A 3 GHz SRF reduced-β Cavity for the S-DALINAC

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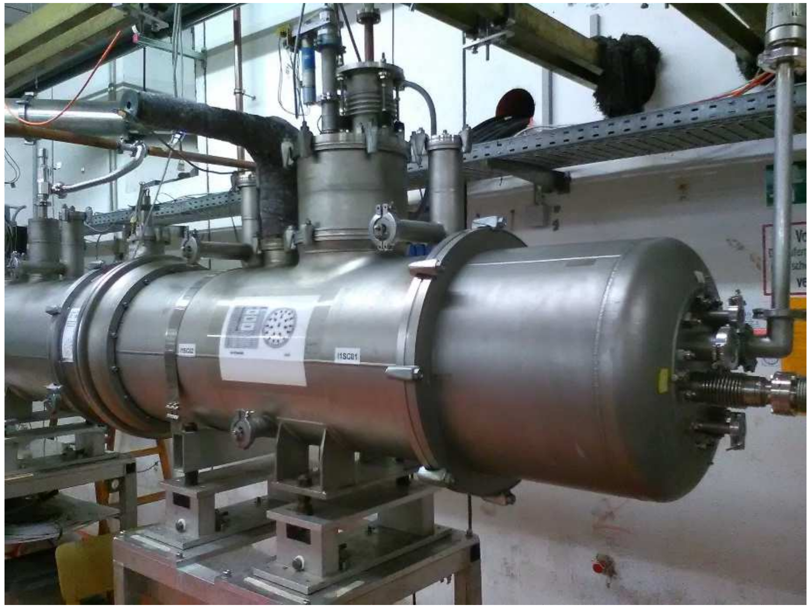

Gefördert durch die DFG im Rahmen des GRK 2128

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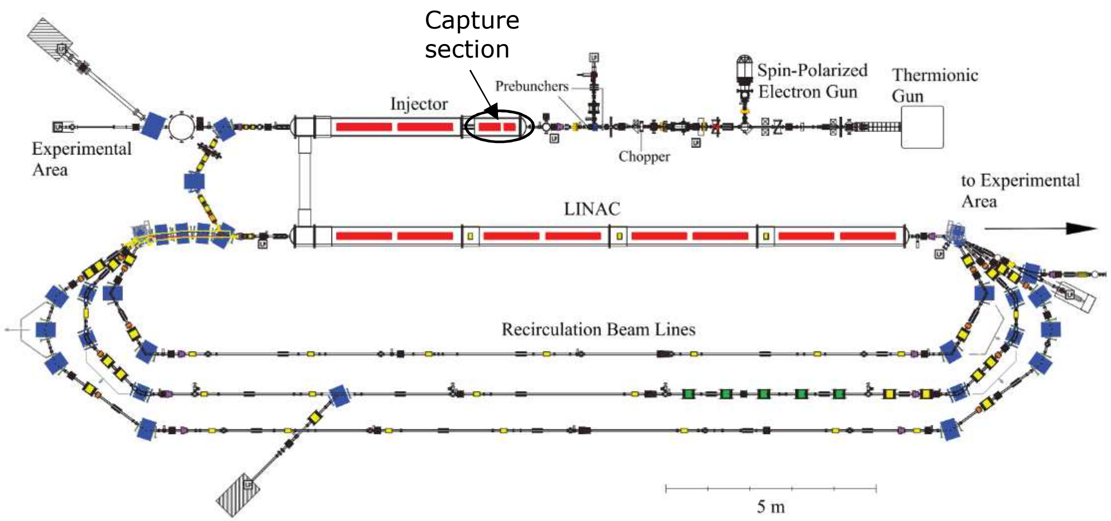
- Reduced-β cavity
- RF design
- Mechanical model
- Current status
- Conclusion

Introduction
Layout of the S-DALINAC



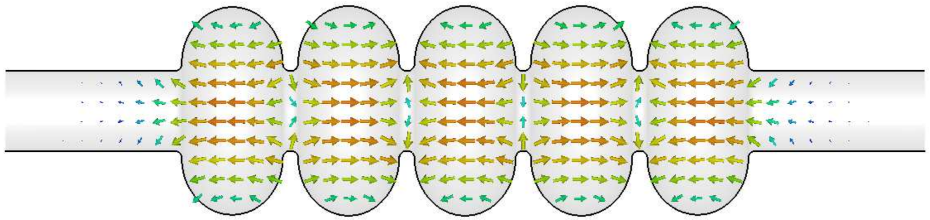
- E_{in} = 250 keV (thermionic gun)
- E_{in} = 100 keV (planned to be upgraded to 200 keV) (spin polarized gun)
- f = 3 GHz; CW
- I < 20 µA
- 11 SRF cavities; bulk Nb; T = 2 K

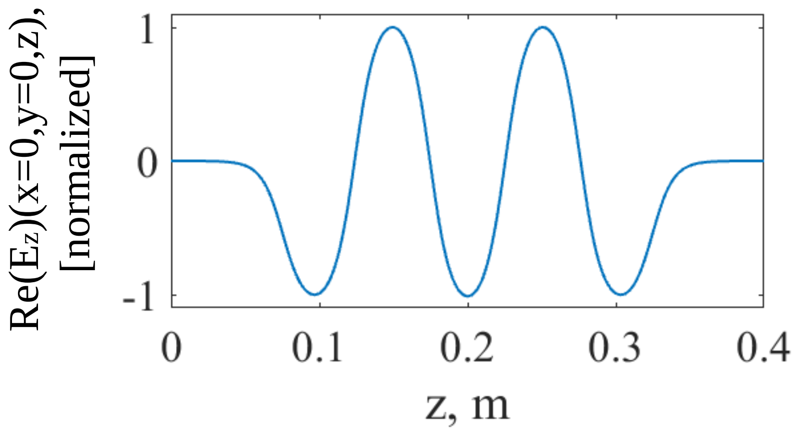
Introduction
Current setup

- 5 cell cavity in the tuner frame:

- The main parameters:
  - SRF β = 1 cavity
  - f = 3 GHz
  - E_{acc} = 3 MV/m
  - TM_{010}
  - π – mode
  - T = 2 K

- Electric field distribution of TM_{010} mode (transverse cut-plane 2D view):



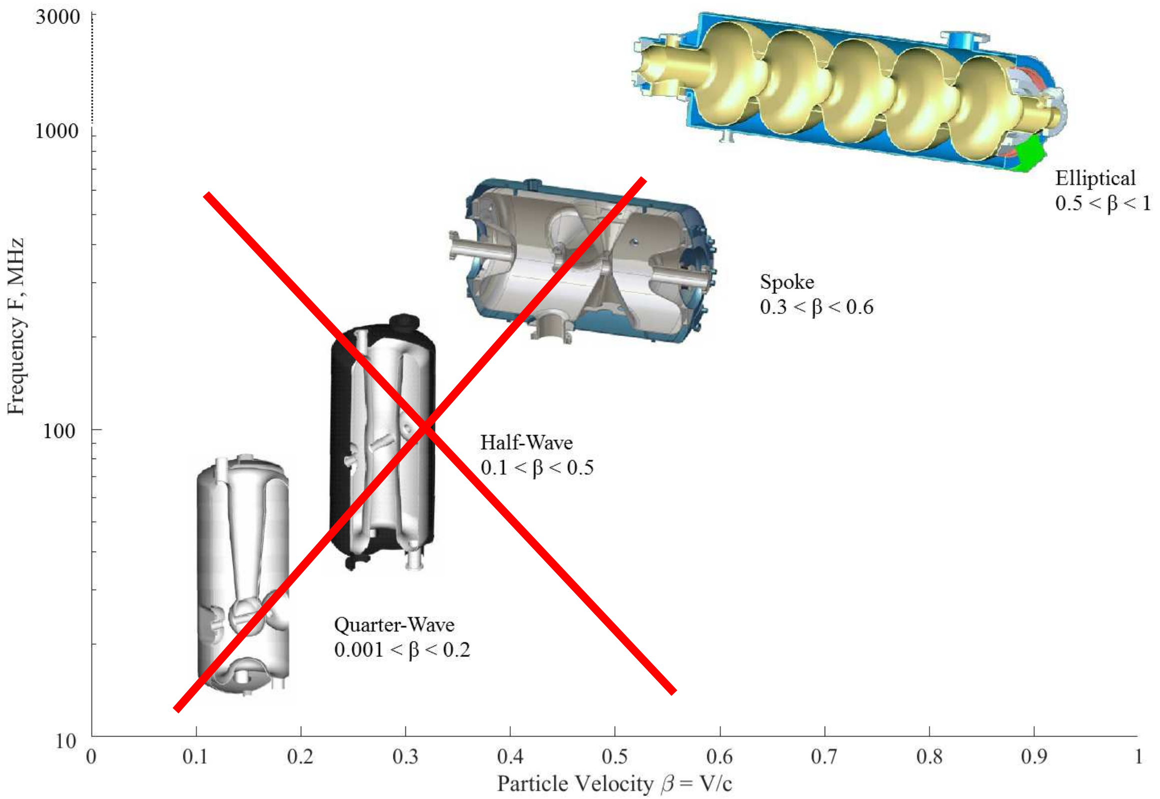


Introduction
Motivation for the upgrade

- 5 cell cavity is affected by plastic deformation
- Energy spread of accelerated beams does not reach a required value and the current capture section is one of the reasons
- Injecting a 200 keV beam directly into a $\beta=1$ RF structure results in inefficient acceleration because of the mismatch in phase
- Q-value drops over time

Upgrade
SRF cavity types

- SRF cavities spanning the full range of beta:



Operating frequency of the S-DALINAC is 3 GHz

↓

$\lambda \approx 10\ cm$

Upgrade
Criteria for a new accelerating structure

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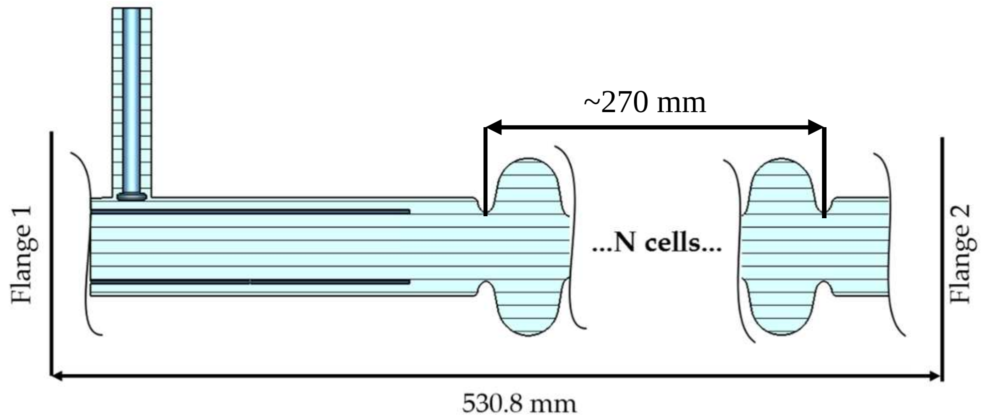
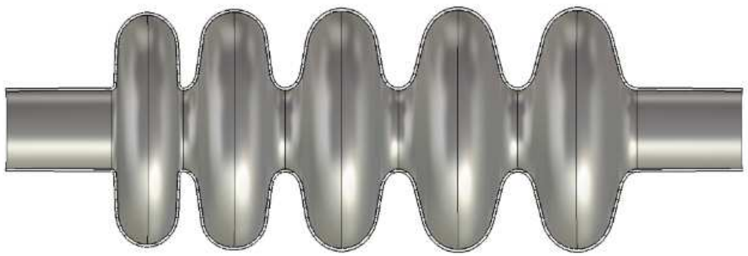
- Operating frequency 3 GHz (TM_{010}; π – mode)
- Output energy from the capture section at the S-DALINAC of 1 MeV
- Flat top peak electric field on the central axis of the cavity E_0 < 10 MV/m
- No significant increase of the energy spread of the beam
- Fitting inside the present cryostat
- Compatible with the present input coupler
- Minimal investment cost
- Reliable in operation (mechanical model)

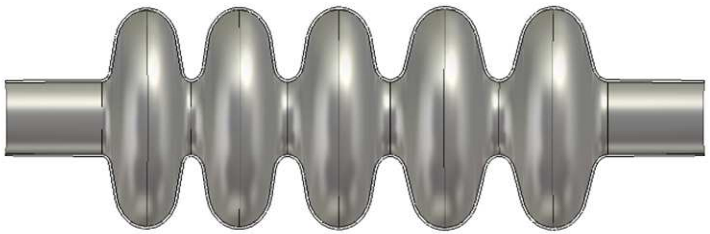


Upgrade
Proposed designs

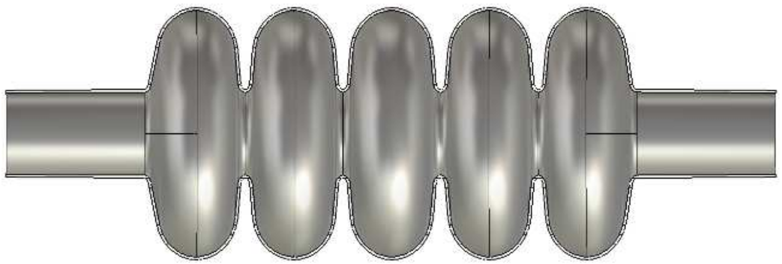
- 5 cell β-graded cavity (for 100 keV):



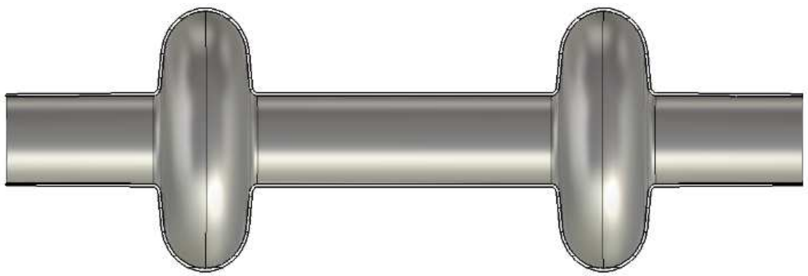
- 5 cell β-graded cavity (for 250 keV):



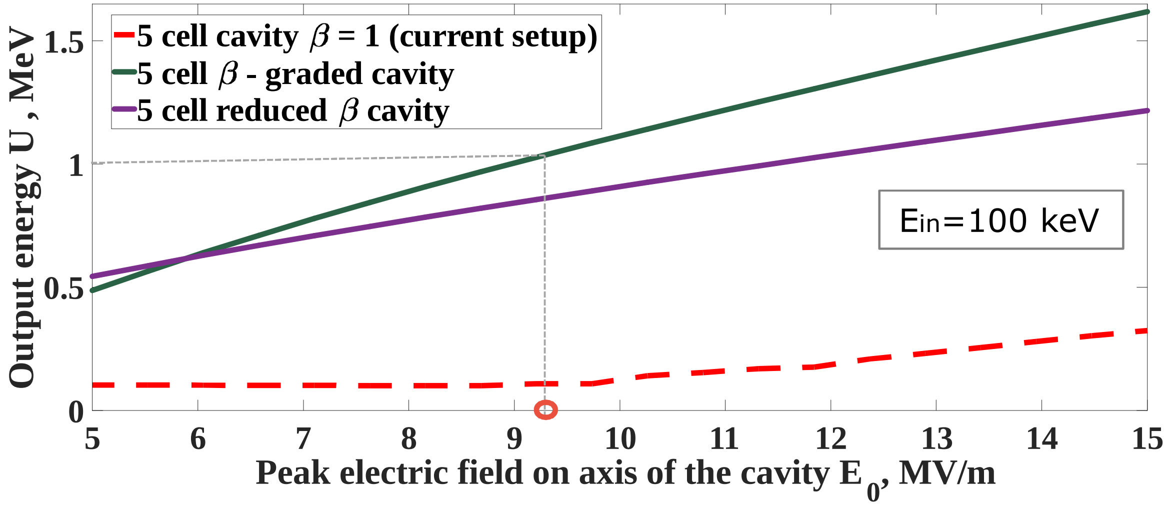
- 5 cell reduced-β cavity (100/250 keV):



- Independently driven cavities (100/250 keV):



Upgrade
Proposed designs

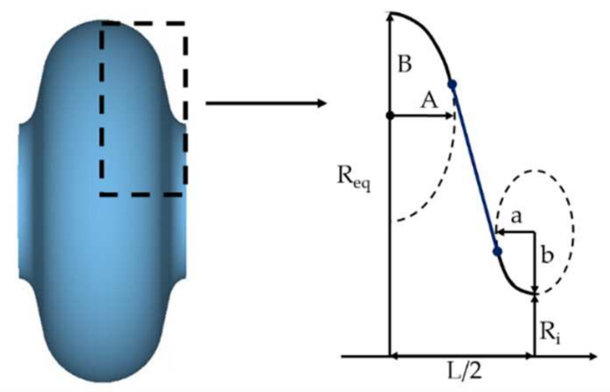


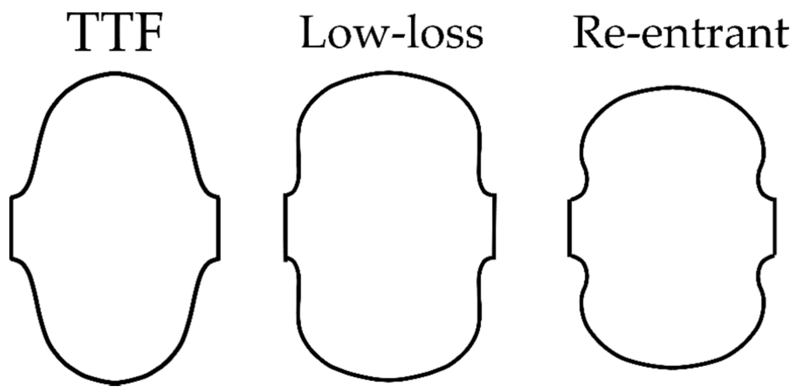
- Results for the β-graded cavity were better then expected
- This lead to the idea of use of a reduced β cavity
- Reduced β cavity is less flexible but more reliable in operation

- It is not possible to accelerate the 100 keV beam using the current setup
- Implementing a β-graded elliptical cavity is in our case not recommended because of failing stability during operation and increased cavity prod. costs
- The reduced-β cavity is capable of providing 1 MeV to the 100 keV beam after an additional optimization of the structure
- The main advantage of the reduced-β cavity over the β-graded cavity is the much less complicated geometry

Reduced-β cavity
Cell shape

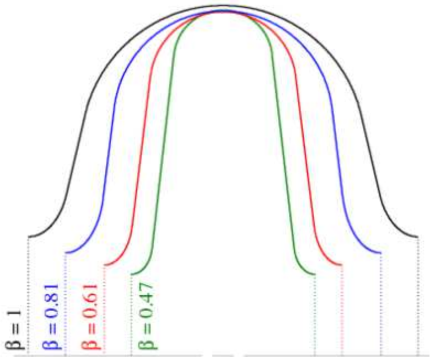
- Geometry of a single cell of a multi-cell elliptic cavity is formed by two ellipsoids
- Single cell 1.3 GHz TESLA $\beta = 1$ cavity was chosen as an anchor shape
- Geometric parameters were scaled in a way such resonant frequency of the fundamental TM_{010} mode is equal to 3 GHz
- Scaled shape requires an additional optimization since $\beta_g < 1$





Reduced-β cavity

- A progression of compressed elliptical cavity shapes at the same rf frequency but for decreasing β values



$$L = \frac{\beta c}{2f} = \frac{\beta \lambda}{2}$$

SNS
β=0.61

SNS
β=0.81

Reduced-β cavity:

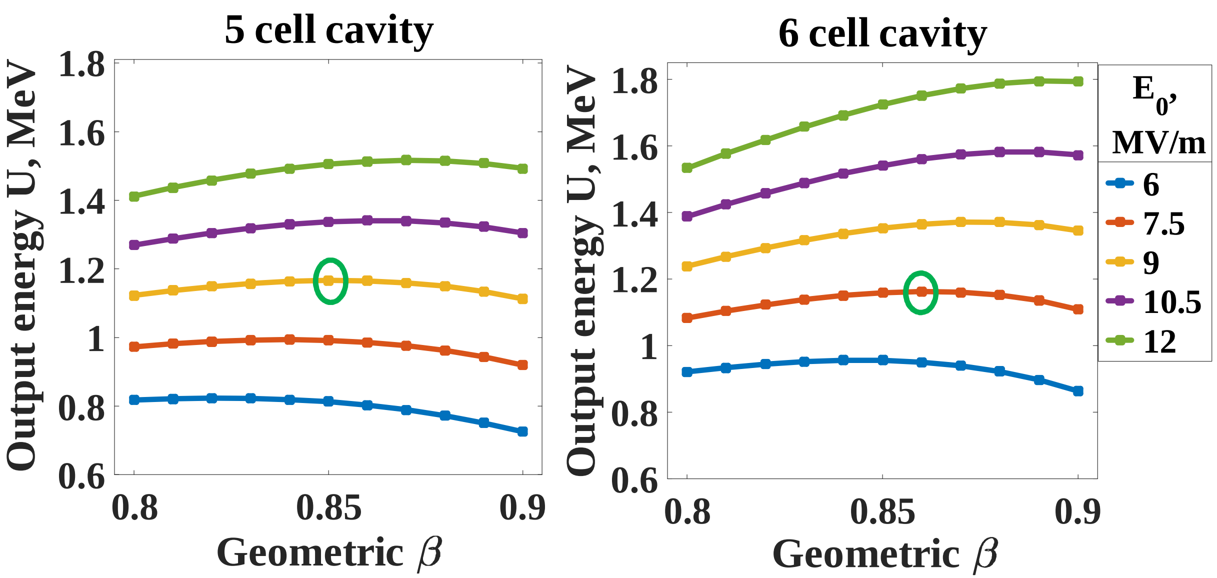
- The same length of each cell
- β < 1

Parameters to estimate:

- Number of cells
- Optimal value of geometric β
- Energy acceptance

E_0 < 10 MV/m, U > 1 MeV, low energy spread

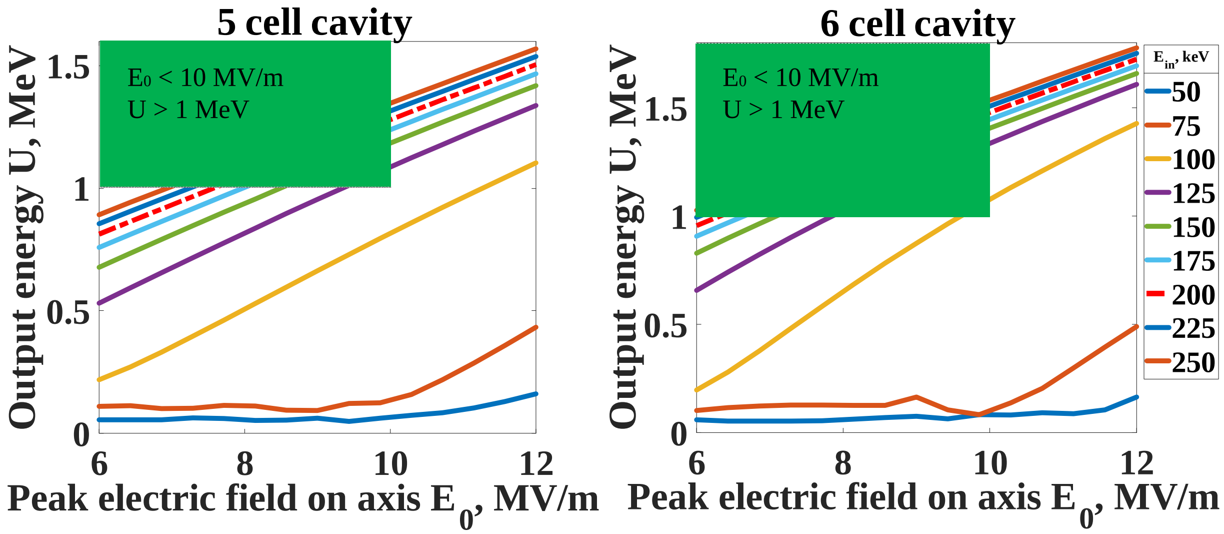
Reduced-β cavity
Number of cells and geometric β



- E_{in} = 200 keV
- An N+1 cell cavity can be operated with a lower value of E_0 compared to an N cell cavity to achieve the same energy gain

- The optimal value of the geometric β will depend on the operating value of E_0
- The 6 cell cavity is favoured, however, the mechanical model must be evaluated carefully

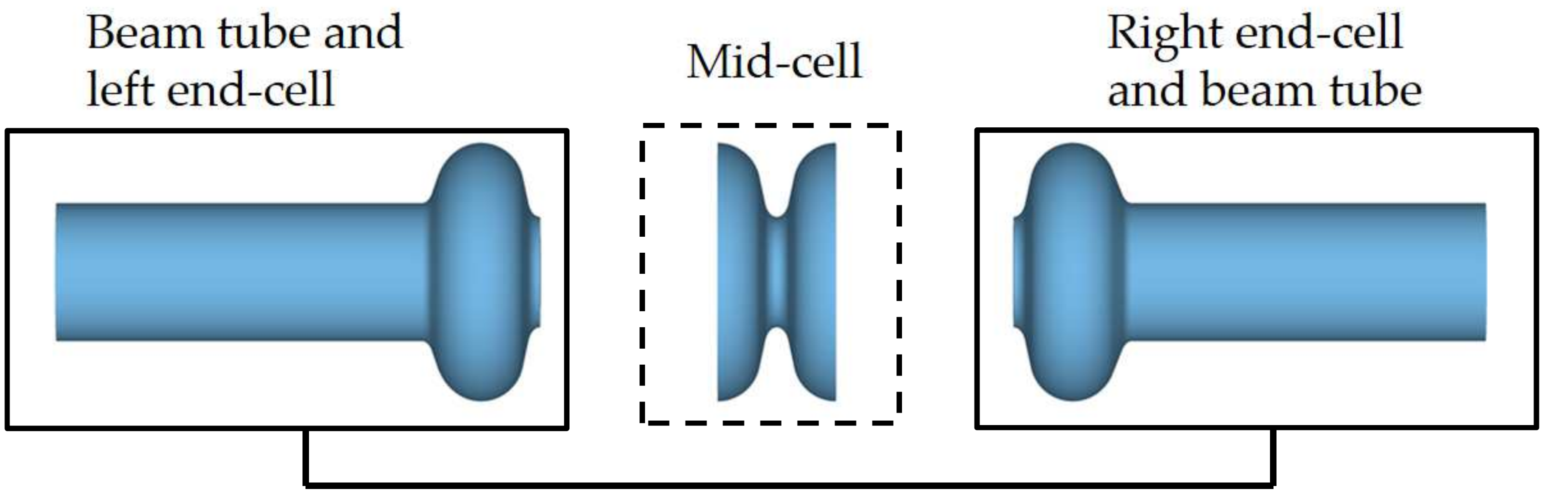
Reduced-β cavity
Energy acceptance



- 5 cell cav. β = 0.85
- 6 cell cav. β = 0.86
- Both cavities are capable to accelerate the 200 keV beam to the necessary energy

- The six cell cavity is also capable to accelerate the 100 keV beam, which is an advantage over the 5-cell cavity

RF design
Problem decoupling



- Mid-cell designed independently
- End-cells consists of a half mid-cell and independently designed half-cell (half end-cell)

RF design
Dispersion diagram

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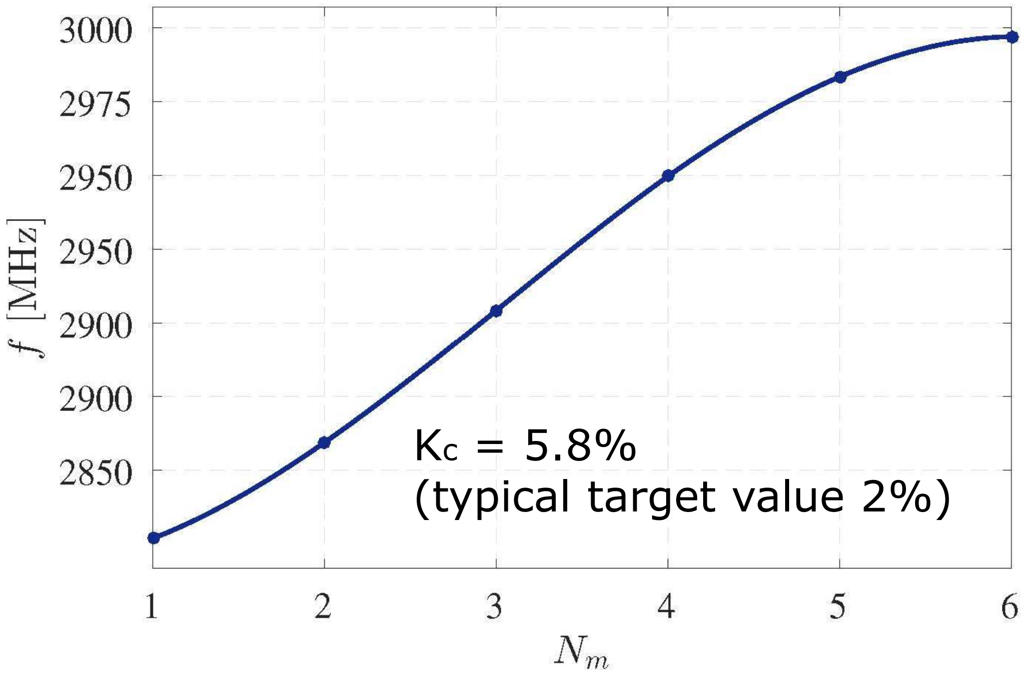
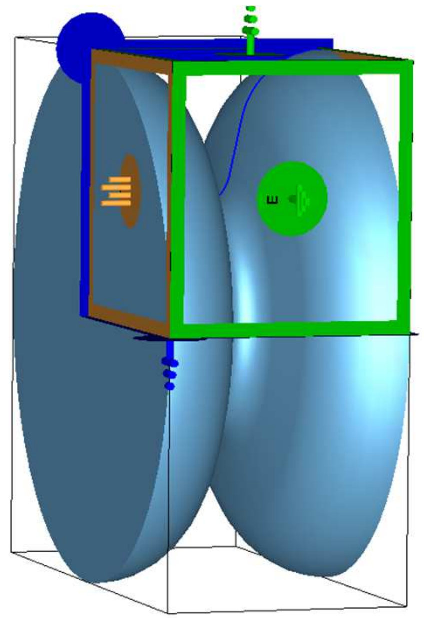
- Dispersion diagram of the TM_{010} mode (6-cell cavity):



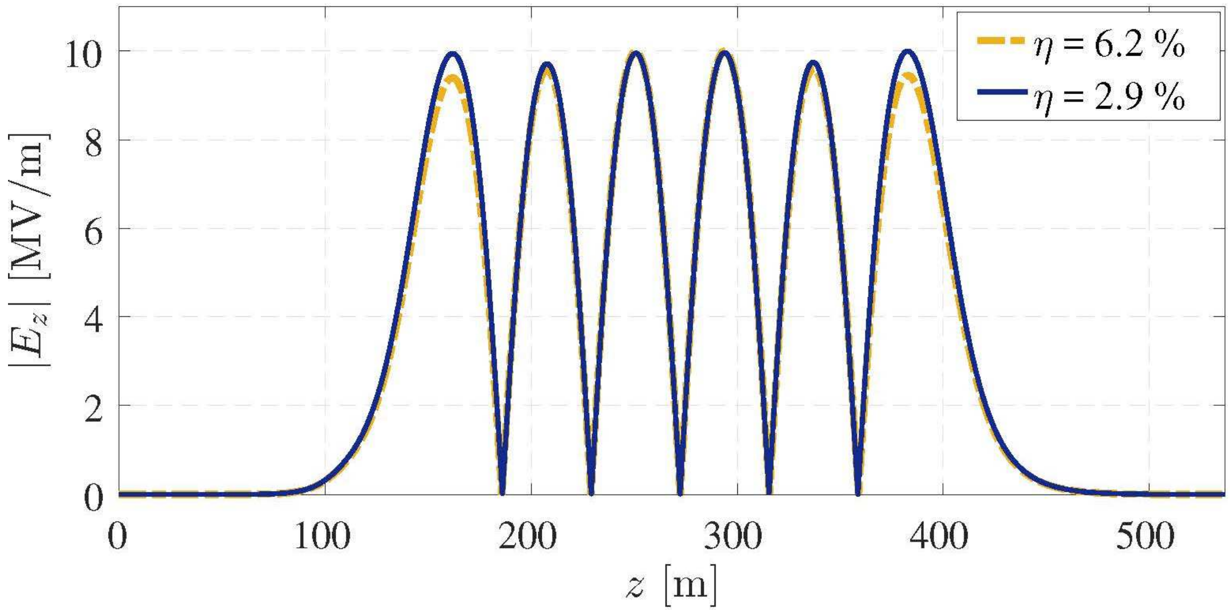
- Mid-cell with indicated boundary conditions:

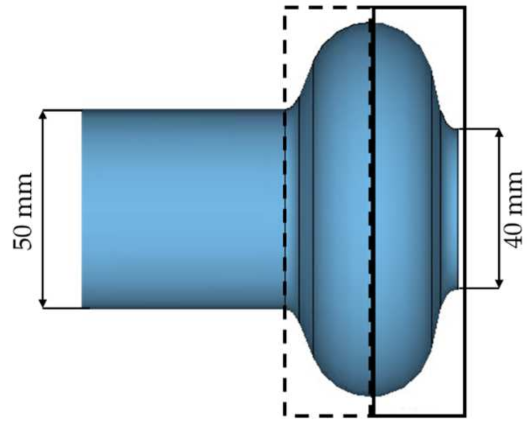


- Coupling coefficient: $k_c = 2 \cdot \dfrac{f_\pi - f_0}{f_\pi + f_0} \cdot 100\%$

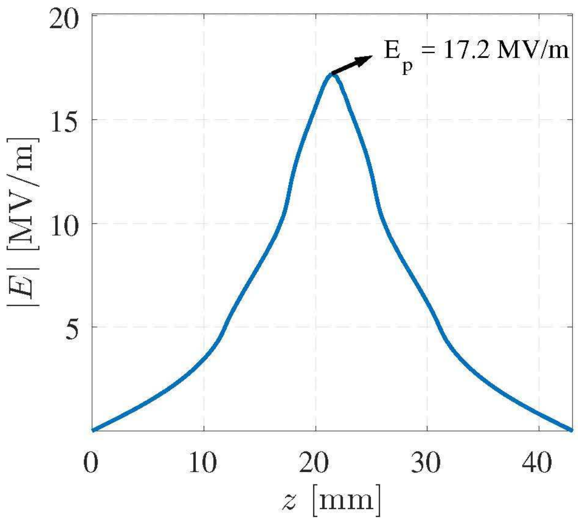
RF design
Field flatness

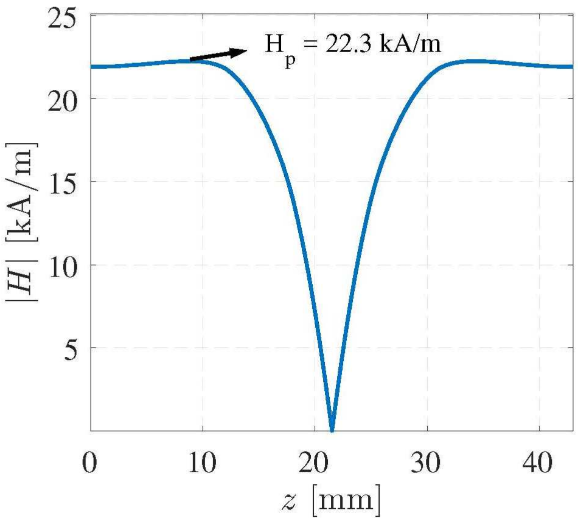
- Beam pipes introduce an additional capacitance to the cavity
- Field flatness is tuned by optimizing geometry of end-cells
- For the 6-cell cavity end-cells are identical
- Precise field flatness tuning is simulations is not required due to manufacturing error on practise



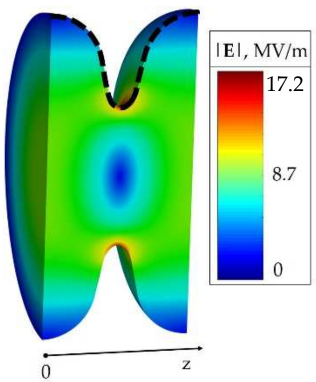


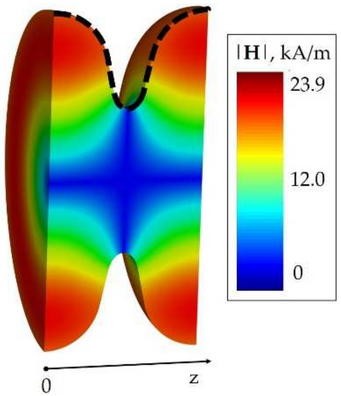
RF design
Peak fields





- Field amplitudes on surface were computed for the TM_{010} ;pi mode
- Figures on the left indicate field amplitudes evaluated on curve





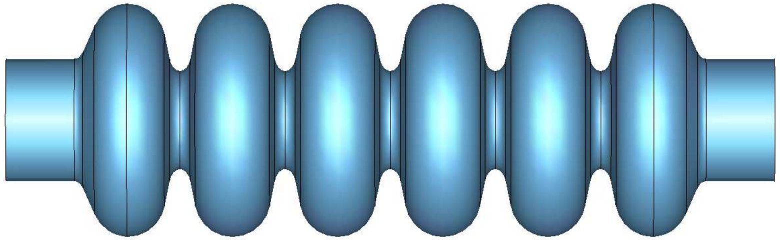
*Reliable amplitude range**:*

Peak magnetic field	Peak electric field
48-56 kA/m	30-35 MV/m

**A. Facco, TUTORIAL ON LOW BETA CAVITY DESIGN

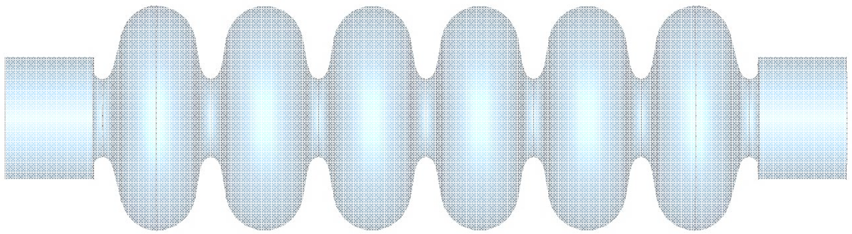
RF design
Longitudinal stiffness

- Current model



- Longitudinal stiffness +1kN/mm
- R/Q value is lower however mechanical stability have a higher priority

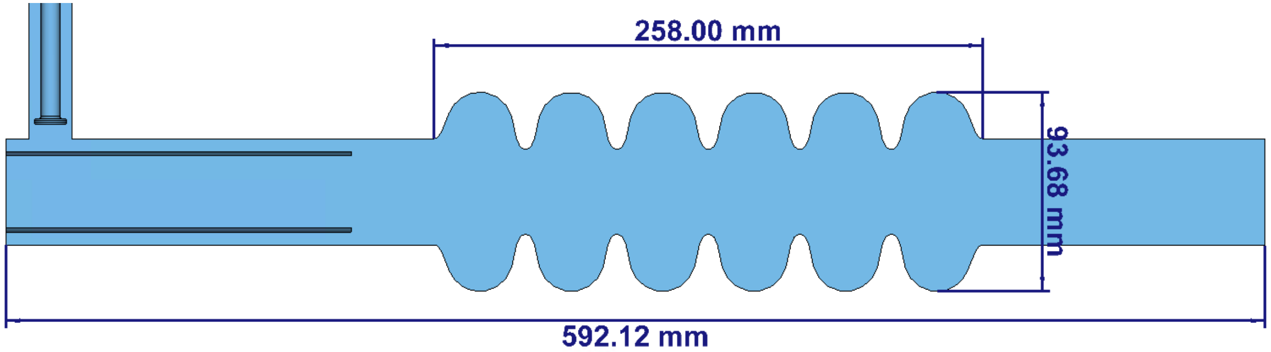
- Previous layout



+ R/Q is higher -> higher efficiency
- Complicated connection to beam pipes

RF design
RF parameters

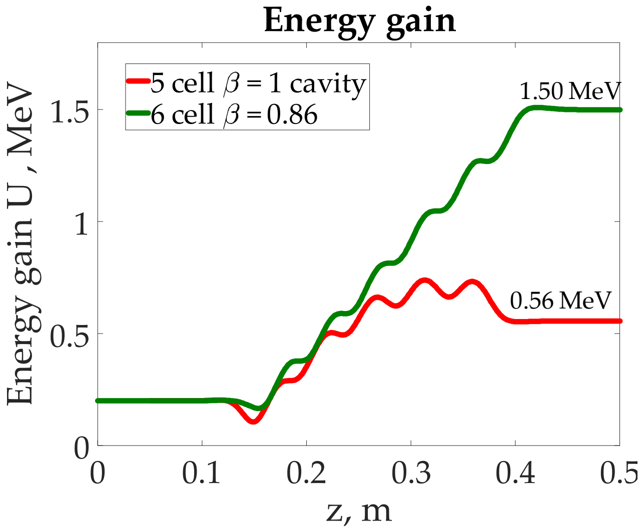
- Side view of the 6 cell reduced β=0.86 cavity:



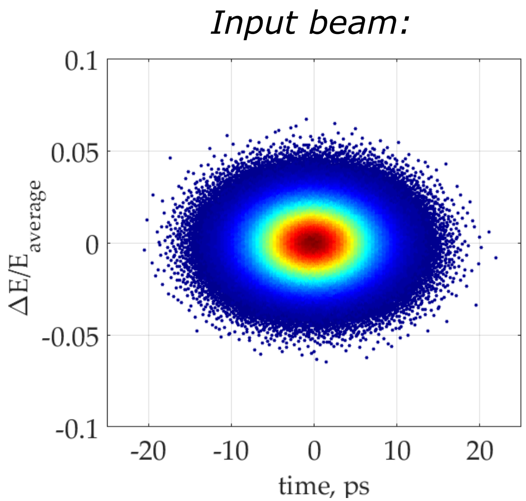
- RF parameters:

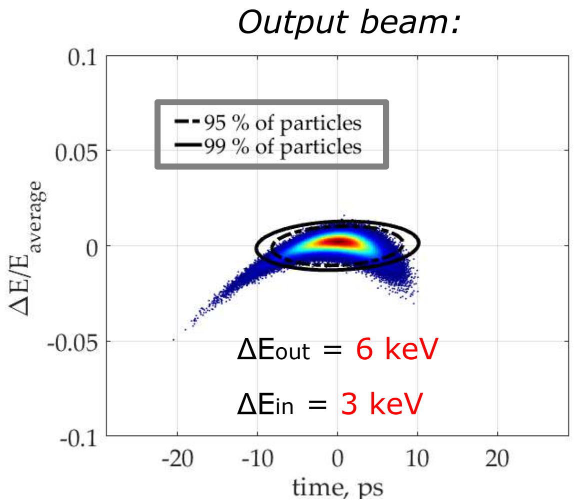
Mode	F, GHz	βg	Kc, %	E_0, MV/m	Eacc, MV/m	R/Q , Ω	G, Ω
TM_{010}; pi	2.997	0.86	5.8	10	5	347	253

RF design
Comparison with the current setup



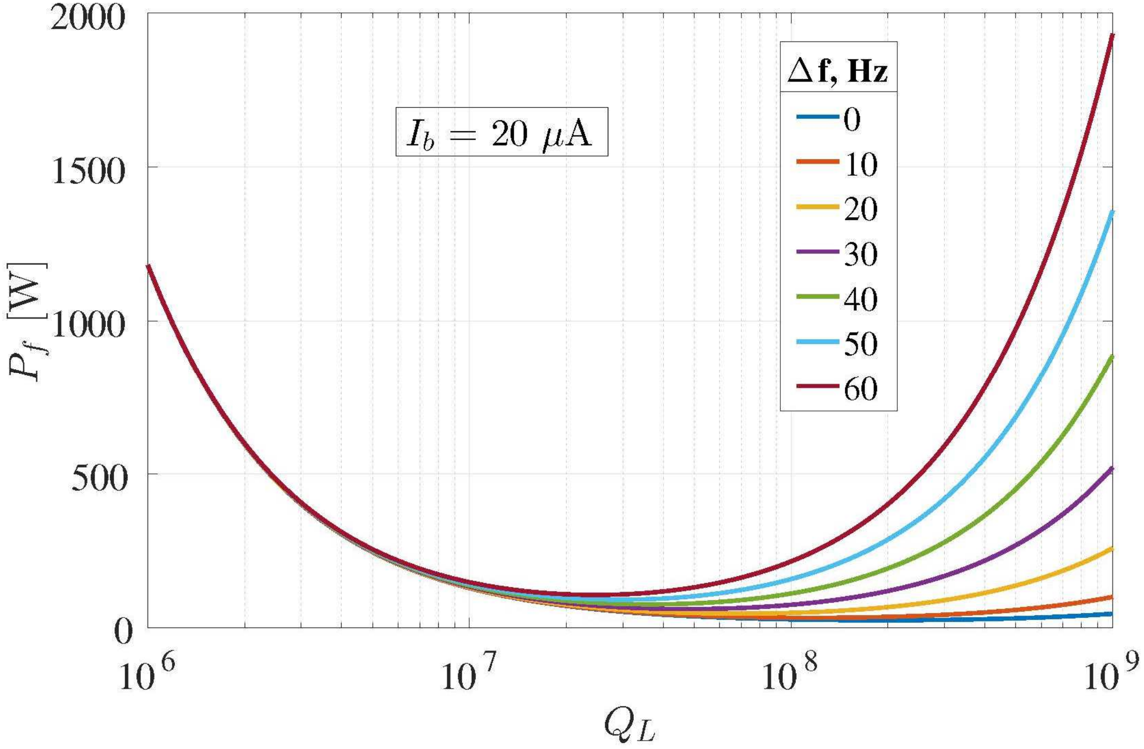
Energy spread





	Current setup (5 cell cavity β = 1)	Proposed design (6 cell cavity β = 0.86)
Peak E-field on axis, MV/m	10 MV/m	
Output energy of the beam, MeV	0.56	1.50
Energy spread growth, keV	>30	3

RF design
Power coupling



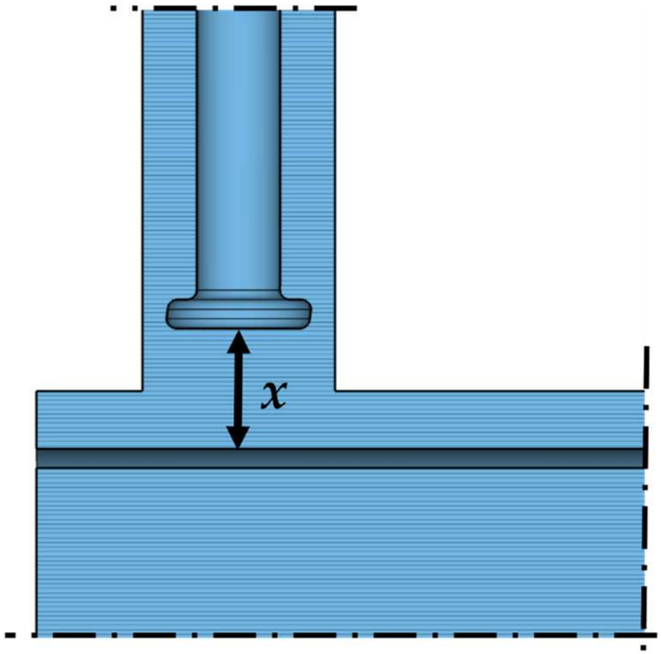
- RF amplifiers provide max. 500 W
- Estimated power P_f <100 W necessary to maintain 10 MV/m on axis
- Detuning is unknown
- Optimal $Q_L = 10^7 \ldots 10^8$

$$P_f = \frac{V_{acc}^2}{4\left(\frac{R}{Q}\right)Q_L} \cdot \left(\left(1 + \frac{\left(\frac{R}{Q}\right)Q_L I_b}{V_{acc}}\cos\phi_b\right)^2 + \left(\frac{\Delta f}{f_{1/2}} + \frac{\left(\frac{R}{Q}\right)Q_L I_b}{V_{acc}}\sin\phi_b\right)^2\right)$$ [1]

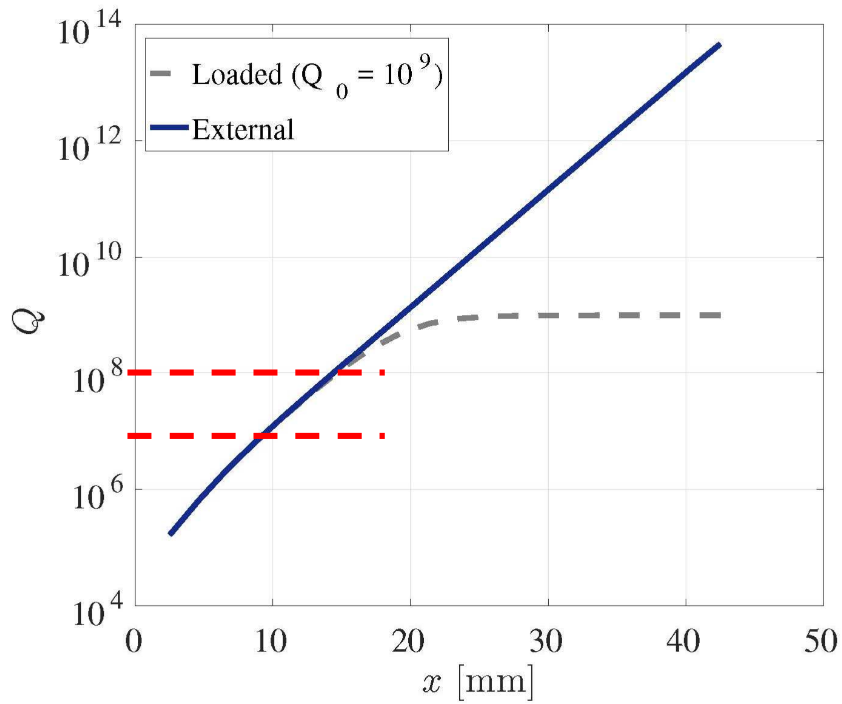
[1] H. Padamsee, J. Knobloch, and T. Hays. RF superconductivity for accelerators.

RF design
Power coupling

- Cross section of the input power coupler of the 6-cell cavity



- Q-factor vs penetration depth of inner conductor of coaxial line



Mechanical model
Introduction

- ANSYS is used for structural analysis
- Mechanical model of the 3.9 GHz β=1 cavity (DESY XFEL/TTF) was used to gain information about mechanical behaviour of an SRF cavity in this frequency range
  - o Wall thickness: 2.8 mm before polishing inner surface -> 2.5 mm after
  - o No stiffening rings required – cavity is rigid enough* without them (cheaper production costs, less analysis)

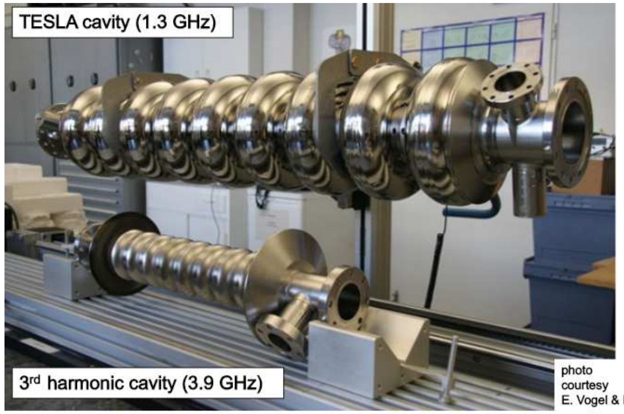
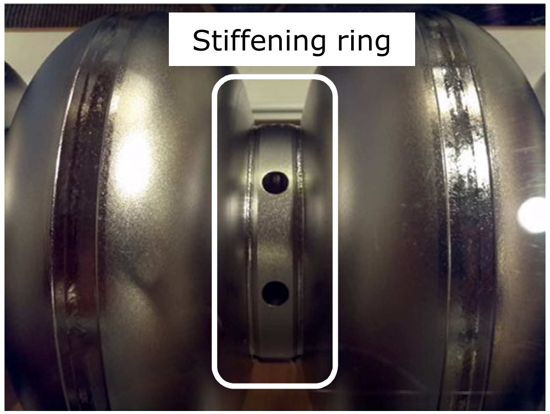


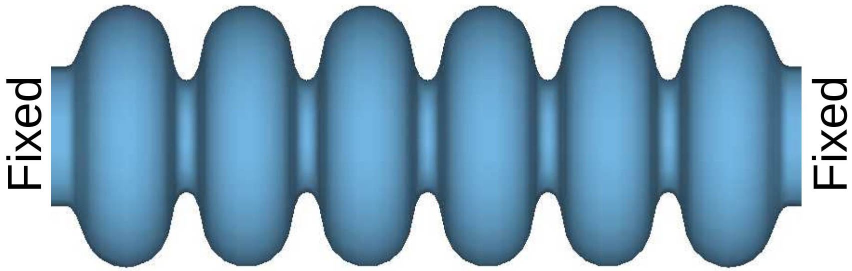
photo courtesy E. Vogel & DESY



*DEVELOPMENT OF THE 3.9 GHZ 3RD HARMONIC CAVITY AT FNAL, N. Solyak, H. Edwards et., al. SRF 2003
*This fact was also mentioned in a private communication of Simon Weih with RI GmbH representative

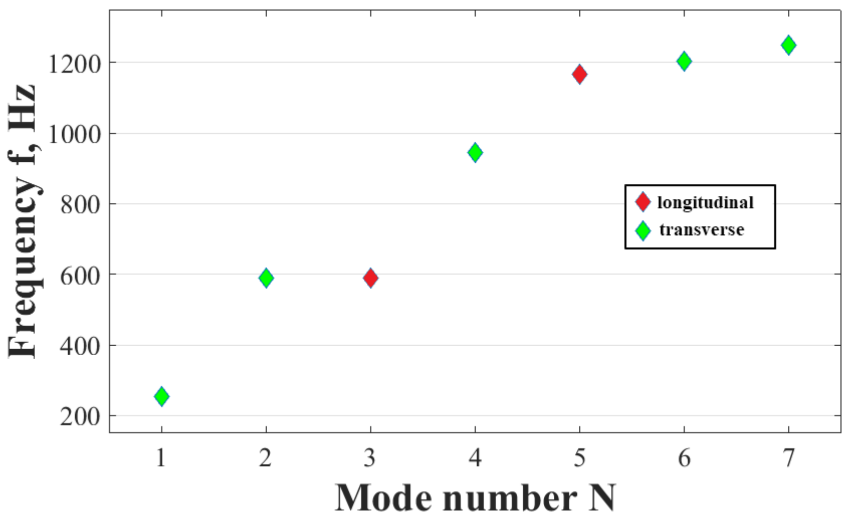
Mechanical model
Microphonics

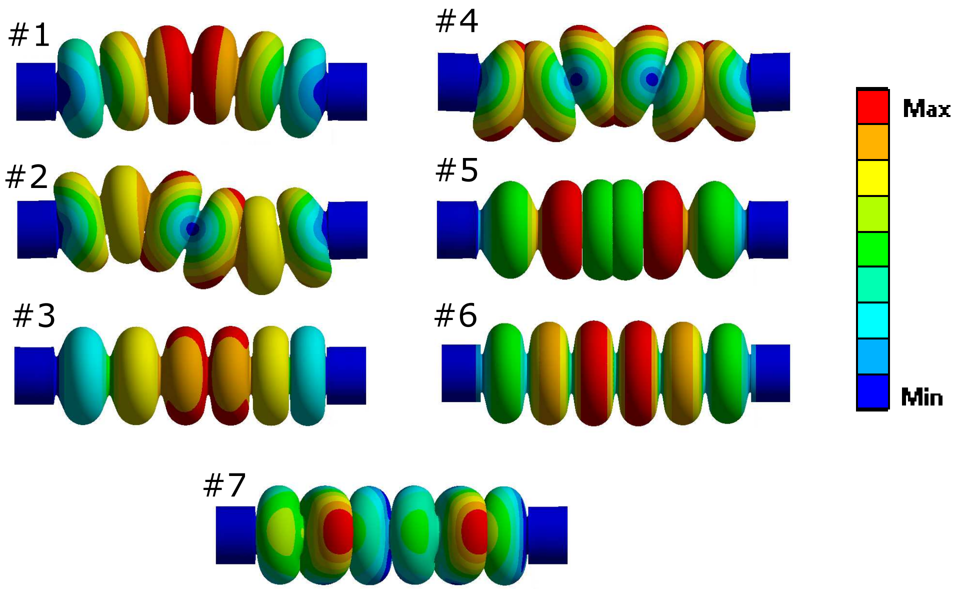
- **Microphonics** can be defined as dynamic cavity detuning caused by structural vibrations transmitted to the RF structure
- The source can be:
  - Ground motion
  - Helium pressure fluctuations
  - Lorentz forces
  - Any external source of noise



Mechanical model
Microphonics

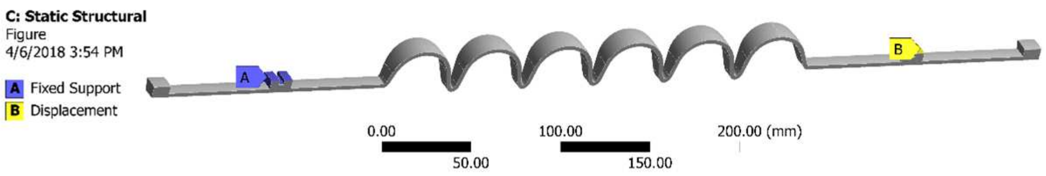
- Resonant frequencies of the first 7 mechanical modes were obtained
- Main purpose of these computations is not to estimate detuning of the cavity due to microphonics but to know the location of the longitudinal modes in a frequency range below 1 KHz





Mechanical model
Characterization related to tuning

- External mechanical loads act on cavity walls and shift the resonant frequency of the fundamental mode and also affect the field flatness
- Tuning system for the cavity during the operation is required to compensate deformations and remain the designed value of the frequency of the fundamental mode
- Three characteristics are required for the tuner: df/dp, df/dl and longitudinal stiffness of the cavity
- Boundary conditions used in simulations:



- Material properties used in simulations:

Material	Niobium
Wall thickness, mm	2.5 (2.8 before polishing)
Temperature, K	2
Young's modulus, GPa*	118
Poisson ratio*	0.38

*TD ER-10163, M.Merio, October 2011

Mechanical model
Characterization related to tuning

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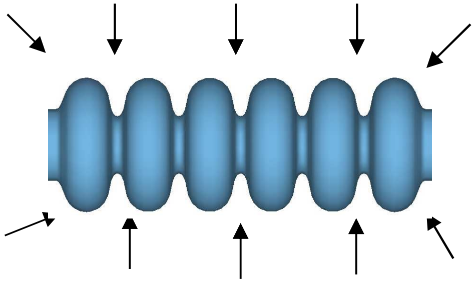
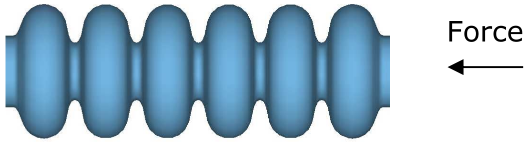
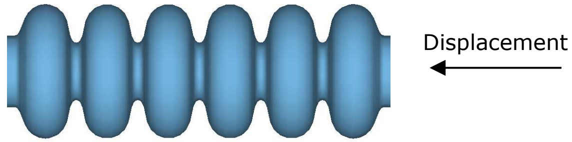
- Frequency vs pressure



- Longitudinal stiffness of the cavity

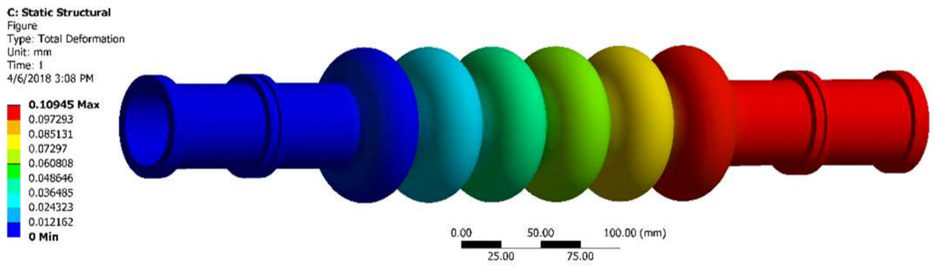


- Frequency vs Displacement



Pressure sensitivity df/dp, Hz/mbar	Longitudinal stiffness K, kN/mm	df/dl, kHz/µm
30	4.6	2.1

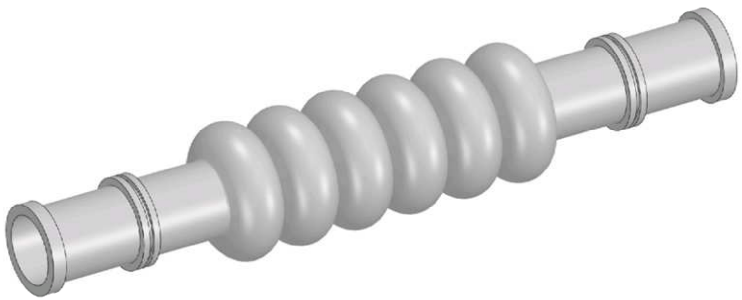
- Example: deformation caused by applied pressure (the scale of the deformation is exaggerated)

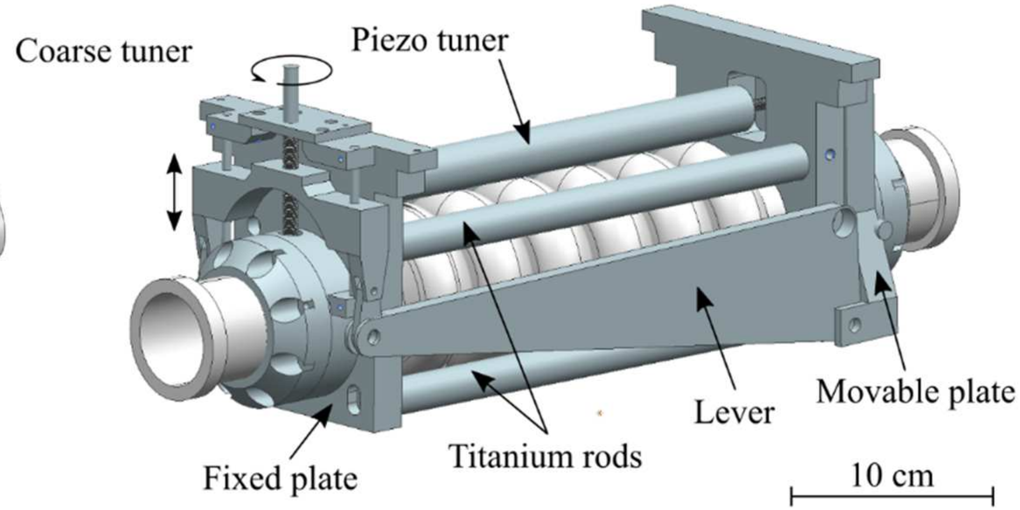


ACCELENCE

Current status

- Agreement with Research Instruments
- Manufacturing will take ~1 year from now
- Estimated price ~ 100 000 EUR (including inside surface preparation)
- Additional beam diagnostics system at the S-DALINAC is required for commissioning of the 6-cell cavity





Conclusion

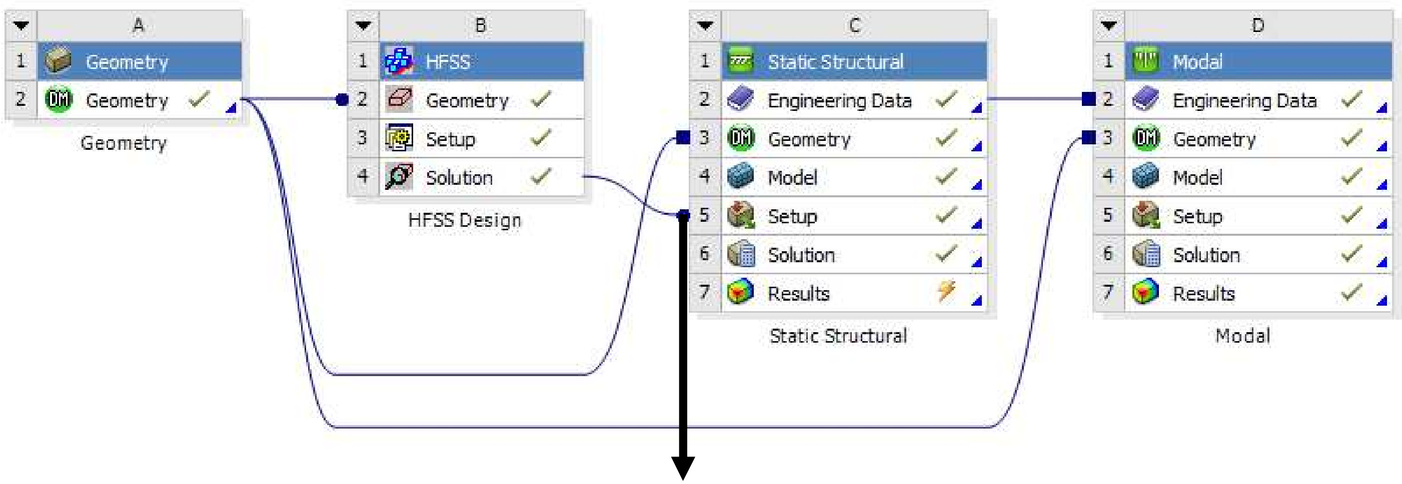
- Reduced β cavity has more advantages than other proposed layouts with respect to design criteria for a new cavity
- RF design is done (without HOM dumping system)
- Necessary RF power is covered by RF amplifiers available at the S-DALINAC
- Cavity is compatible with the present input power coupler
- Cavity fits into the existing cryostat
- Production should be finished in 2020

Mechanical model
ANSYS

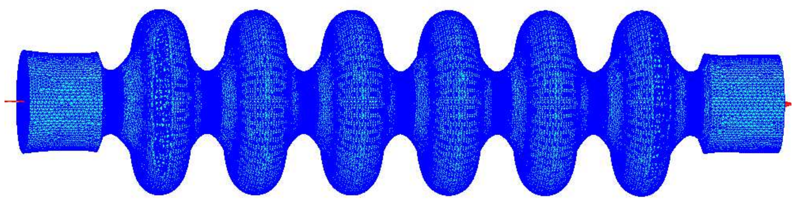
Eigenmode solver

Mechanical: external loads

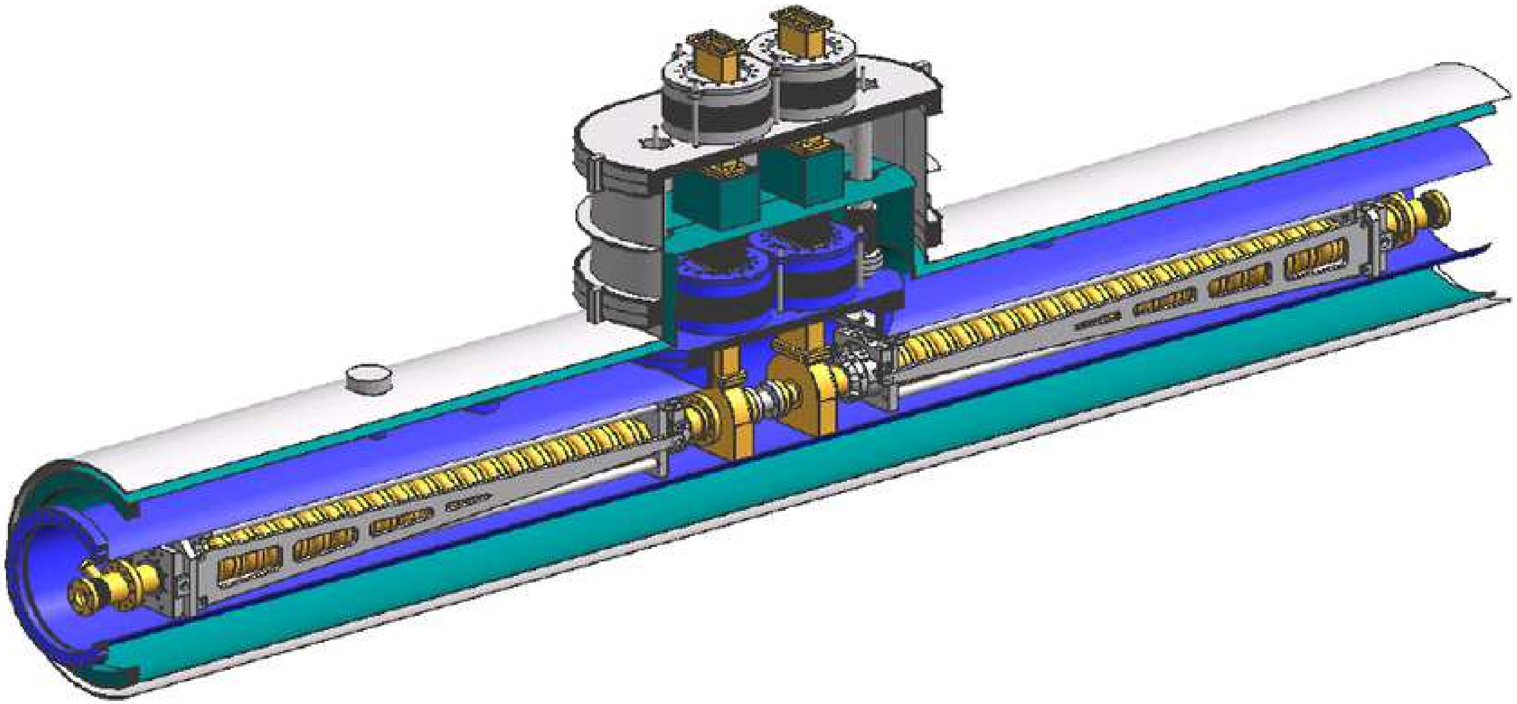
Mechanical: microphonics

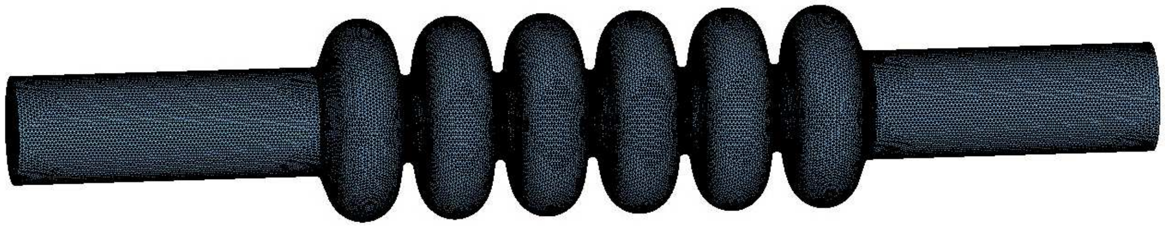


Deformed mesh* is sent to HFSS -> df/dp; df/dl

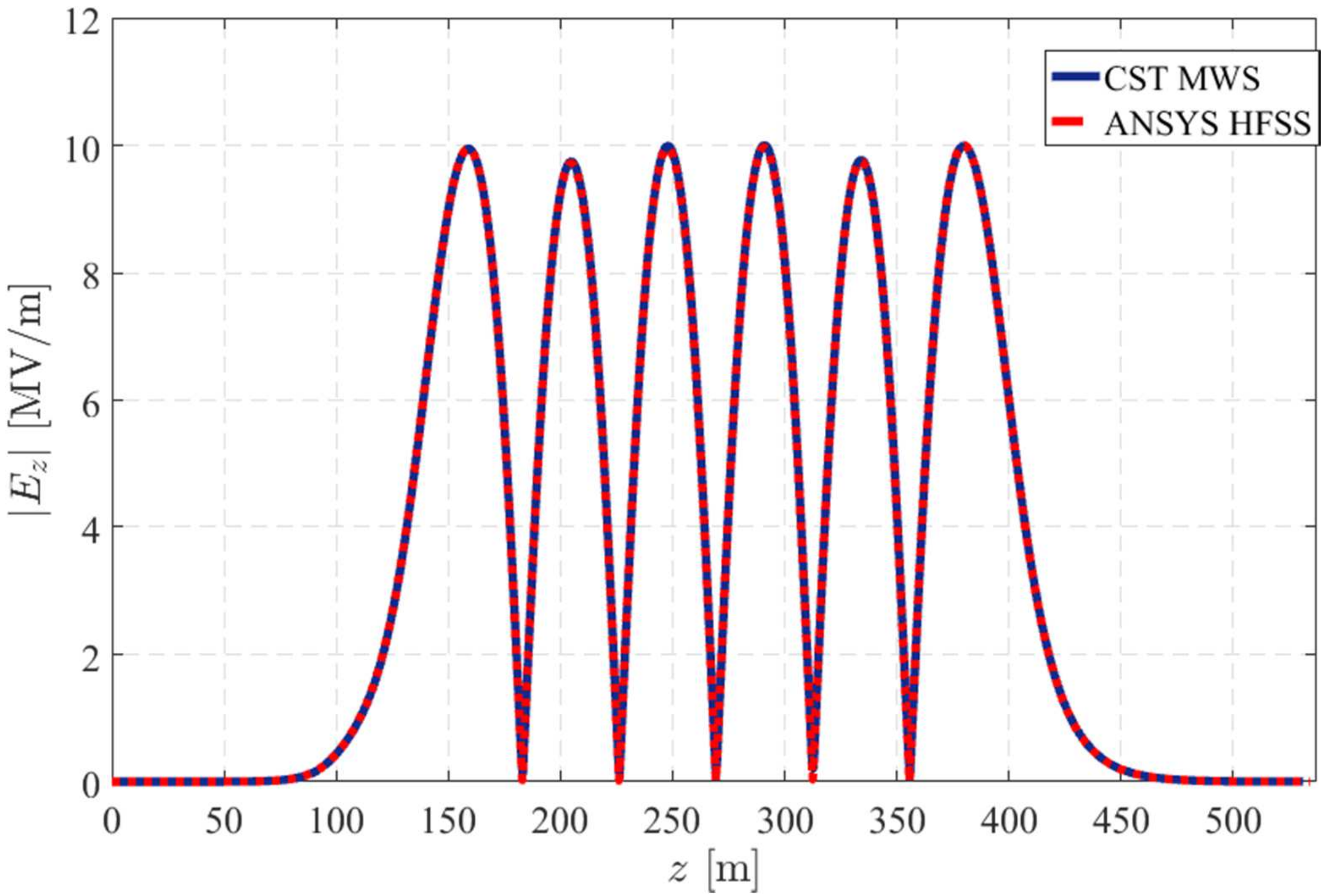


*the scale is exaggerated





~3 mln.



CST MWS
ANSYS HFSS
$|E_z|$ [MV/m]
z [m]
0
2
4
6
8
10
12
0
50
100
150
200
250
300
350
400
450
500