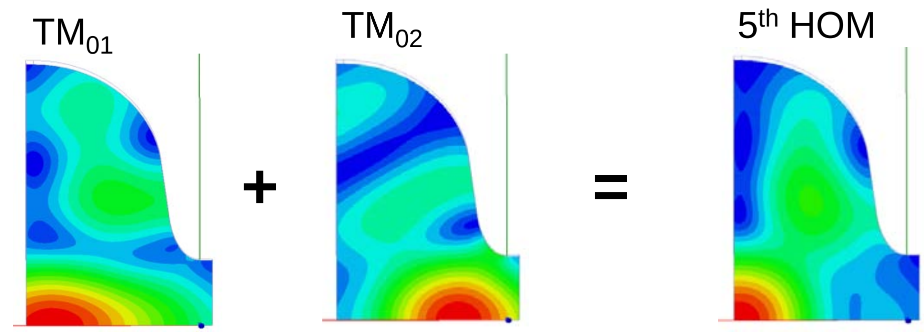
- It is very narrow.
- It is not coupled with the beam pipe.



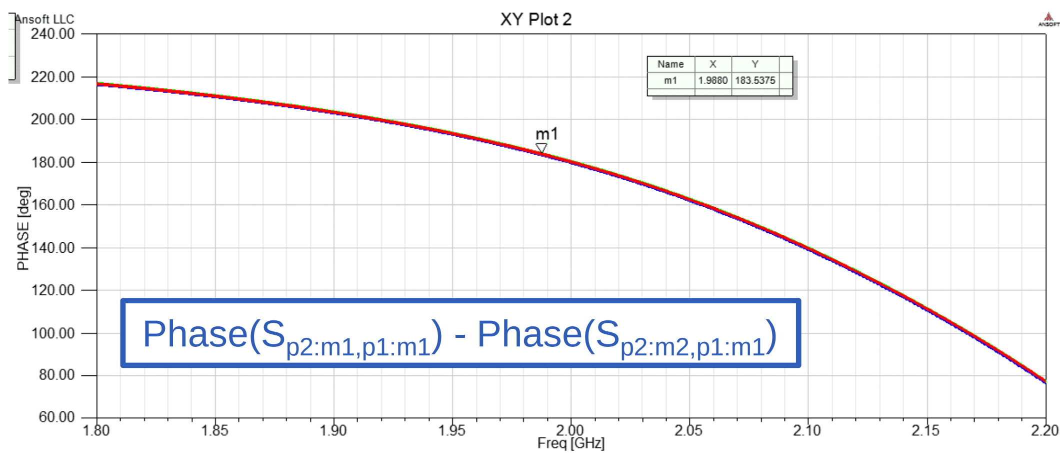

Field map of the π -mode of the $5^{th}$ passband and transverse field distribution over the aperture.
On the aperture one has the field distribution close to $TM_{02}$ mode and thus, small coupling:

$f_{\pi} - f_0 \approx 40$ kHz

The $5^{th}$ monopole passband is a mixture of $TM_{01}$ and $TM_{02}$ modes

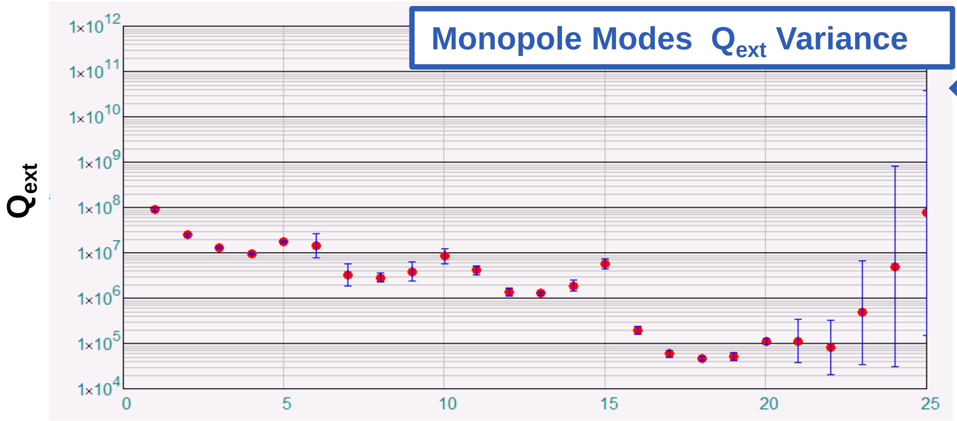



Both $TM_{01}$ and $TM_{02}$ are good coupled with the $TM_{01}$ mode in a pipe, but they do cancel each other because of $180^0$ phase shift !

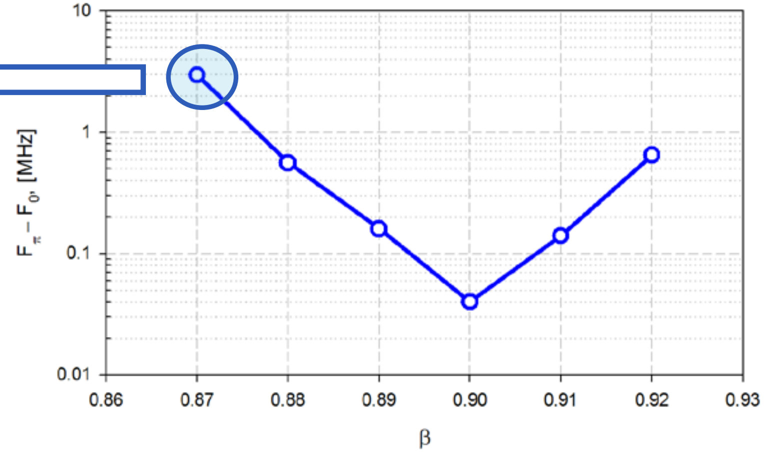


# 5-cell cavity simulation, 5th monopole passband

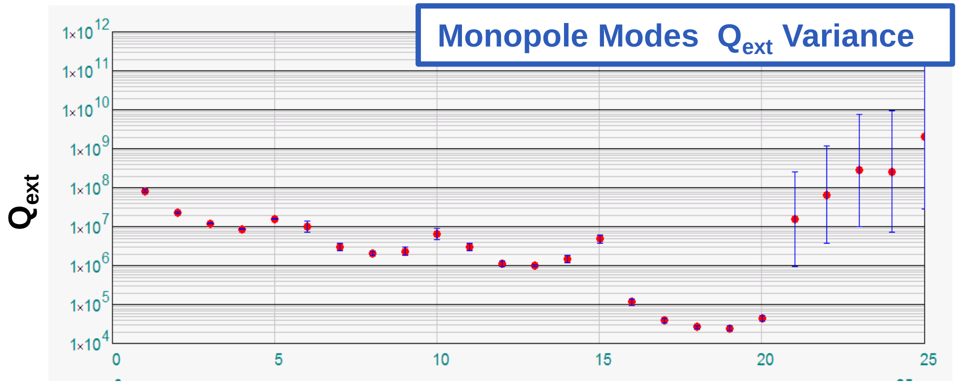
- Due to the “unlucky” phase relations, the current design of β= 0.9 structure has a very weak coupling of 5th monopole passband with the pipe.
- There are two possible ways how to correct it: a) change the cell length (geometrical beta) and b) change the pipe aperture




650 MHz, beta= 0.87 structure, $R_{pipe}$= 50 mm




The width of the 5th monopole band vs beta

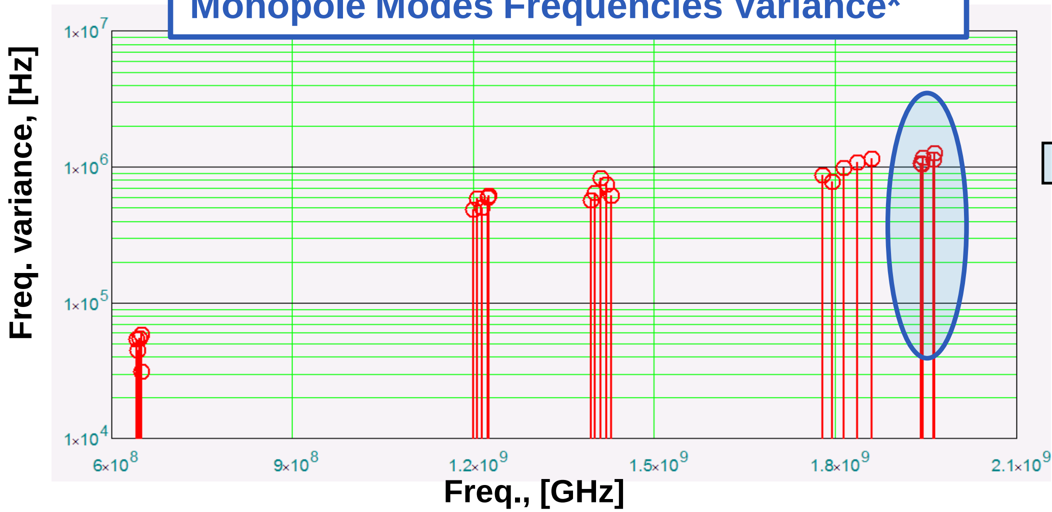



650 MHz, beta= 0.90 structure, $R_{pipe}$= 55 mm

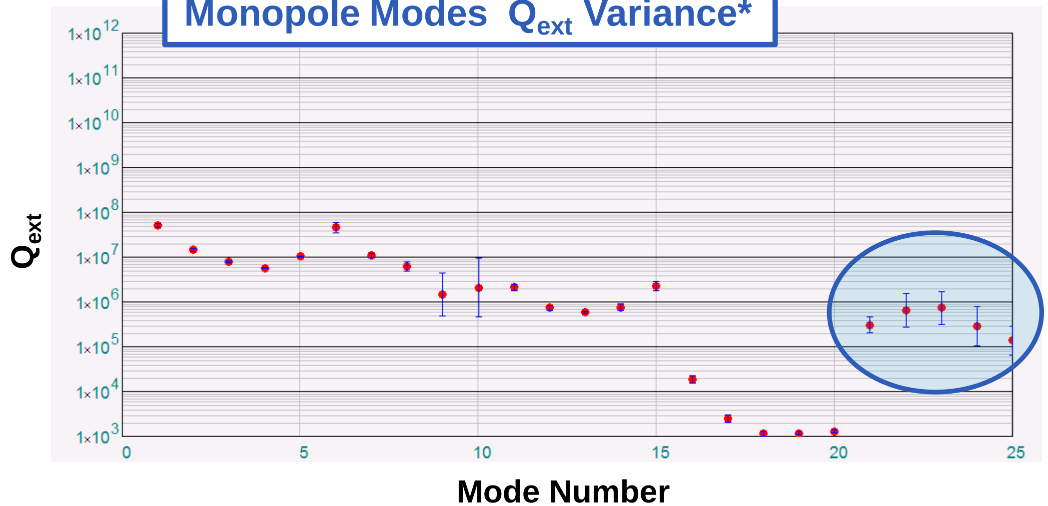
- **For the effective 5th passband $Q_{ext}$ suppression we need to apply both methods a) and b)**
- **Increasing beta has an advantage because it provides the cell shape with lower surface fields**

# 5-cell cavity simulation, $5^{th}$ monopole passband

## Monopole Modes Frequencies Variance*

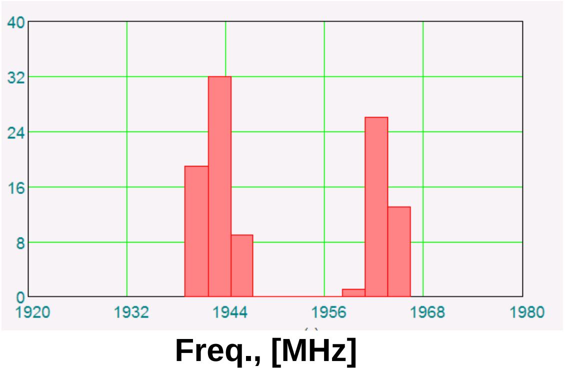


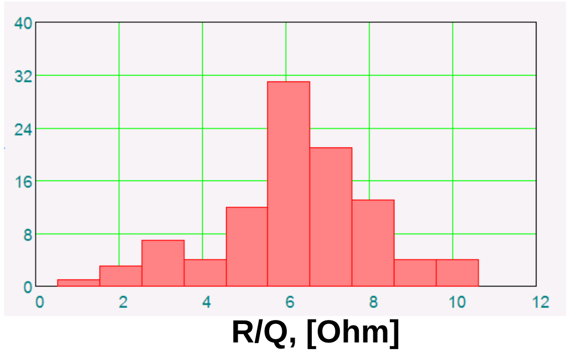

## Monopole Modes $Q_{ext}$ Variance*

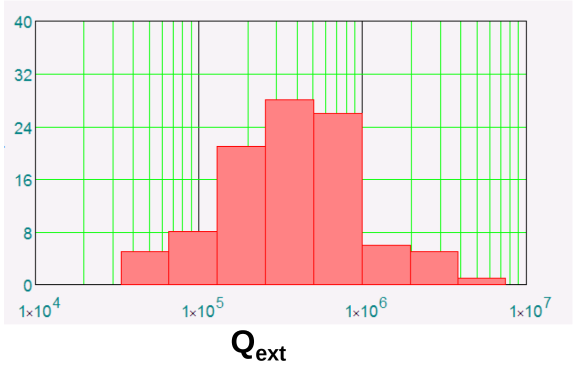



* 650 MHz, beta= 0.92 structure, $R_{pipe}$= 60mm

## $5^{th}$ Monopole Passband Histograms*



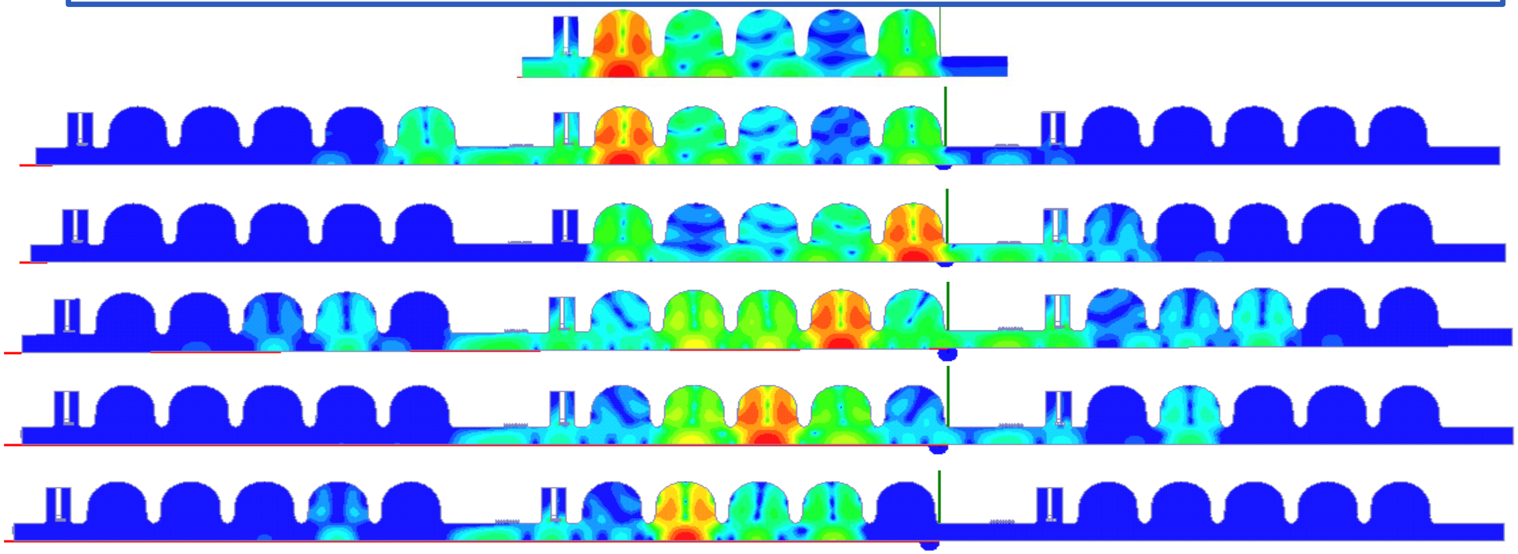



# 5-cell cavity simulation, 5th monopole passband

- The cutoff frequency of $TM_{01}$ mode in R=60mm beam pipe is below the 5th monopole passband, so, the pipe is open for $TM_{01}$ mode propagation.
- The single structure simulation provide only the estimation of the lower boundary of 5th passband $Q_{ext}$, assuming the perfect matching of the pipe ends.
- For the accurate result one has to simulate the chain of at least 3 randomly generated structures with mechanical tolerances and take into account the stainless steel bellows between the structures.

**Map of the electric fields in the chain of 3 structures connected with bellows***



***The simulation is still ongoing…**

**Installations of dedicated HOM-couplers allows further $Q_{ext}$ reduction of HOMs !**

# CONCLUSIONS

An alternative version of a cavity for high-energy section of the Project X is suggested; The cavity has the following features:

1. Larger aperture, 120 mm instead of 100mm;

2. About the same field enhancement factors and <10% higher ohmic losses;

3. HOM passbands wide enough to provide good HOM damping and thus, operation at high current.

The cavity may be used for ADS applications.