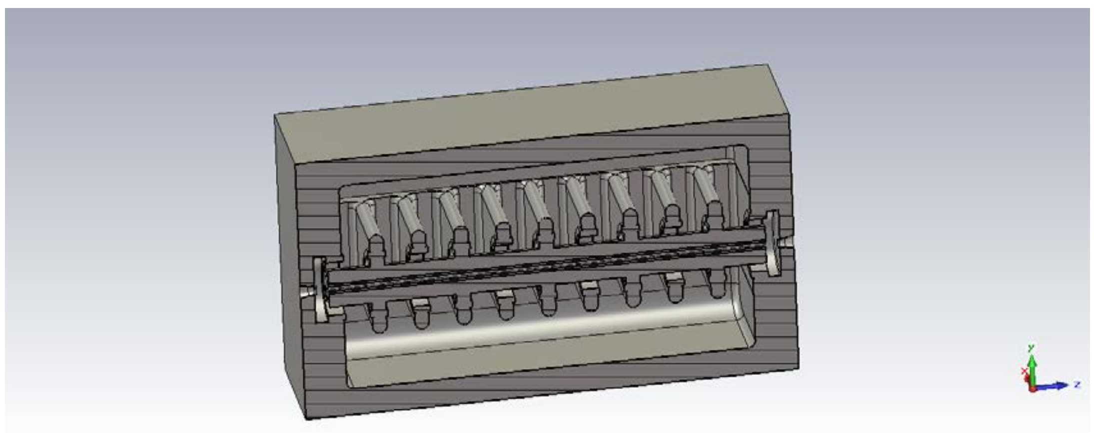
Proposal of a 325 MHz Ladder RFQ for the FAIR Proton Linac



Max Schütt – HIC for FAIR Accelerator Physics Day,
Frankfurt a. M., 10.10.2014

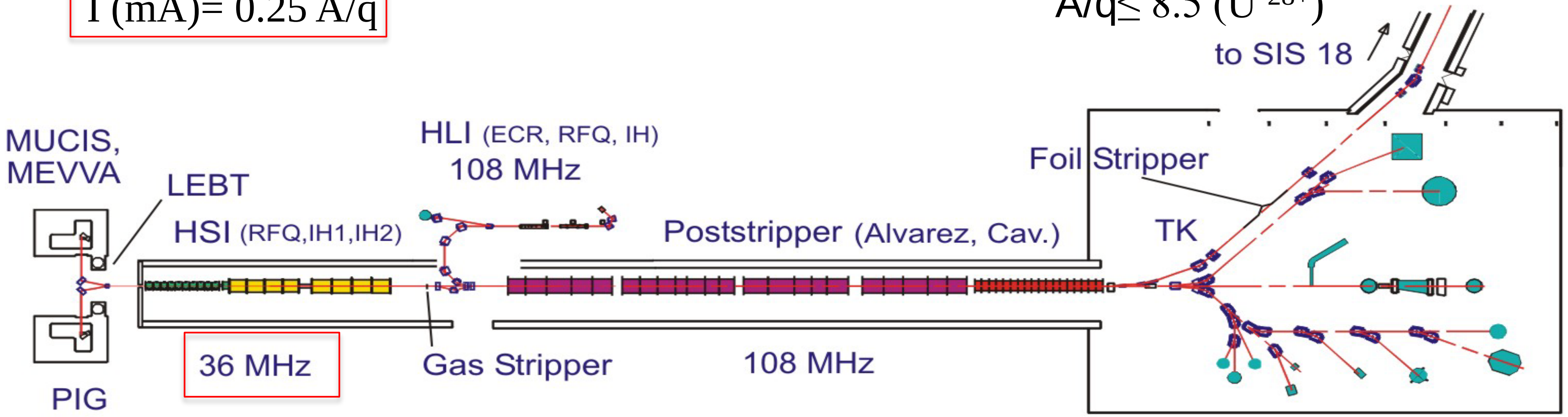
Outline

- Introduction & Motivation
- Analytical Model
- Simulations & Tuning
- Prototype Modeling
- Summary, Outview & Timeline

RFQ's at GSI

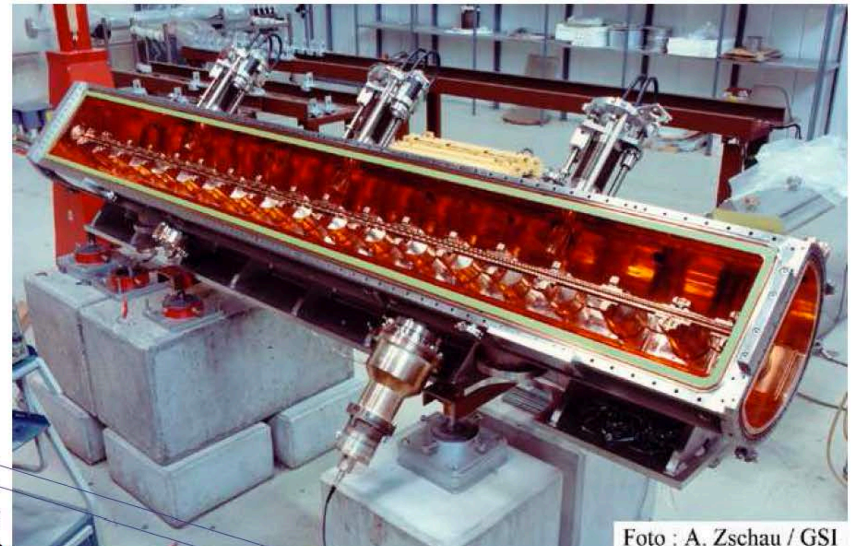
Current Situation:

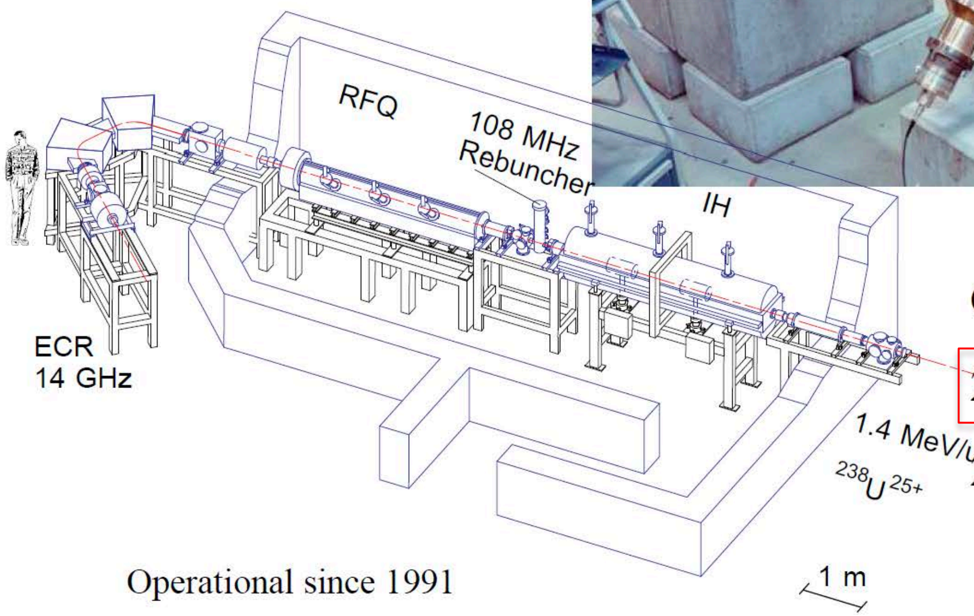
4-Rod IH-RFQ	IH 1 & IH 2	5 Alvarez Type DTL
2.2 – 120 keV/u	120–743 keV/u -1.4 MeV/u	1.4 – 11.4 MeV/u
Built in 1999	Built in 1999	Built in 1975
A/q $\leq$ 65 (U^{4+})	I (mA)= 0.25 A/q	178 DC Quadrupole
I (mA)= 0.25 A/q		A/q$\leq$ 8.5 (U^{28+})



RFQ's at GSI

First ECR-RFQ-IH-DTL combination





GSI HLI

2.5-300 keV/u, U 28+

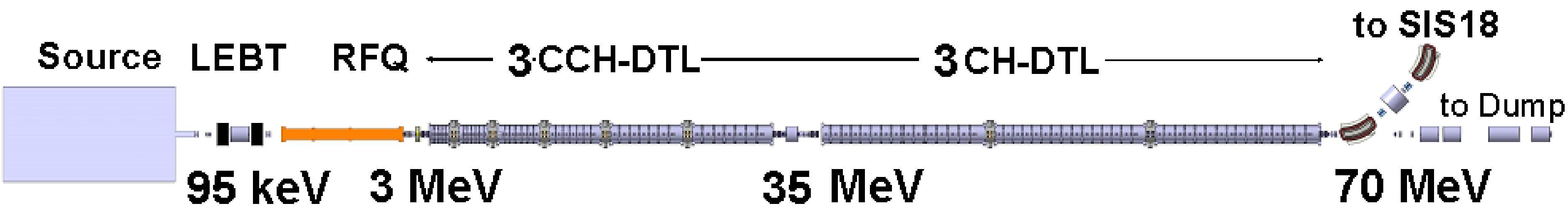
25% df

Operational since 1991

Possible upgrade: higher duty factor, matching, (water tube erosion)

FAIR P-LINAC

Solution:



Beam Energy (MeV)	**70**
Beam Current (mA)	**35 - 70**
Beam Pulse (µs)	**36**
Repetition Rate (Hz)	**4**
Frequency (MHz)	**325.224**
Norm. Emittance at output (µm)	**2.1 / *4.2***
Momentum Spread	**$\leq \pm 10^{-3}$**
Beam Loading (peak) (MW)	**4.9**
RF Power (peak) (MW)	**2.2**
Klystron (3 MW Peak Power)	**7**
Solid State Amplifier (50 kW)	**3**
Total Length (RFQ + CH)	**≈ 27 m**

IAP

RFQ-Parameters

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RFQ Parameters:

Parameter	Value	Parameter	Value
f	325.224 MHz	Voltage	80 kV
Beam current	<100 mA	E_p	<36 MV/m
E_{out}	3 MeV	RF power	<1 MW
$e_{out,N,95\%,trans}$	<1.6 mm mrad	Length	~3 m
$e_{out,N,95\%,long}$	<2 MeV deg	$R_{p,min}$	16.6 kΩm
Pulse length	250 µs	Mass flow	10 l/min

3 Possibilities: 4-Rod-RFQ, 4-Vane-RFQ, Ladder-RFQ

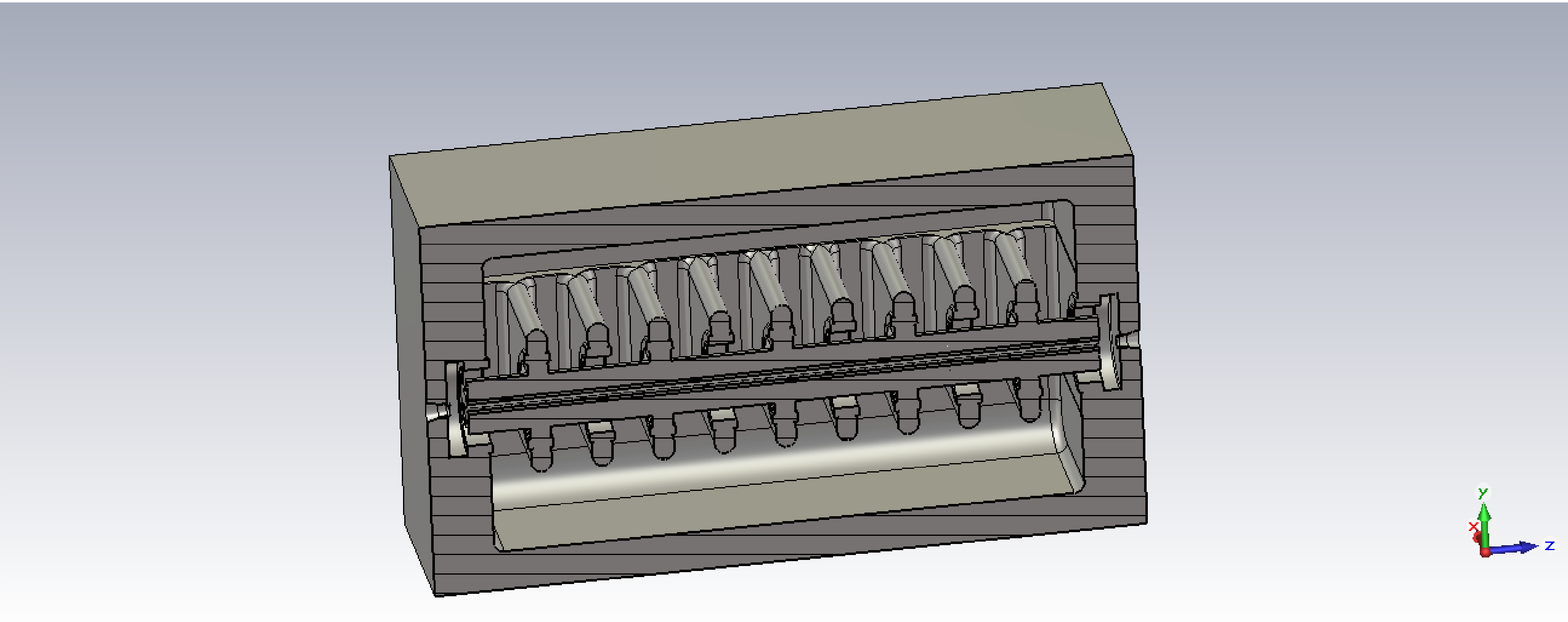
Prototype

RFQ-Prototype Parameters for the Ladder-RFQ prototype cavity:

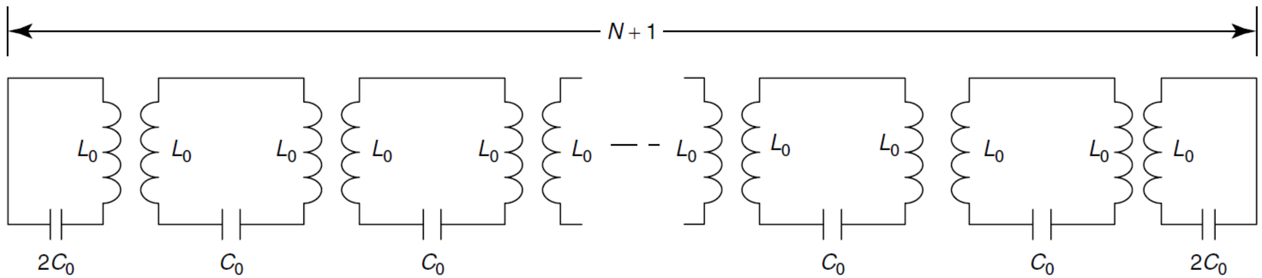
(ideal values)

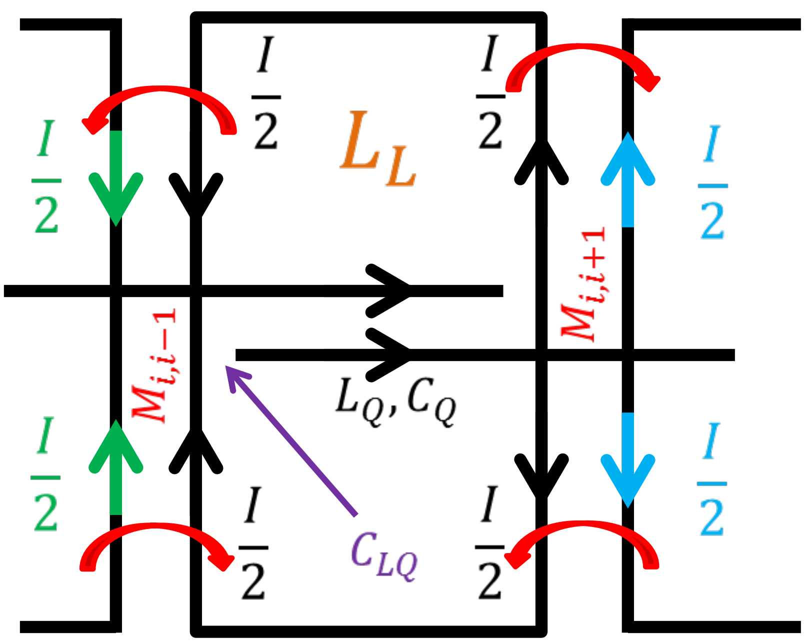
Parameter	Value	Parameter	Value
Frequency	325.224 MHz	No. of Cells	10
Q-Value	7200	Mini-Vane Length	630 mm
Loss peak.	100 kW	Ladder Height	150 mm
Loss av.	200 W	Ladder Width	285 mm
Beam current	max. 100 mA	Ladder Thickness	20 mm
Shunt-Impedance	40 kΩm	Ladder Distance	40 mm
Voltage	80 kV		

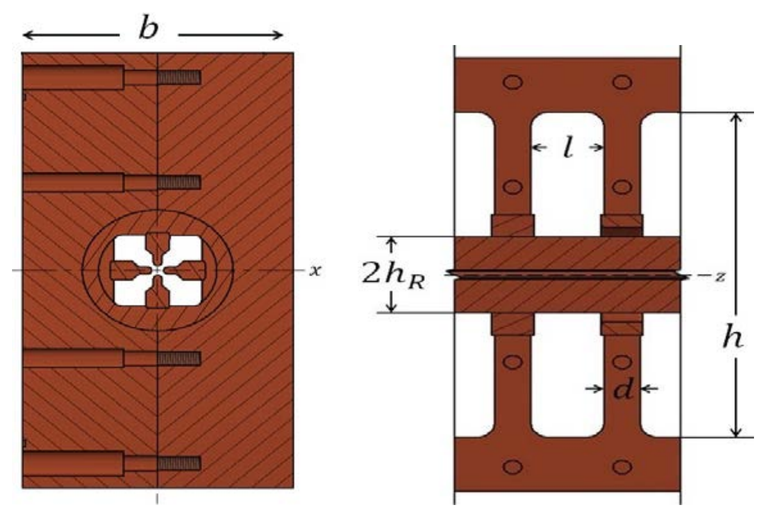
Ladder-RFQ Prototype



Analytical Model





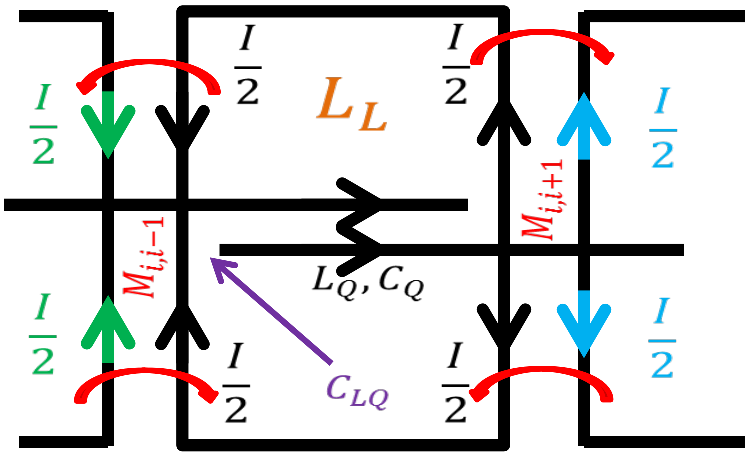


Analytical Model

$$L_L = \mu_0 \cdot \frac{l \cdot h}{4b}$$

$$L_Q = \frac{\mu_0 \cdot l}{2\pi}\left(\ln\left(\frac{2l}{\varepsilon \cdot h_r}\right) - \frac{3}{4}\right) \cdot \eta$$

where ε is the fit parameter: $0.50 \leq \varepsilon \leq 1.0$



$$\eta = \frac{C_Q}{C_{LQ} + C_Q}$$

$[0.80 \leq \eta \leq 0.95]$

[C_{LQ} is the ring-rod capacity]

$$L_{eff} = L_L + L_Q$$

Analytical Model

$$C_Q[pF] = (l+d)[\frac{39.37}{\cosh^{-1}\left[\left(1+\frac{R_0}{\rho}\right)/\sqrt{2}\right]} + \frac{31.05}{R_0/\rho - 0.414} + 25.28 \cdot \ln\left(1+\frac{l_1+l_2}{R_0+\rho}\right) + 8.85 \cdot \frac{V/2-\rho}{h_1+\rho}]$$

Rod – capacity, I. Ben-Zvi et al., Proc. LINAC 1990, last term added for used geometry

$$C_{LQ} = \frac{1-\eta}{\eta} \cdot C_Q$$

$$C_{eff} = [C_Q + C_{LQ}] \cdot [\frac{L_L + L_Q/2}{L_L + L_Q}]$$

Results from the model:

$$\omega_0 = \frac{1}{\sqrt{L_{eff} \cdot C_{eff}}}$$

Single cell resonance

Zero mode resonance

$$k = \frac{L_L}{2L_{eff}}$$

Coupling factor

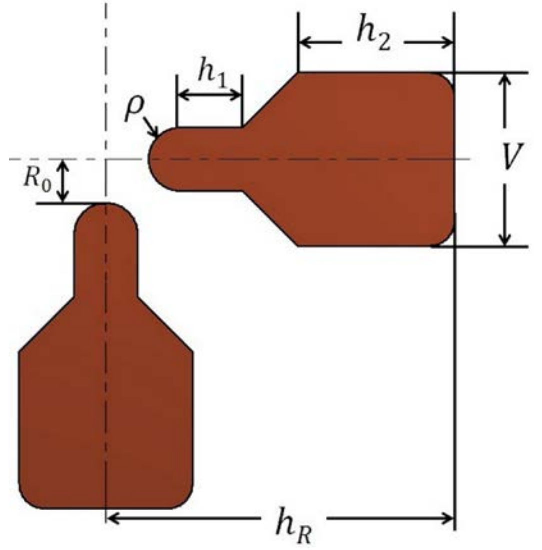
$$\Omega_0 = \frac{\omega_0}{\sqrt{1+k}}$$

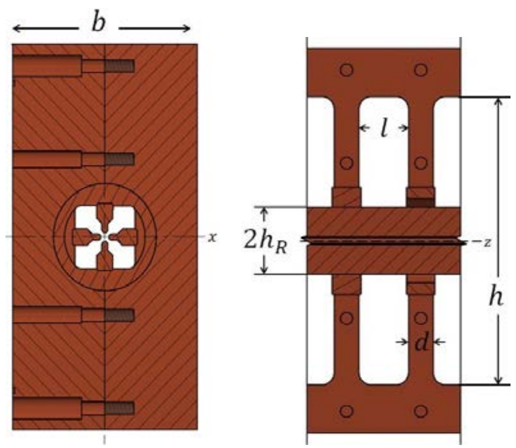
Analytical Model

Input parameters of vane and cell structure for analytical model:

$$h = 240\,mm, b = 160\,mm, l = 40\,mm, d = 20\,mm, R_0 = 3.42\,mm, \rho = 2.56\,mm$$

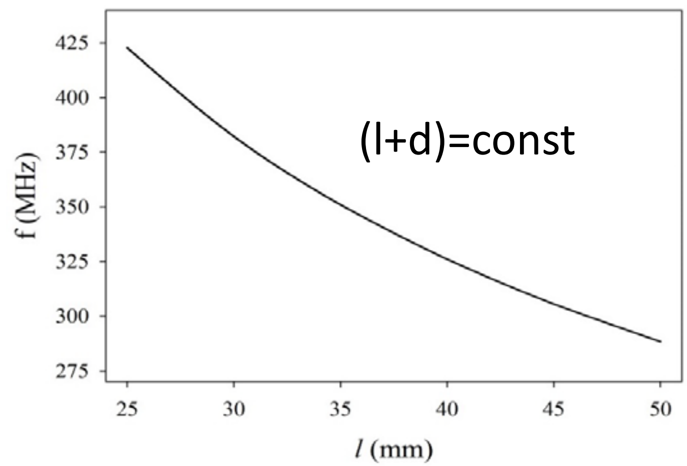
$$h_1 = 5.0\,mm, h_2 = 12.59\,mm, h_R = 28.0\,mm, V = 14\,mm, \varepsilon = 0.75, \eta = 0.85$$

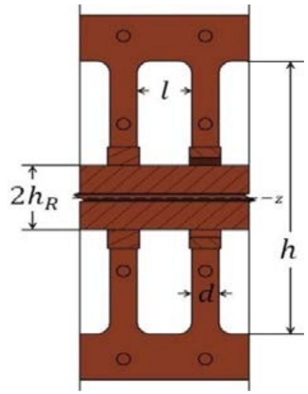


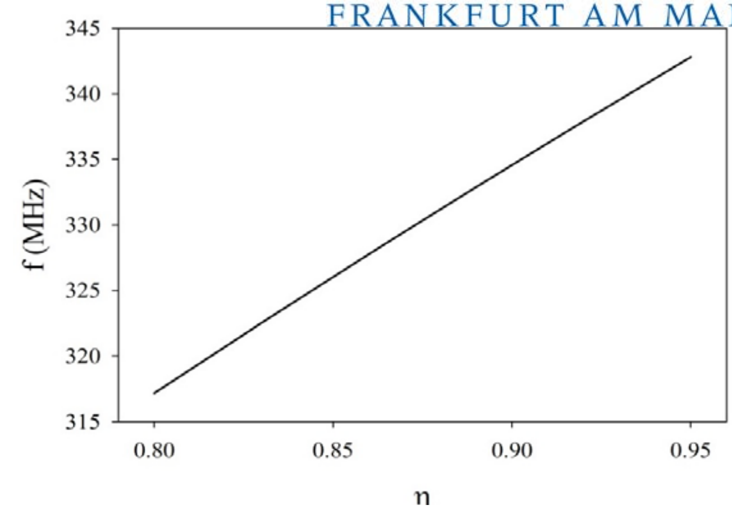


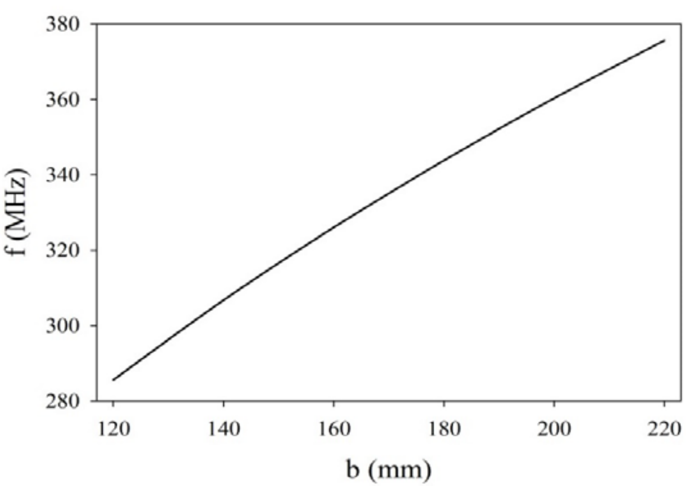
Result: $f_0 = 326\text{Mhz} \pm 10\text{Mhz}$

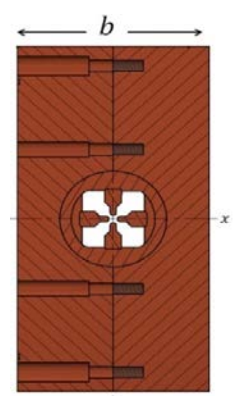
Analytical Model

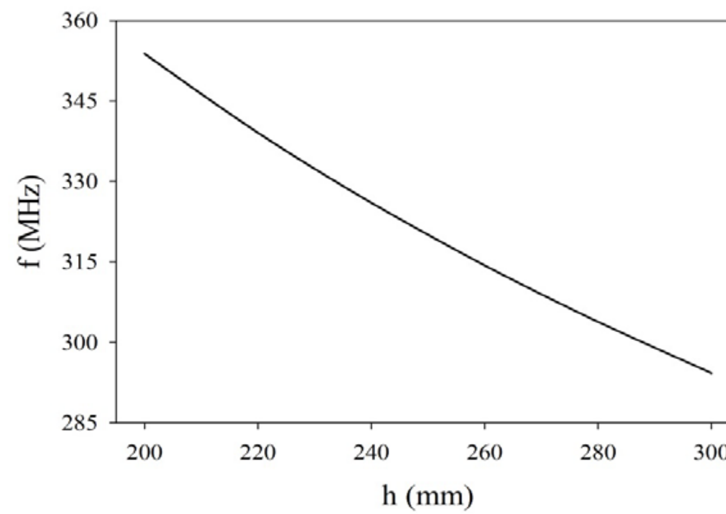






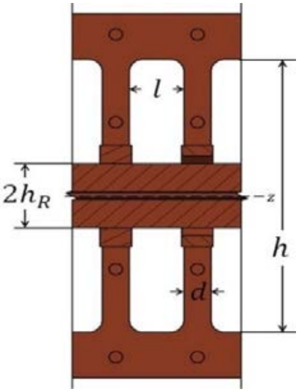


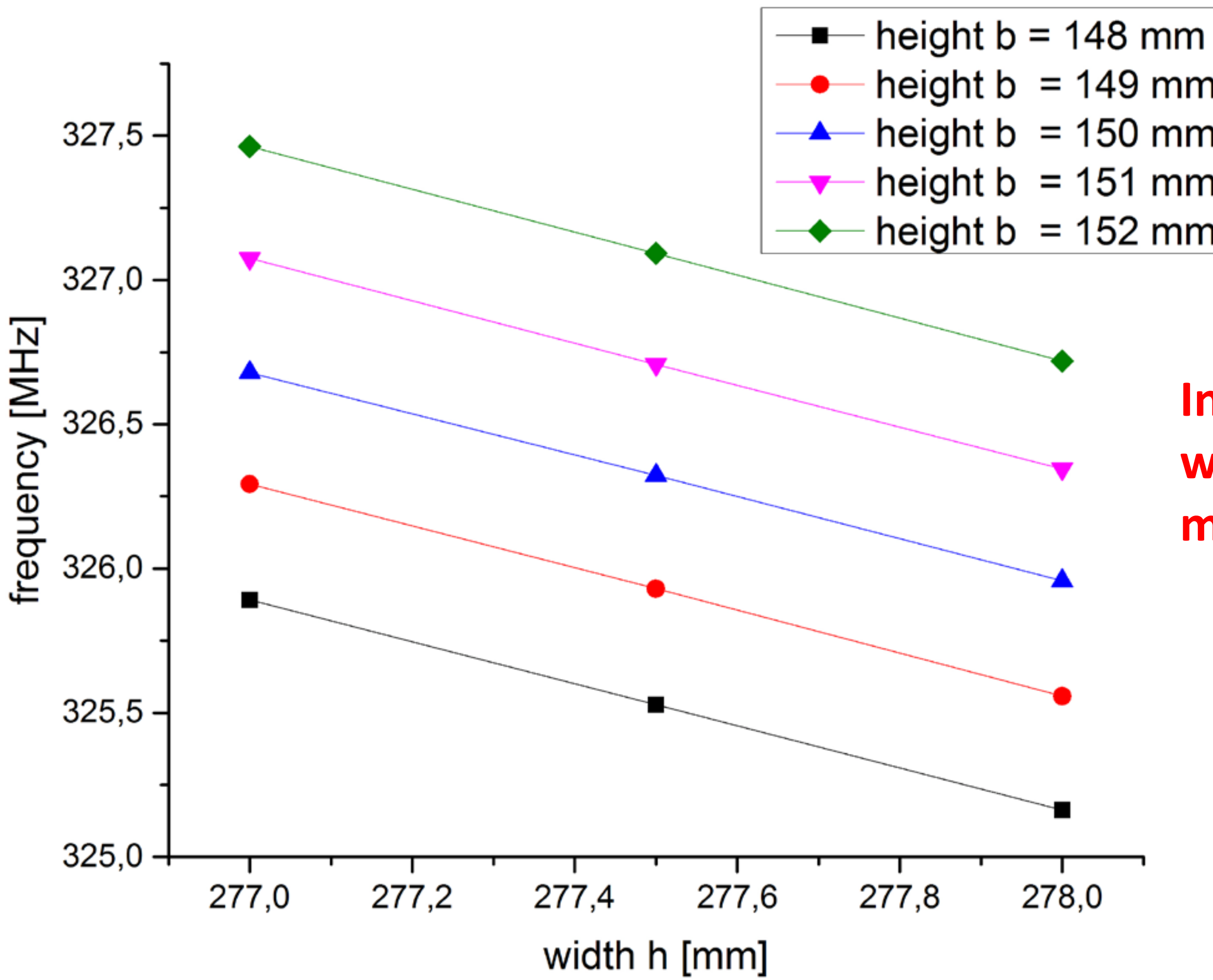




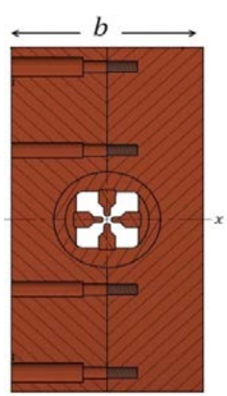
Width and Height are important parameters for determining the frequency of a Ladder RFQ

Simulations Width & Height

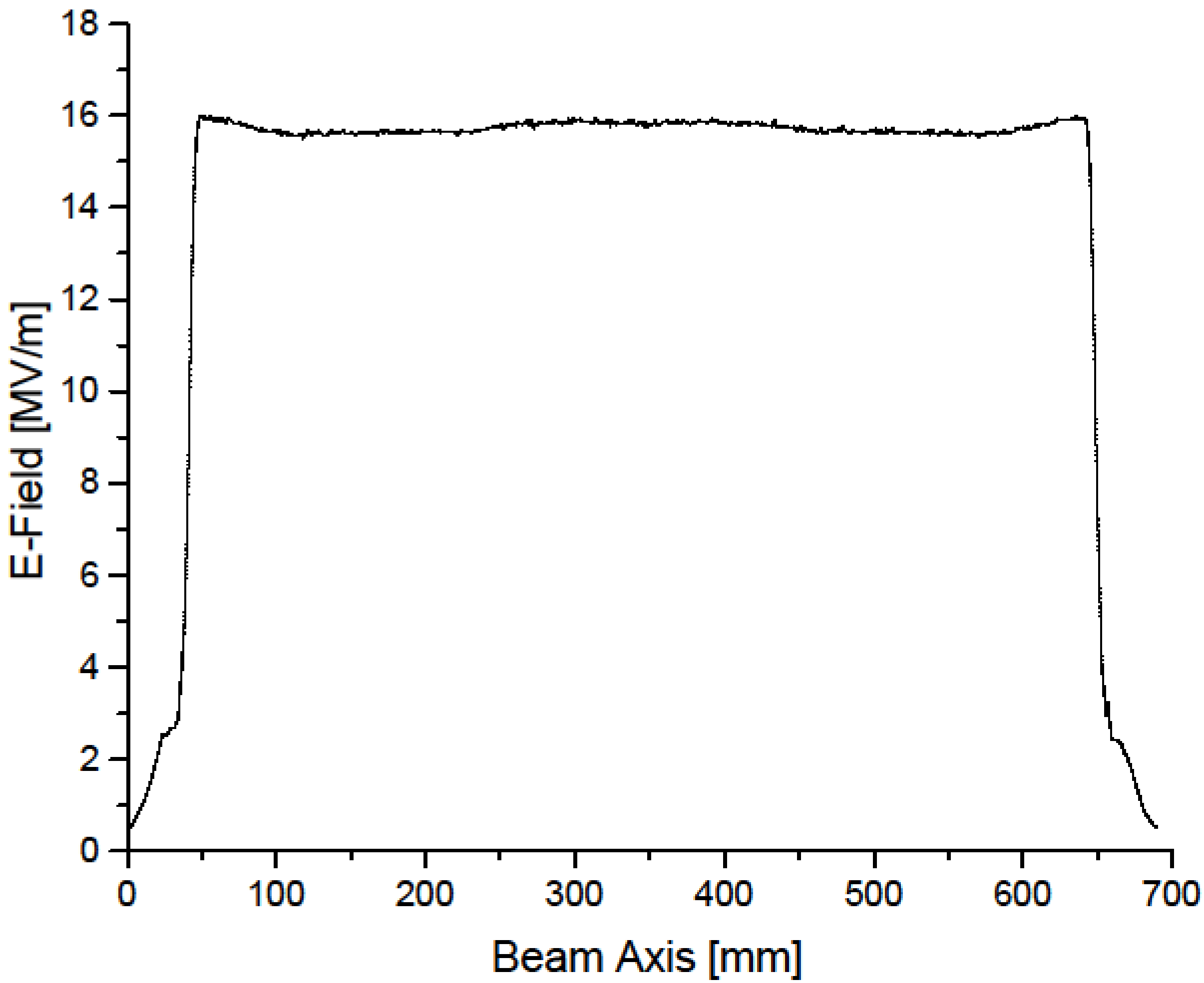




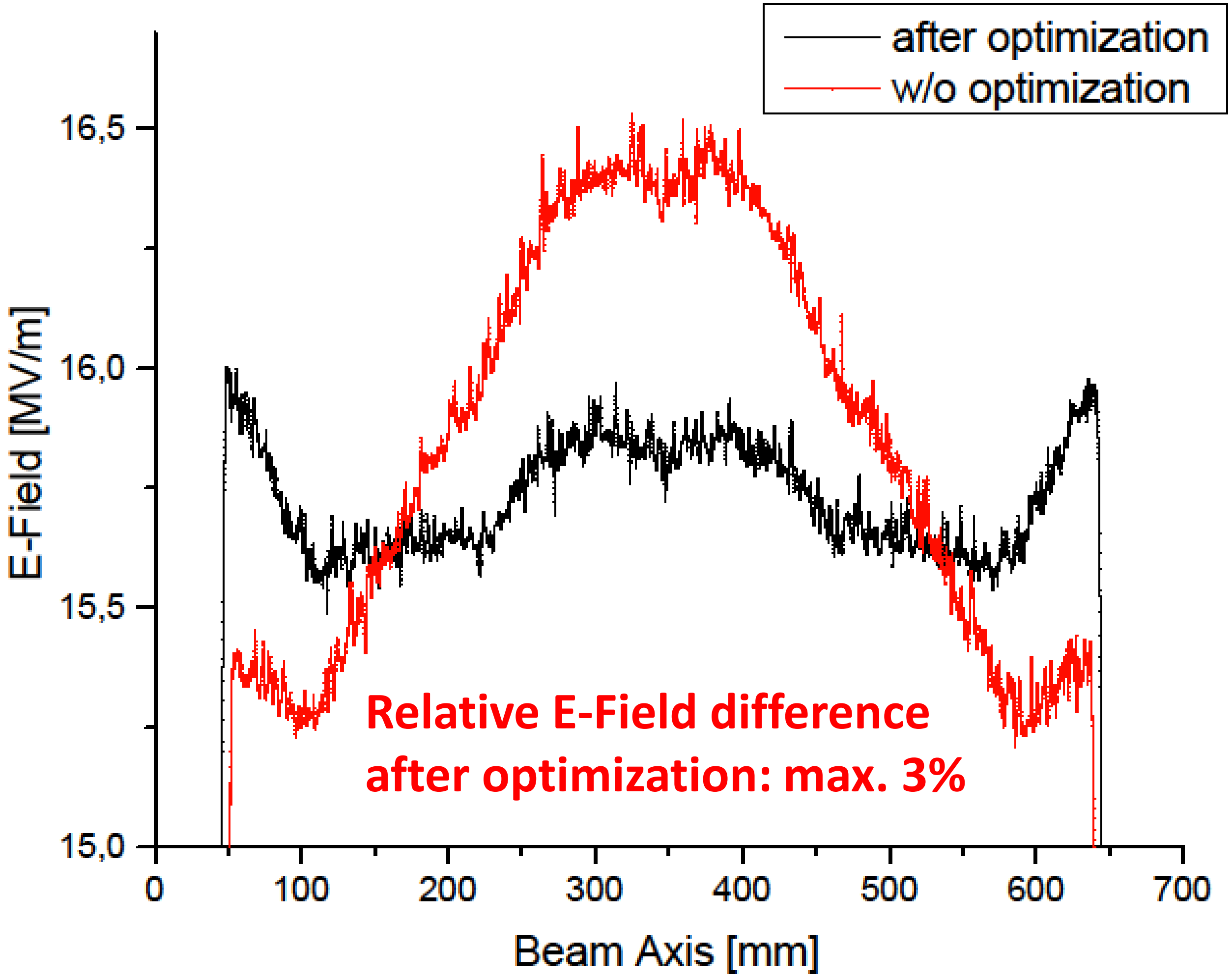
In accordance with analytical model



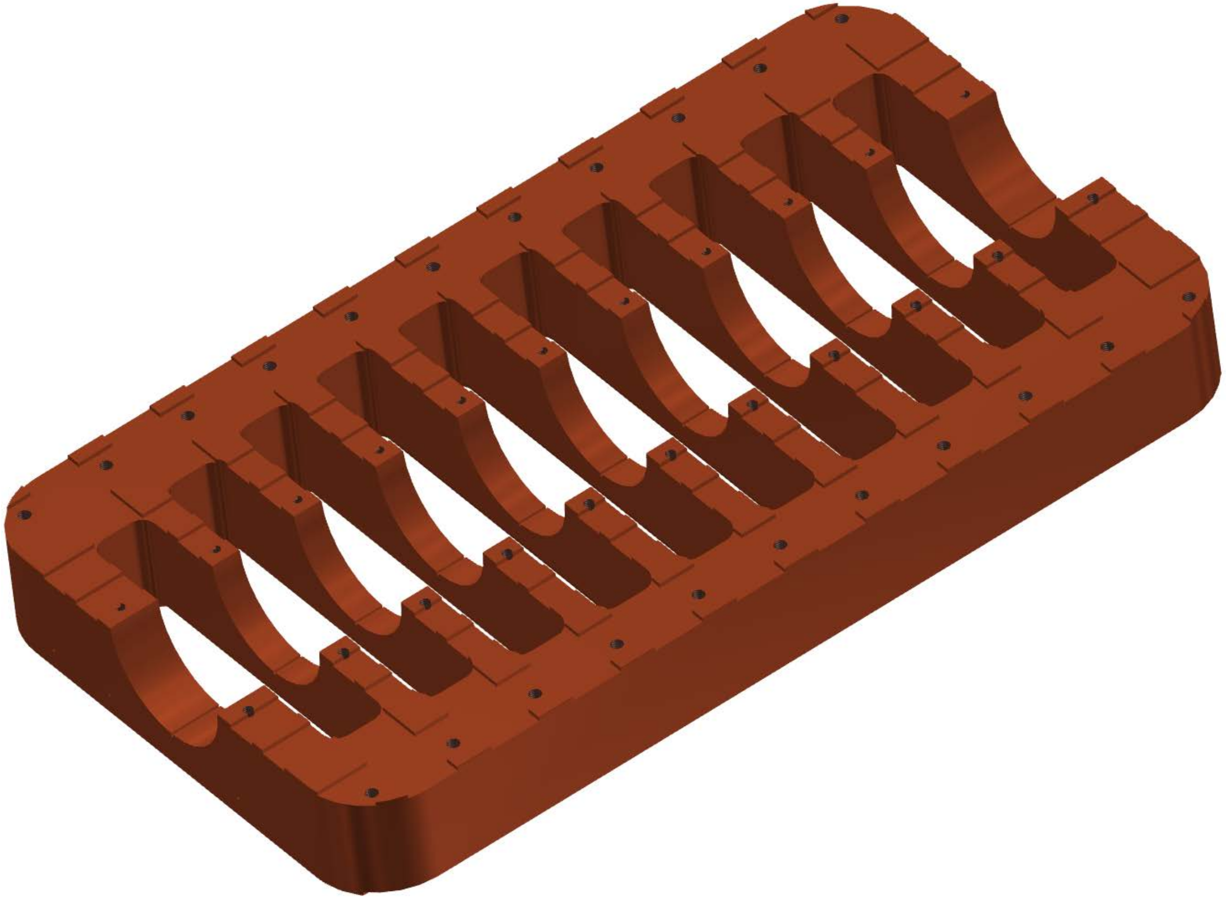
Prototype Field-Flatness



Prototype Field-Flatness



Coarse Tuning (Cell Widths)



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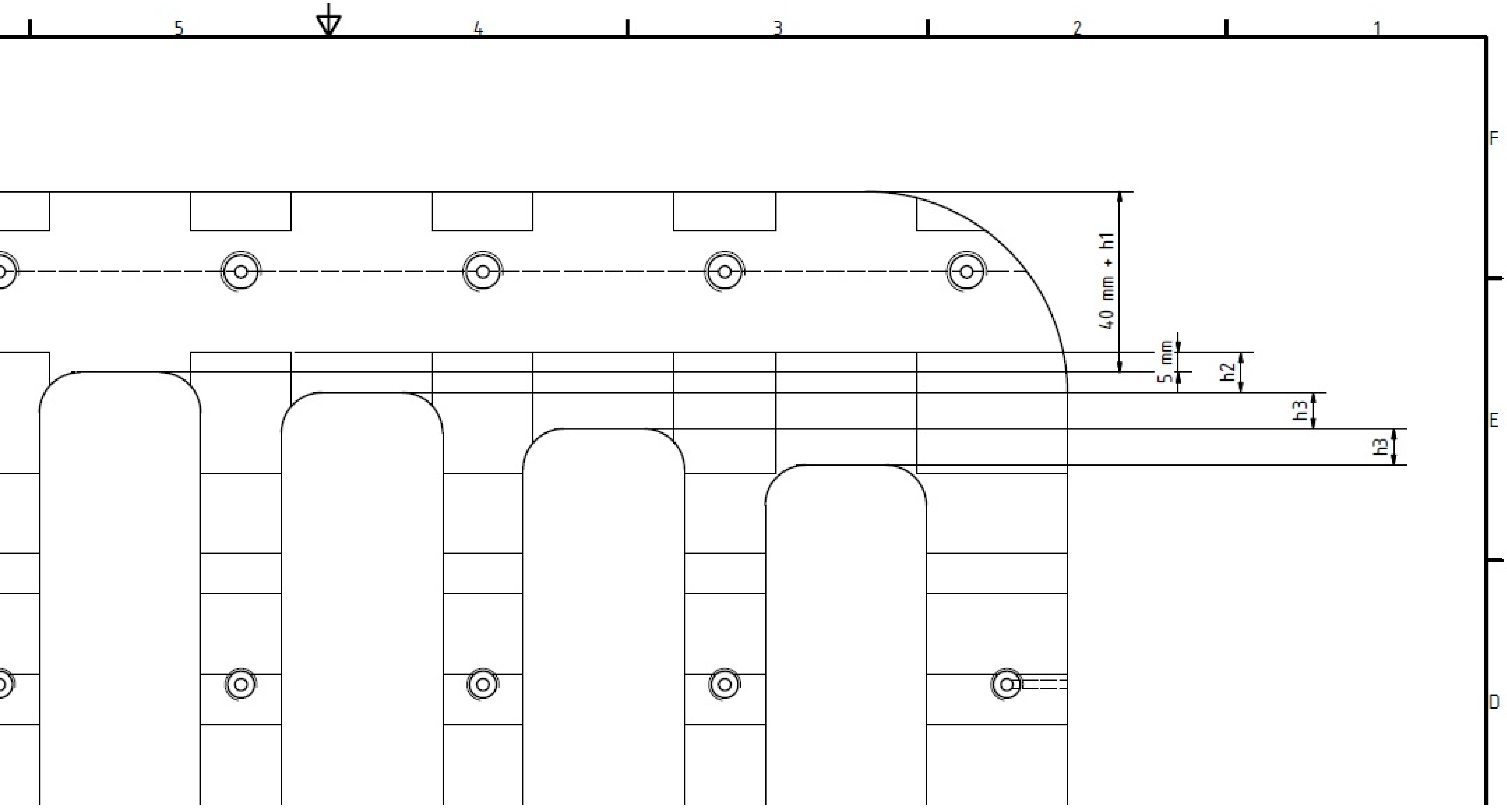

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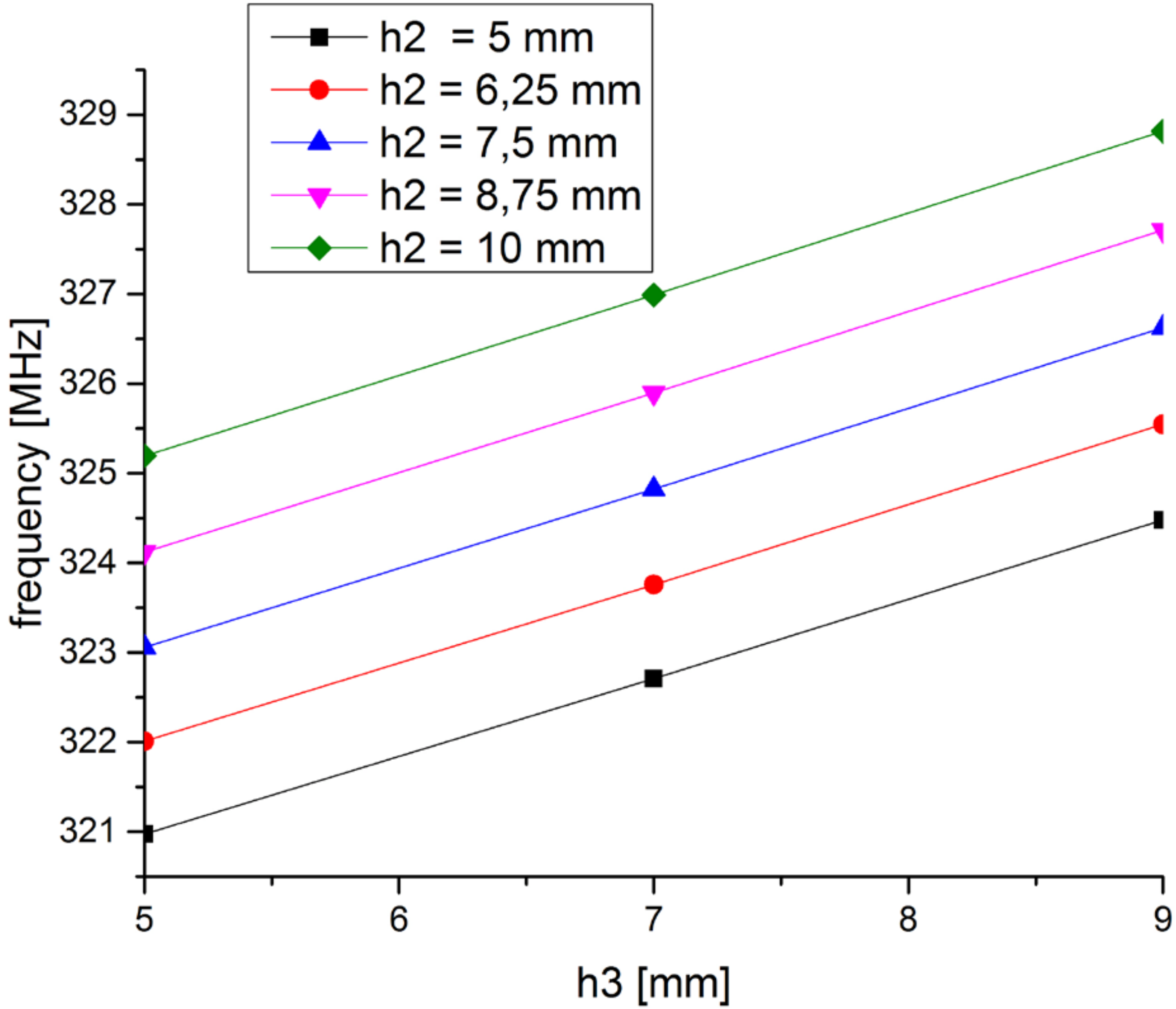
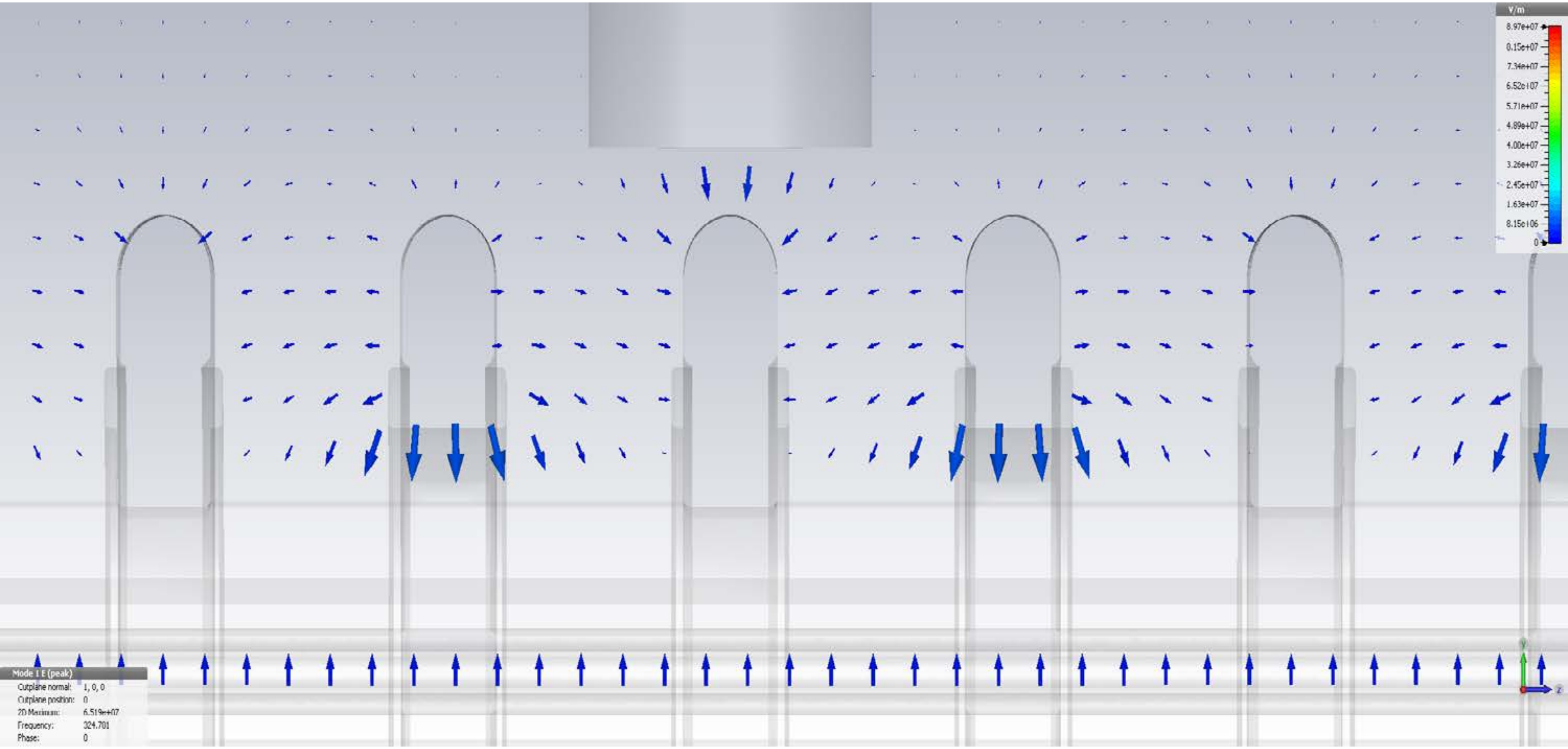
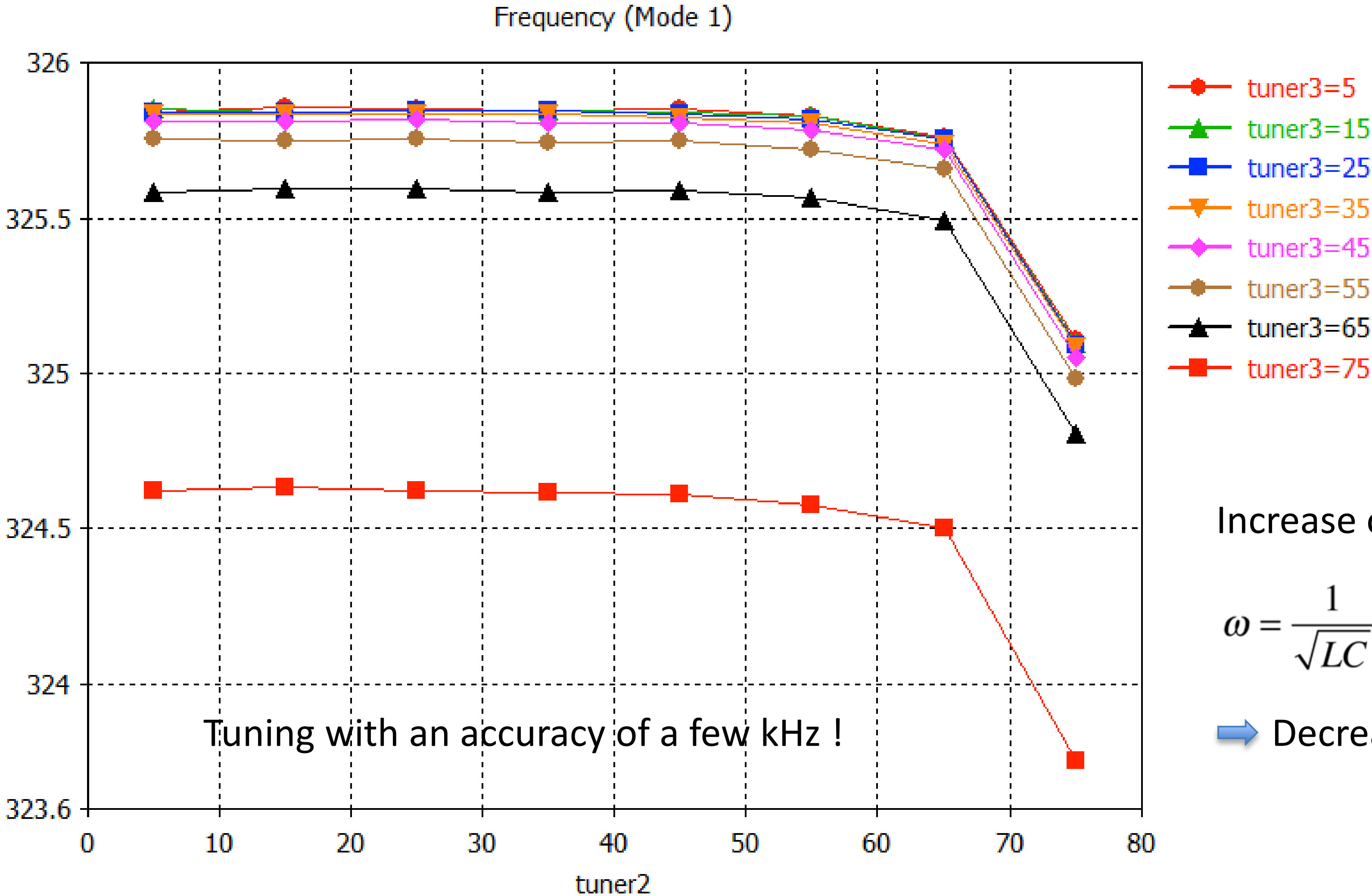


Tuning – fine Capacitive



Tuning – fine Capacitive

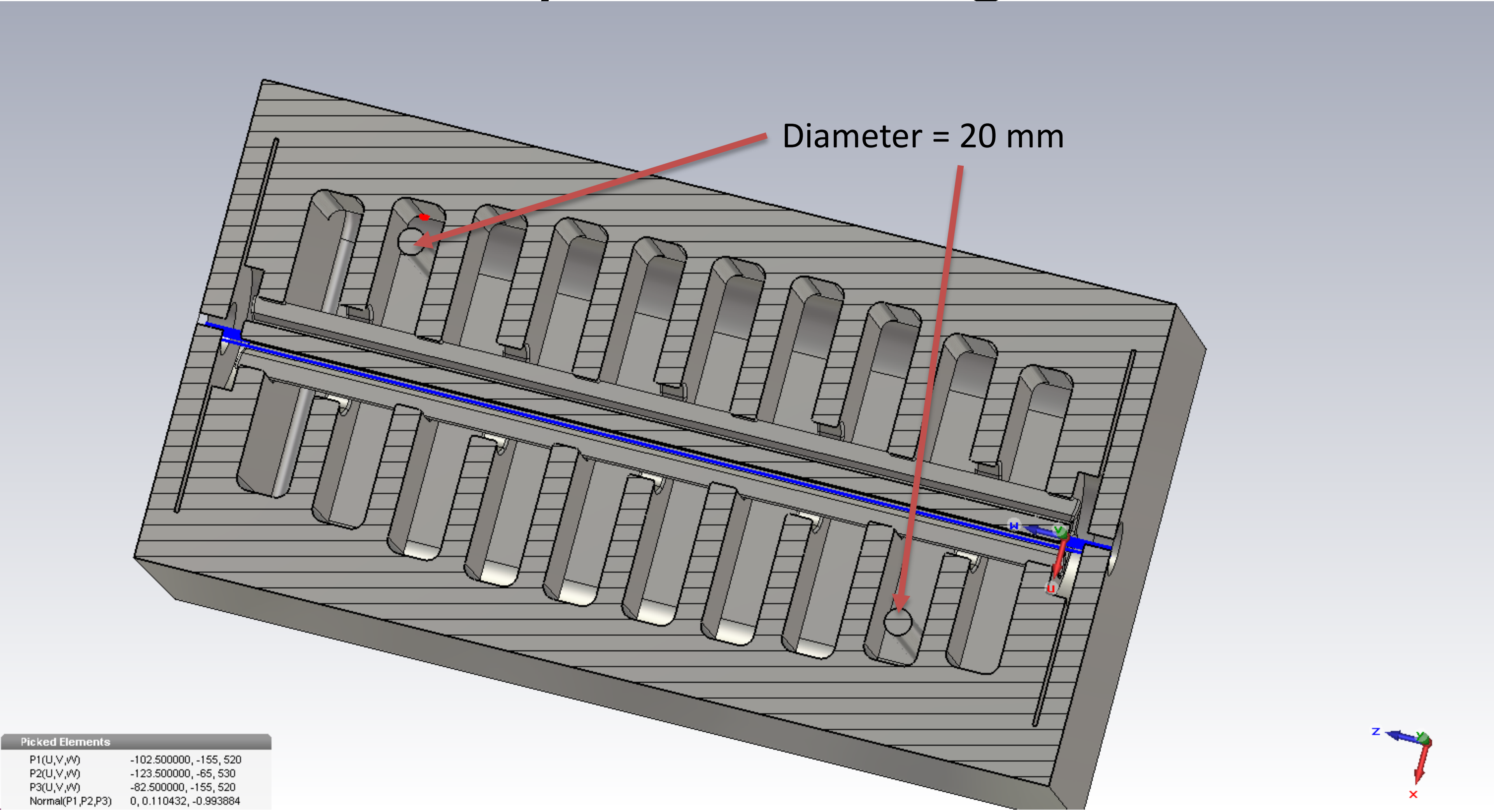


Increase of C

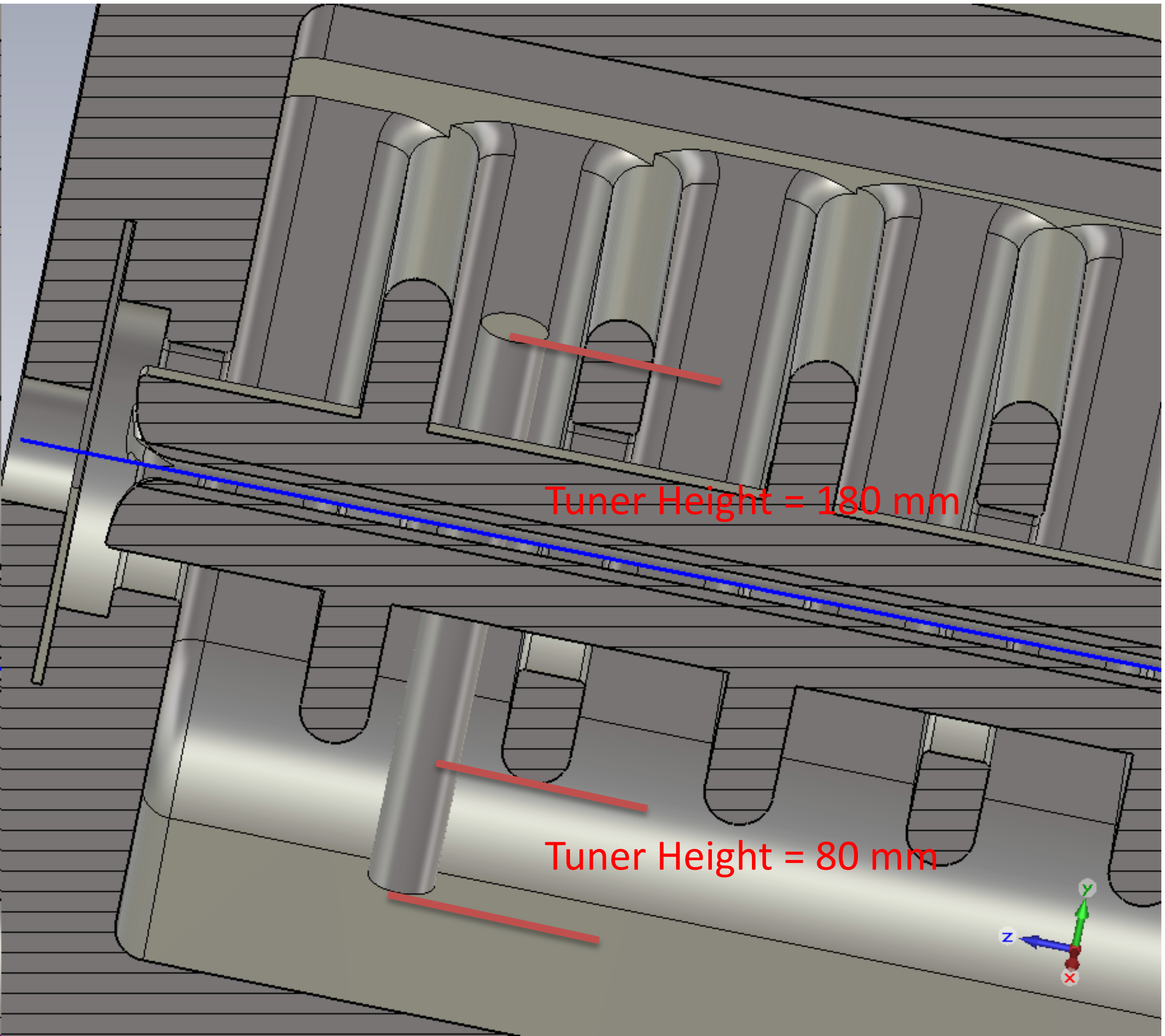
$$\omega = \frac{1}{\sqrt{LC}}$$

➡ Decrease of f

Inductive dynamic tuning



Inductive dynamic tuning



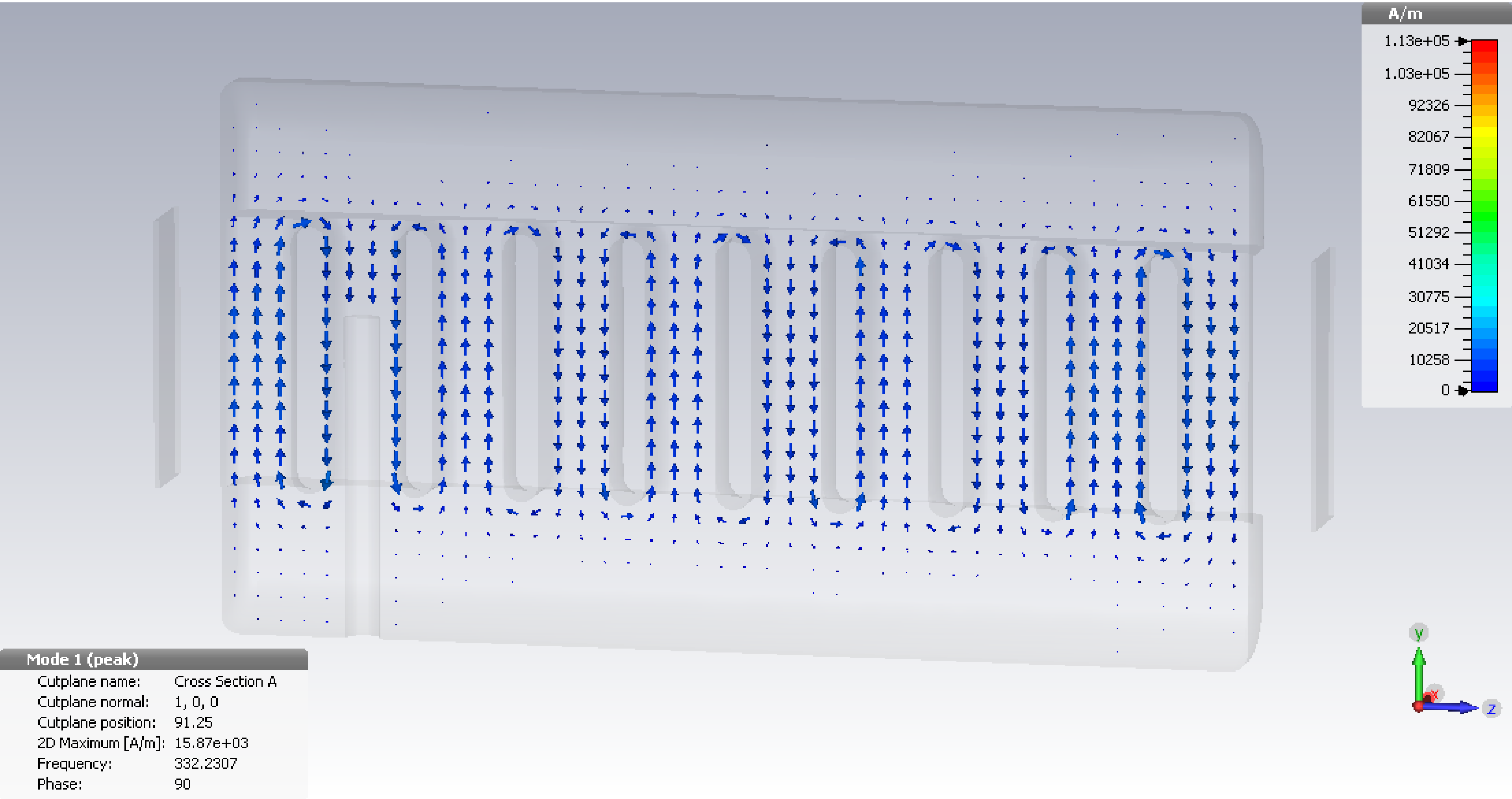
Reduction of L:

$$L \sim \phi$$

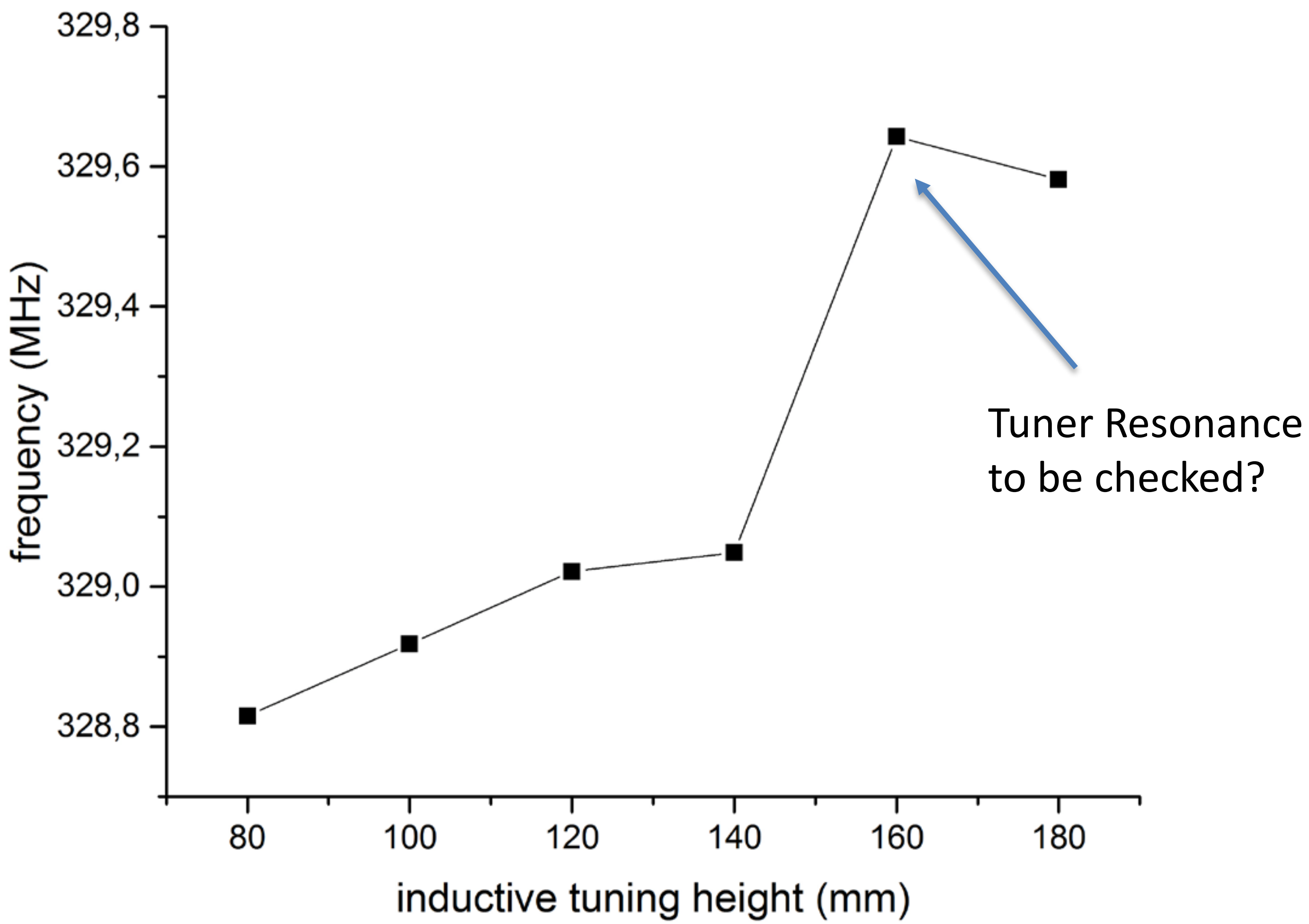
$$\Phi = \int B \, \mathrm{d}A$$

➡ Increase of f

Inductive dynamic tuning



Inductive dynamic tuning

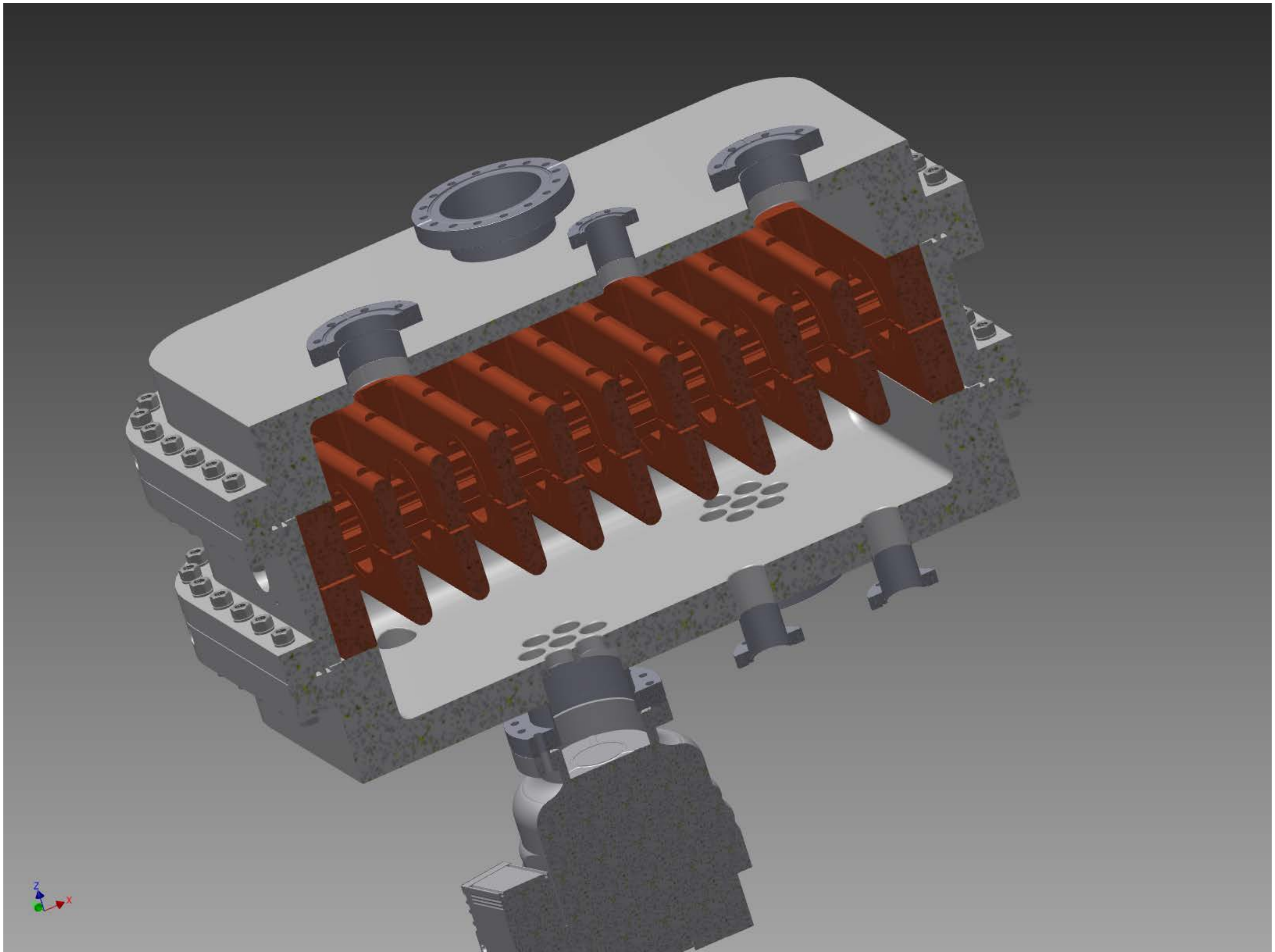


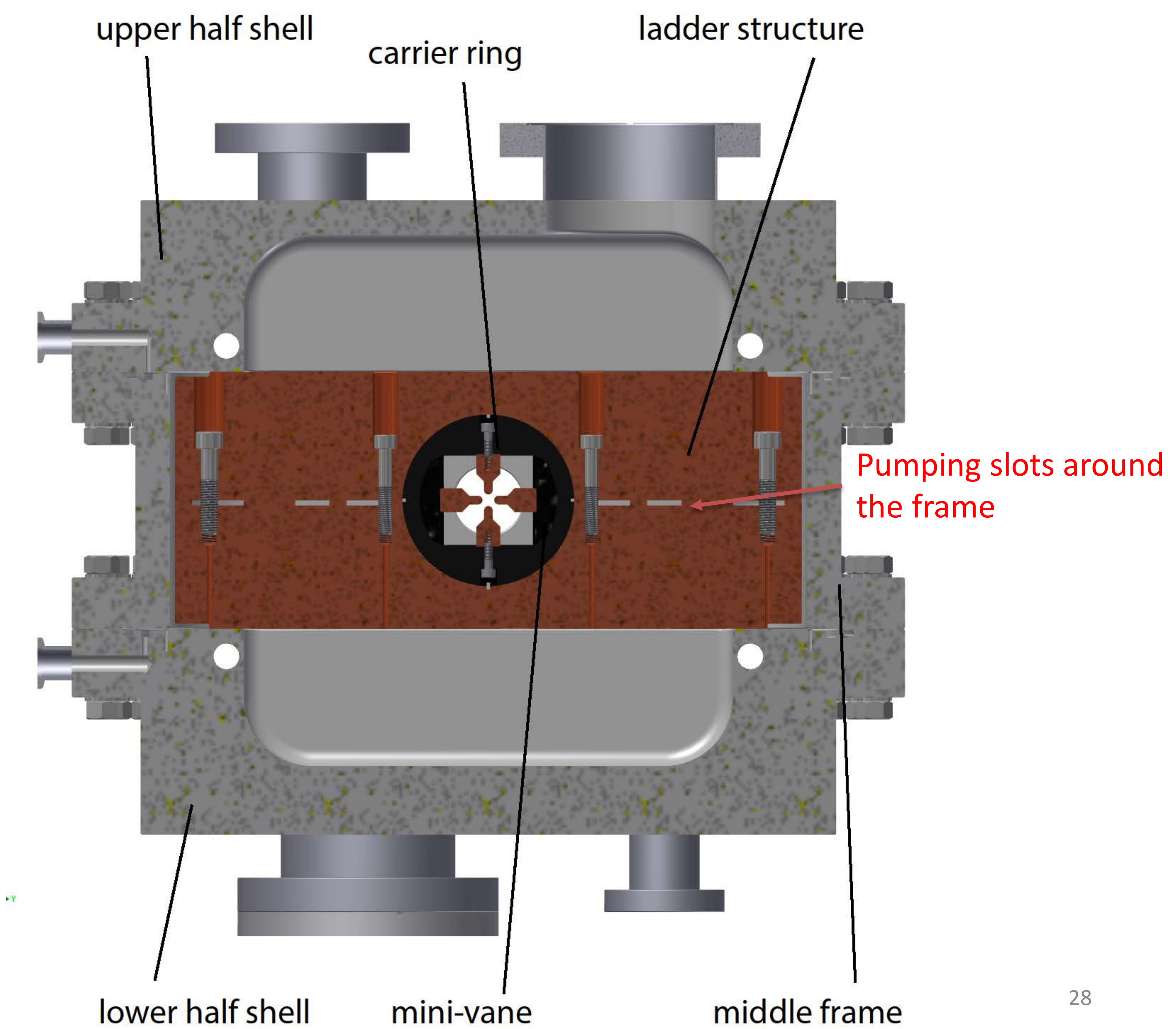
Dynamic Tuning

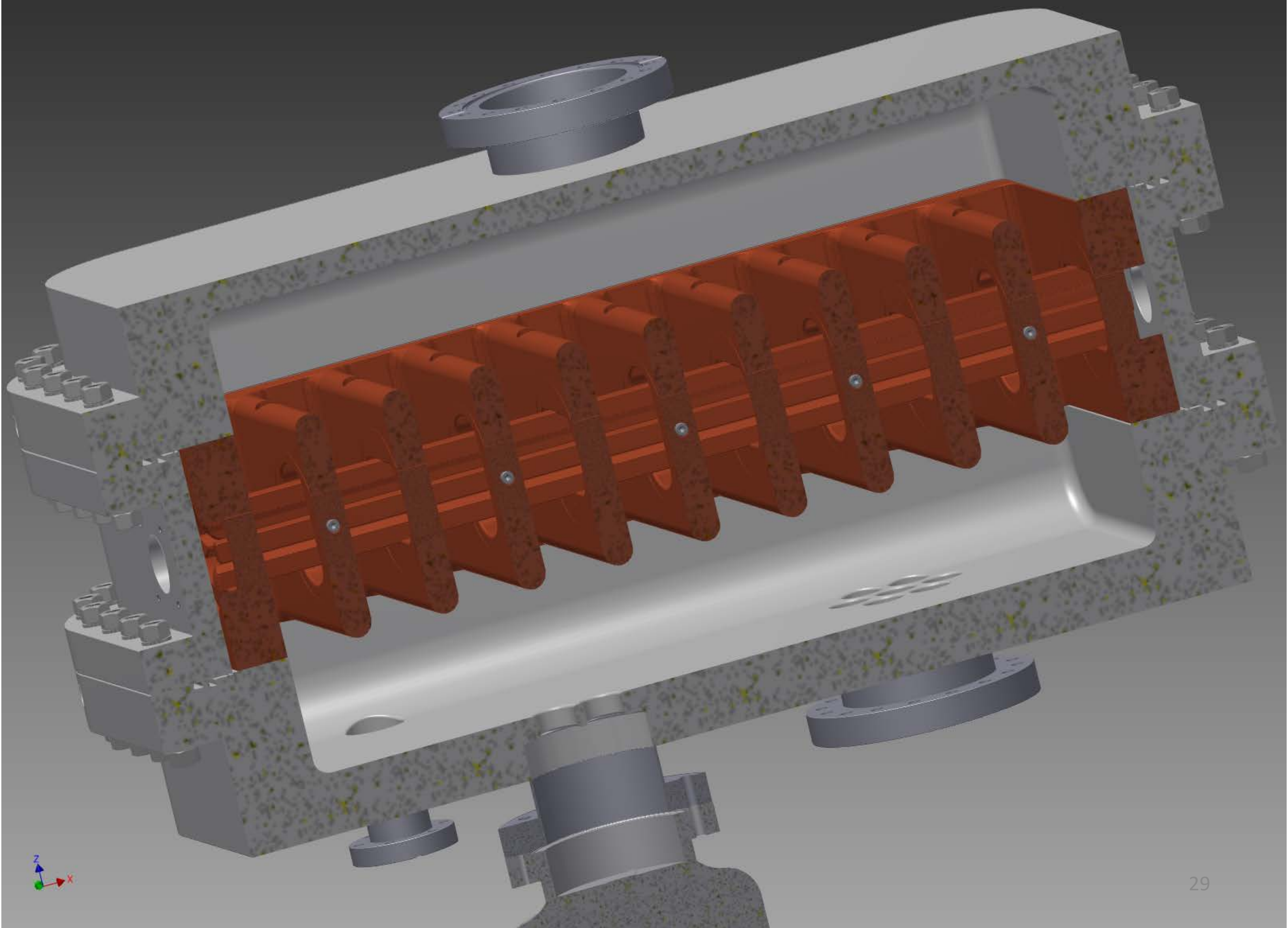
Advantages:

- Tuning possible within a Range of ~2 MHz and with an accuracy of approx. 1 kHz
- Inductive and capacitive tuning – no problems with conductivity, but danger of multipacting and sparking in capacitive case
- mechanically very stable
- Achieving a Flatness of <2%

Prototype
Mechanical Layout

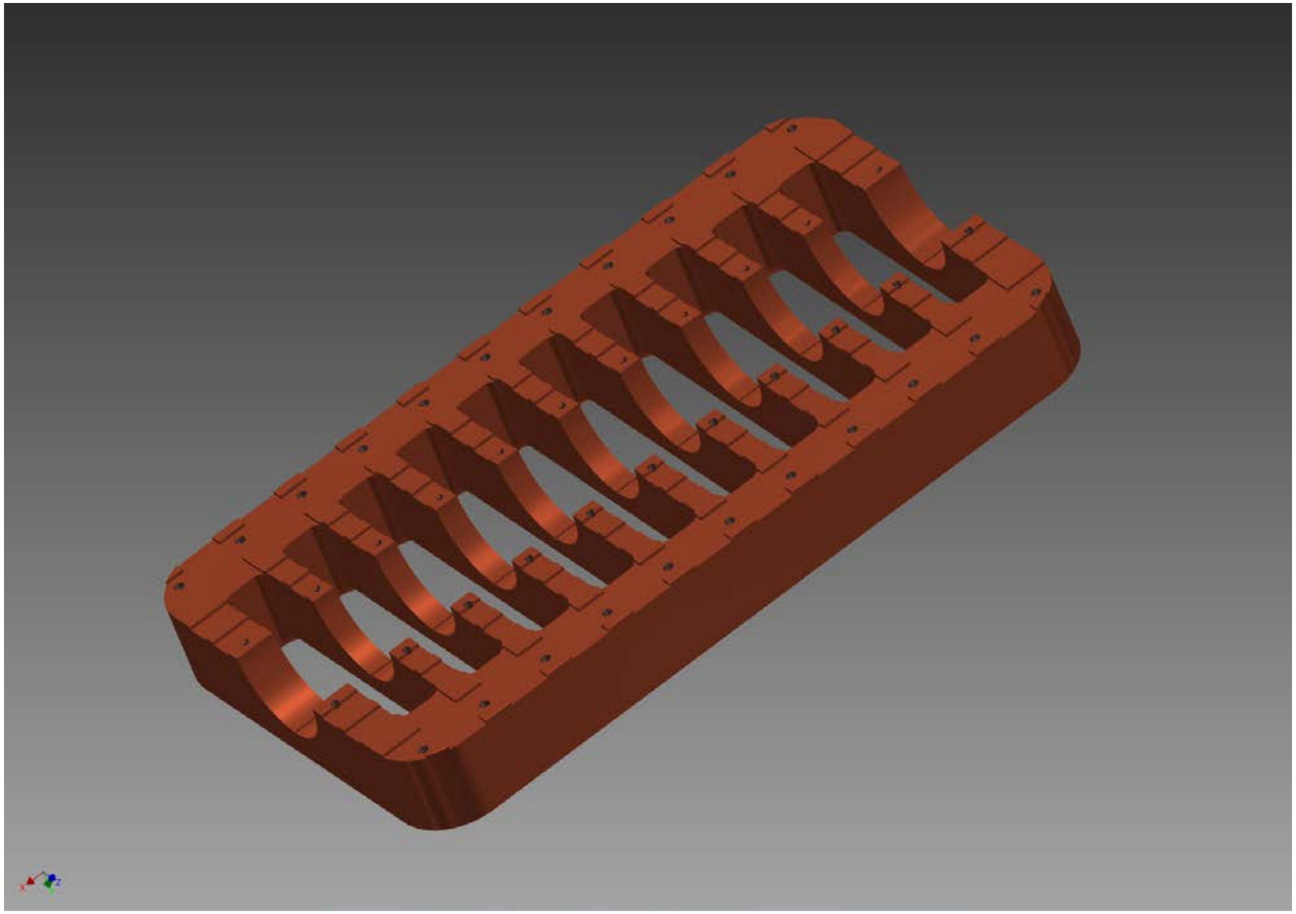


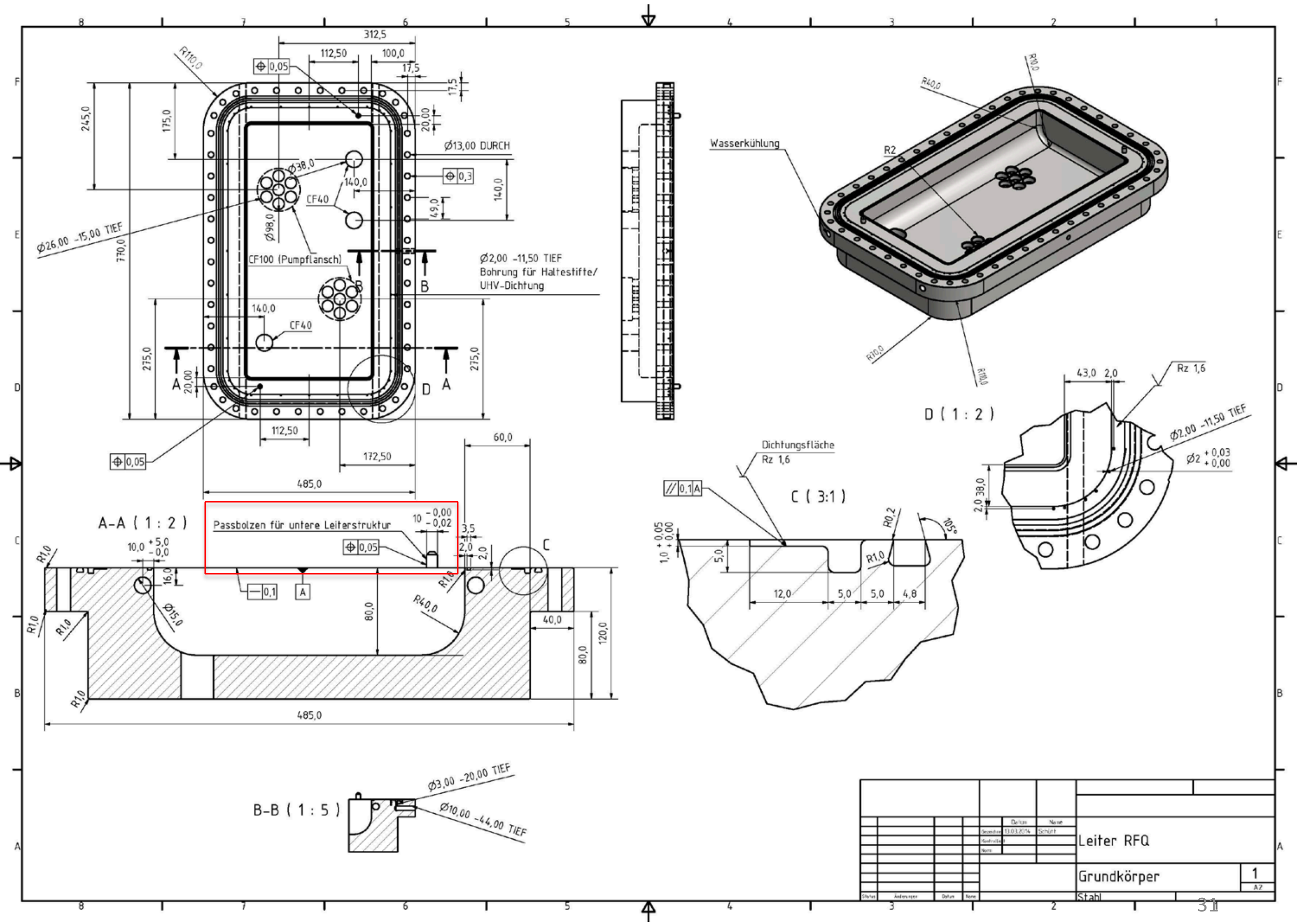

upper half shell
carrier ring
ladder structure
Pumping slots around the frame
lower half shell
mini-vane
middle frame


z
x

Mechanics

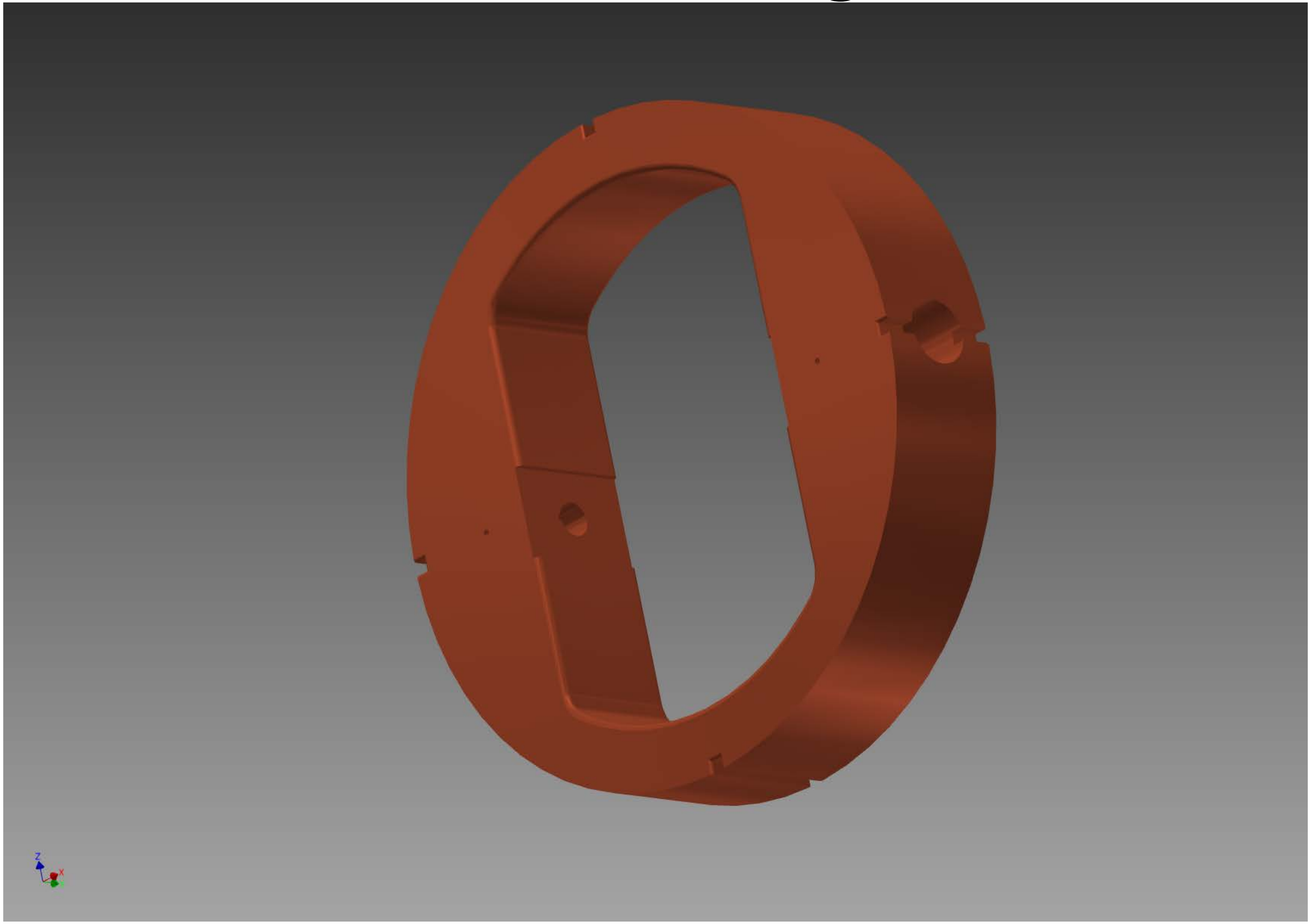
Reduced vis-à-vis surfaces by reasonable notches for efficient pumping:
(hf-currents are in the horizontal plane)





R110,0
312,5
112,50
100,0
17,5
0,05
245,0
175,0
20,00
Ø13,00 DURCH
Ø38,0
140,0
0,3
CF40
Ø98,0
49,0
Ø26,00 -15,00 TIEF
770,0
CF100 (Pumpflansch)
Ø2,00 -11,50 TIEF
Bohrung für Haltestifte/
UHV-Dichtung
B
CF40
275,0
A
D
112,50
172,50
485,0
60,0
A-A (1 : 2)
Passbolzen für untere Leiterstruktur
10 - 0,00 - 0,02
3,5
2,0
10,0 + 5,0 - 0,0
16,0
Ø15,0
0,1
80,0
R40,0
R1,0
40,0
120,0
485,0
C
B-B (1 : 5)
Ø3,00 -20,00 TIEF
Ø10,00 -44,00 TIEF
Wasserkühlung
R2
R40,0
R10,0
R110,0
D (1 : 2)
43,0
Rz 1,6
Ø2,00 -11,50 TIEF
Ø2 + 0,03 + 0,00
38,0
Dichtungsfläche
Rz 1,6
0,1 A
C (3:1)
R0,2
105°
1,0 + 0,05 + 0,00
5,0
R1,0
12,0
5,0
5,0
4,8
Datum
Name
13.03.2014
Schütt
Leiter RFQ
Grundkörper
Stahl
1
A2

Prototype
Carrier Ring

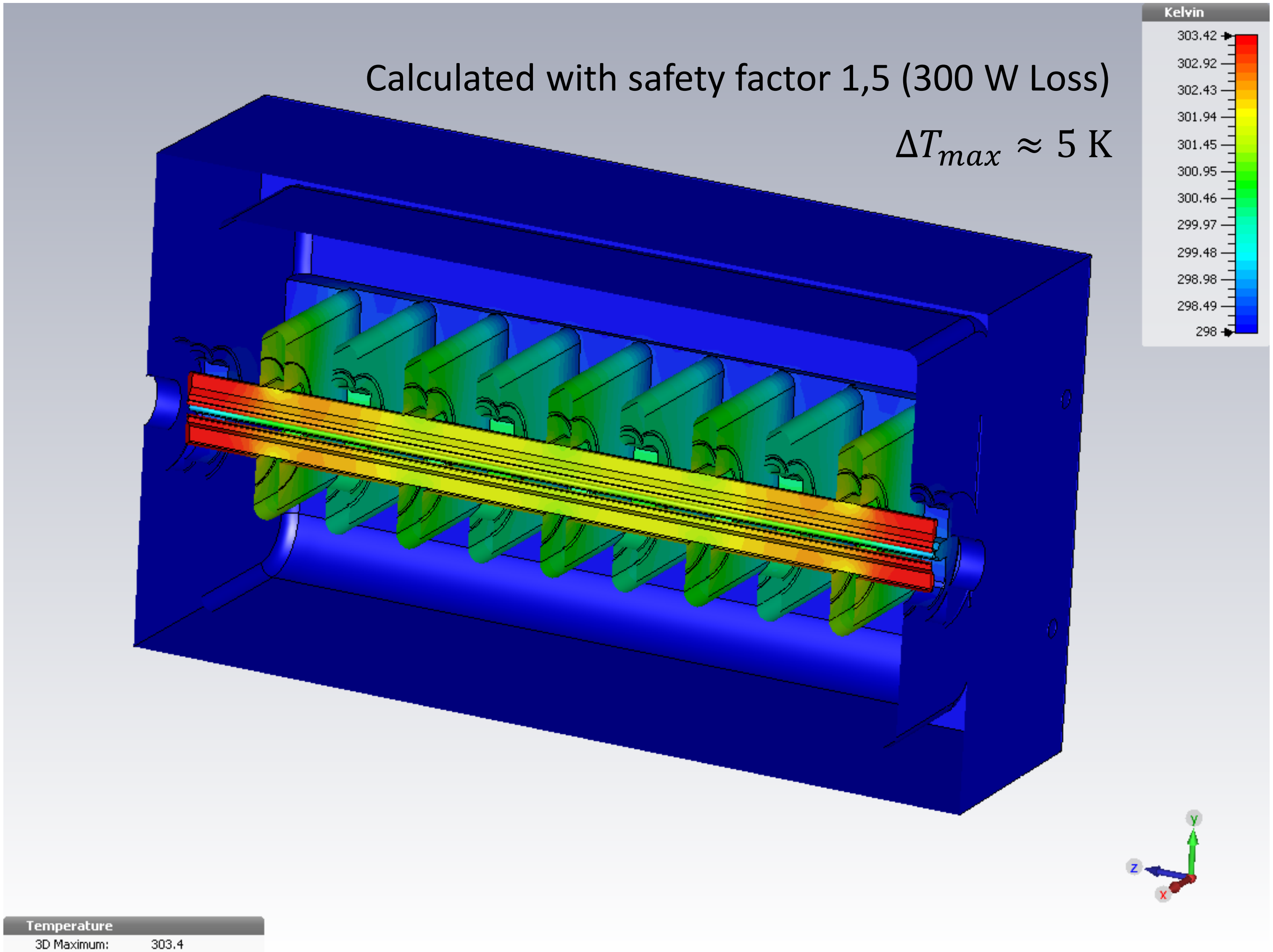


Mechanics
(Assembly Video)

Cooling by air only (surface)

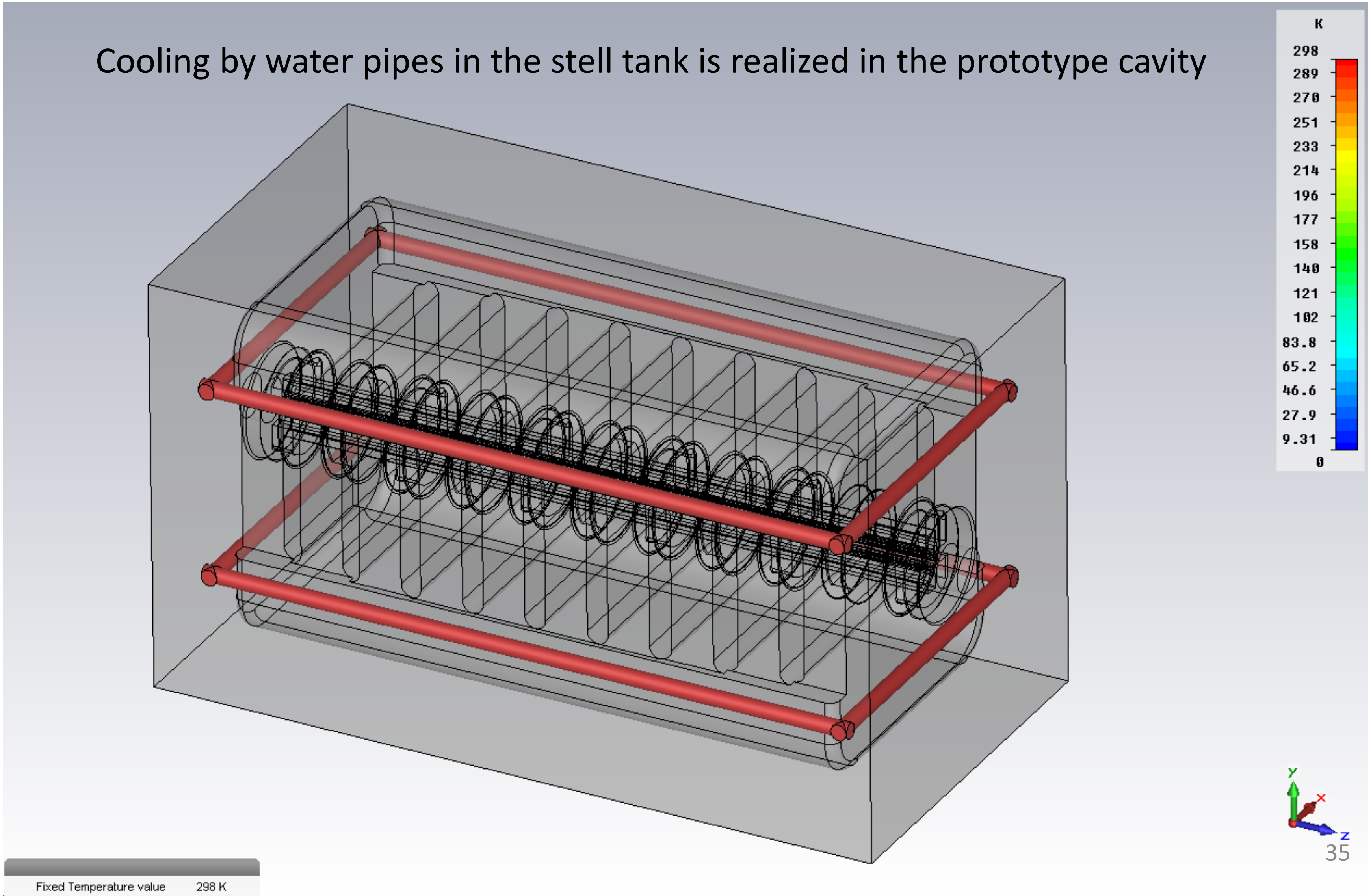
Calculated with safety factor 1,5 (300 W Loss)

$\Delta T_{max} \approx 5 \text{ K}$



Cooling

Cooling by water pipes in the stell tank is realized in the prototype cavity



Summary & Outline

Advantages:

- Mechanical Stability
- relatively “simple” manufacturing process (against 4-Vane)
- Mechanical sizes adequate for 325 MHz
- very low dipole-moments
- Easy access for a fast service and maintenance
- Exchangability of electrode structure

Summary & Outline

Prototyping Timeline:

- Tendering successfully completed and contracted in 05/2014
- Manufacturing Design Documentation started in 06/2014
- Manufacturing Release in 08/2014
- Disposition of Materials and commencement of construction in 09/2014
- Sheduled delivery in 12/2014
- First measurements, tuning and flattness-tests in late 2014 / early 2015

Thank you!