# Status of the superconducting cavity development at RISP.

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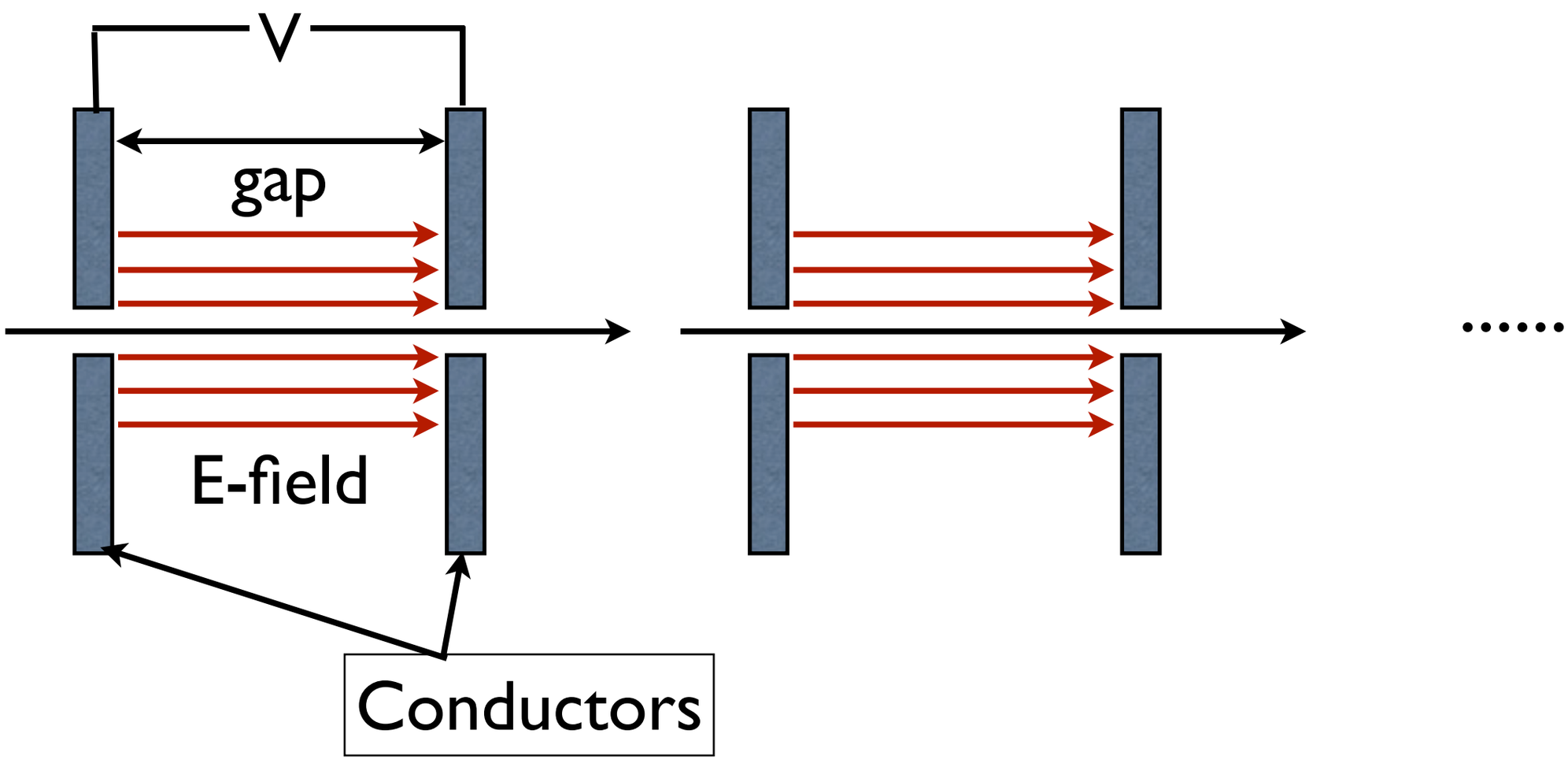
# 1. Introduction

# What is the accelerator?

- An accelerator is a machine that accelerates the charged particles by applying the electromagnetic fields.
- To transfer the energy to the particles, the electric field must be applied along the designated beam line.
- The accelerator is essentially the capacitor.



- The modern accelerators use the RF (radio frequency) technology and superconductors

Alternating accelerating voltage makes the high energy acceleration available.

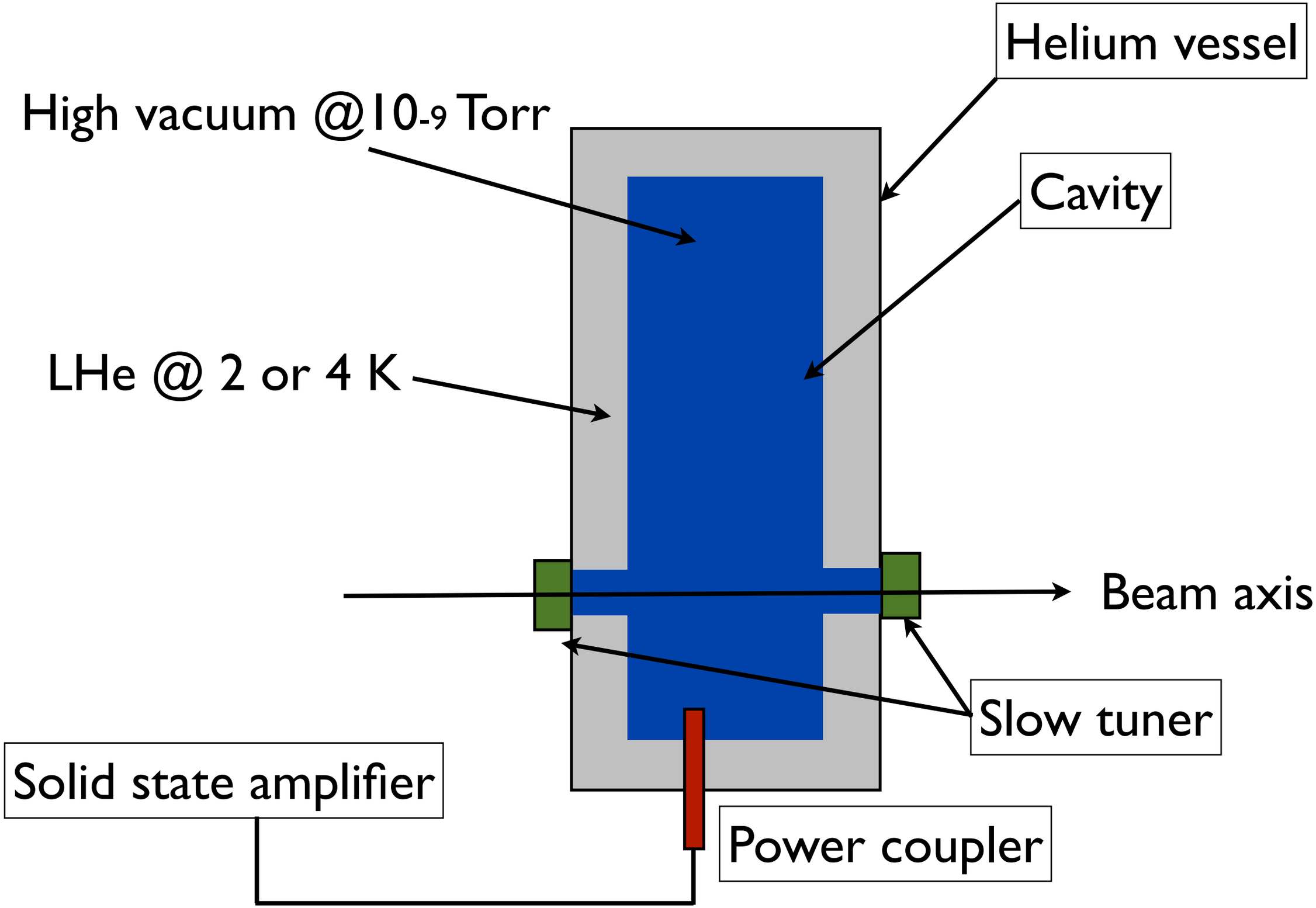
$$V=V_0\sin(\omega t+\phi)$$

The frequency reaches radiofrequency (microwave frequency, in particuar) as the particle velocity increases

- Superconductor introduces the cryogenic system into the accelerator.

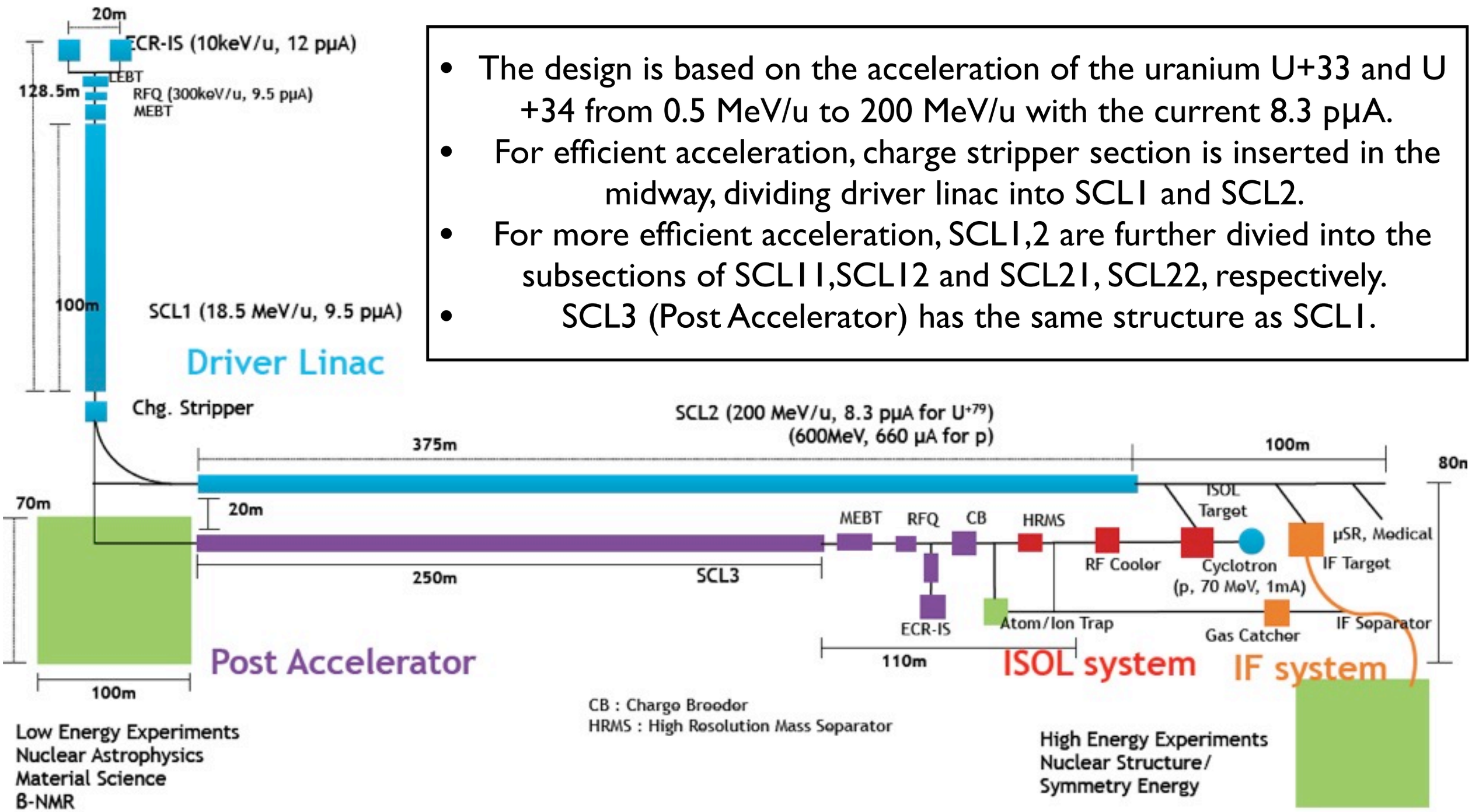
Exeremely low resistance of the superconductor enables the much more efficient acceleration with the smaller heat loss

# Superconducting linac

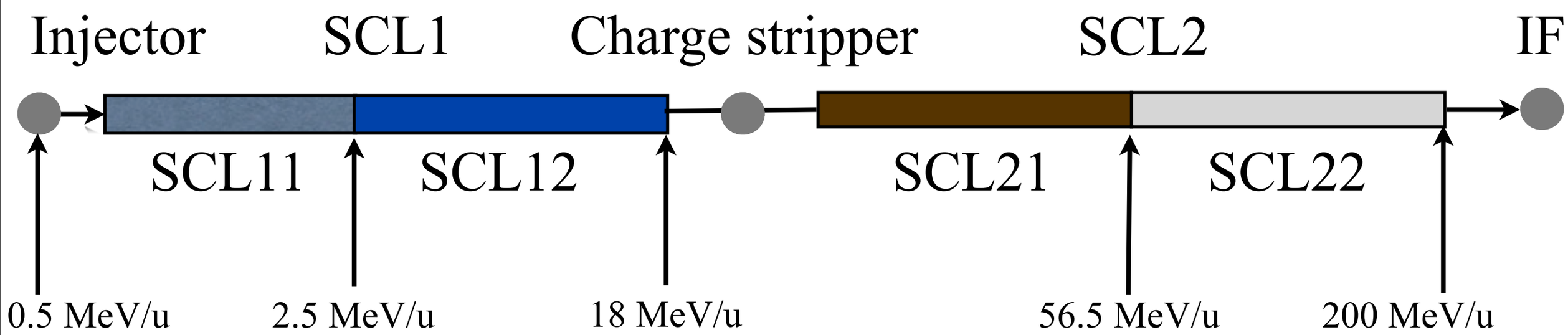


# RAON: The heavy ion accelerator at RISP

- The design is based on the acceleration of the uranium U+33 and U +34 from 0.5 MeV/u to 200 MeV/u with the current 8.3 pμA.
- For efficient acceleration, charge stripper section is inserted in the midway, dividing driver linac into SCL1 and SCL2.
- For more efficient acceleration, SCL1,2 are further divied into the subsections of SCL11,SCL12 and SCL21, SCL22, respectively.
- SCL3 (Post Accelerator) has the same structure as SCL1.

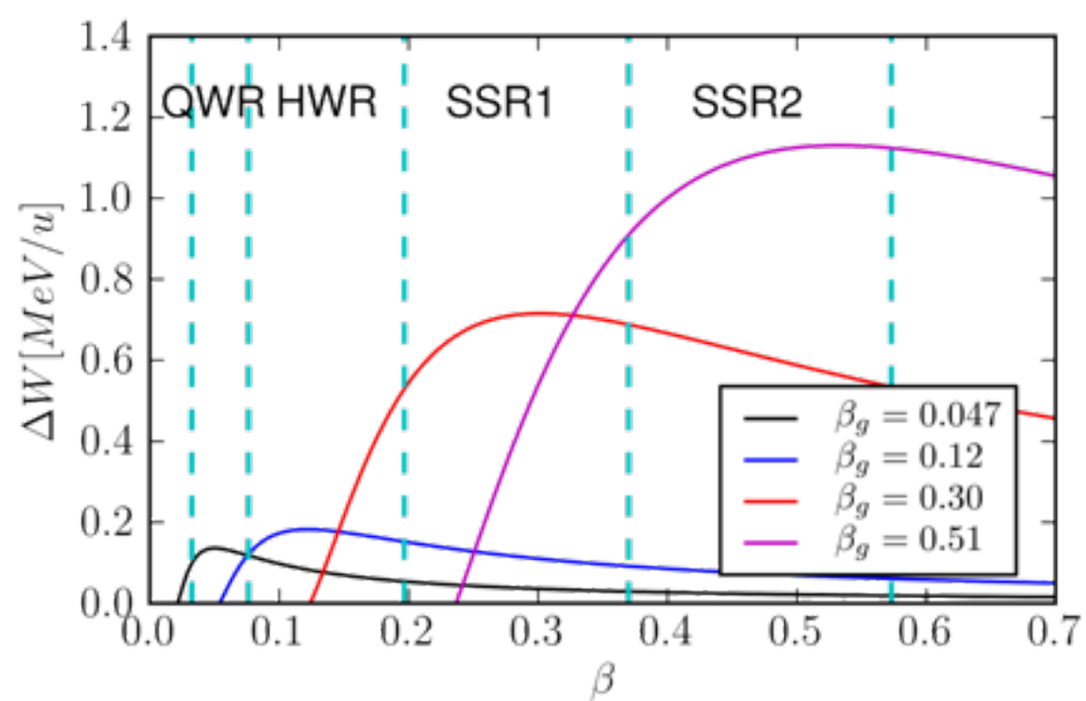


# Driver linac




- In each subsection, the ions are accelerated by a different kind of the SC with associated nominal beta as determined by beam dynamics study.

| subsection | cav.type | cav/cm | cm no. |
|---|---|---|---|
| SCL11 | QWR | 1 | 21 |
| SCL12 | HWR | 2 | 13 |
| SCL12 | HWR | 4 | 18 |
| SCL21 | SSR1 | 3 | 23 |
| SCL22 | SSR2 | 6 | 23 |



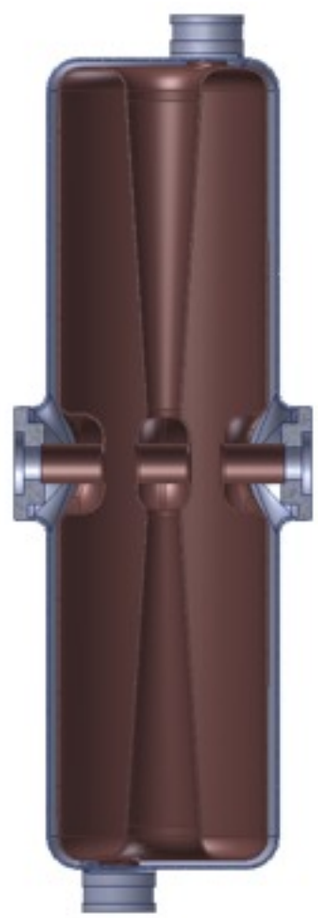
# Superconducting cavities of the RISP

## Parameters of the resonators

| parameters | QWR | HWR | SSR1 | SSR2 |
|---|---|---|---|---|
| f (MHz) | 81.25 | 162.5 | 325 | 325 |
| $\beta_g$ | 0.047 | 0.12 | 0.3 | 0.53 |
| Aperture (mm) | 20 | 20 | 25 | 25 |
| Epeak (MV/m) | 35 | 35 | 35 | 35 |
| Temp. (K) | 4 | 2 | 2 | 2 |

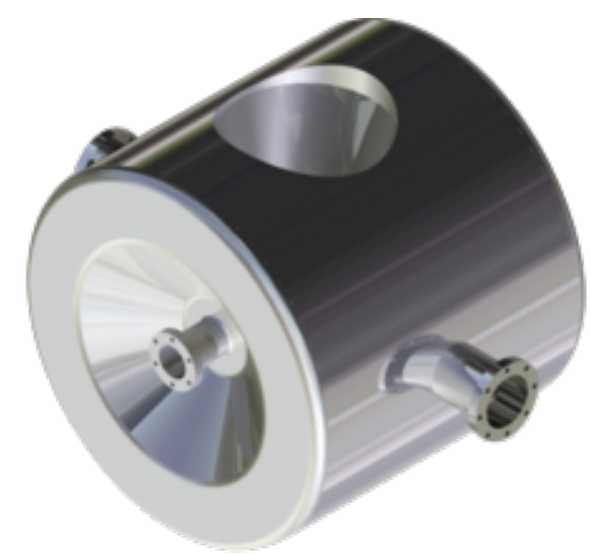
QWR

HWR



SSR1

SSR2



# 2. Design of the HWR

# Performance of the Superconducting cavity: Figures of merit

- Efficient machine, i.e., maximum accelerating gradient with the minimum power supplied.
- The efficiency is characterized by three quantities, i.e.

$$\boxed{Q_0, R/Q_0, TTF}$$

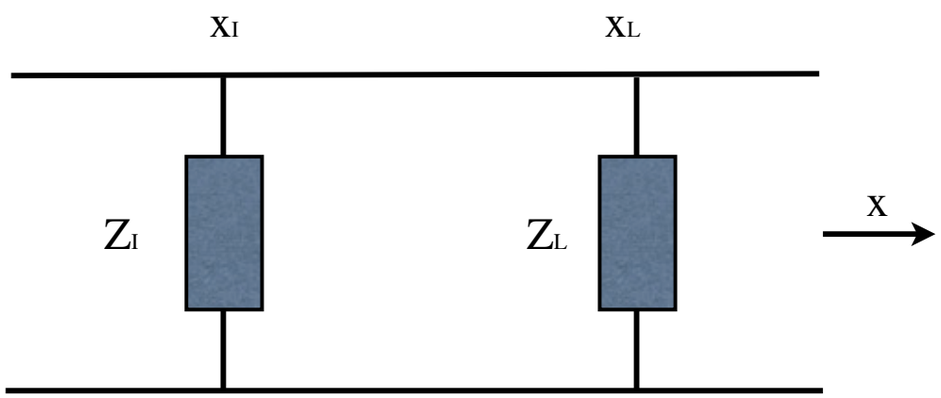
$$Q_0 = \frac{\omega U}{P_{wall}}, \quad R/Q_0 = V_{acc}^2/\omega U, \quad T(\beta) = \frac{\int \vec{E} \cdot \vec{v} dt}{\int \vec{E} \cdot d\vec{l}}$$

- Once the efficiency is established, one could power up to obtain the maximum gradient, but there is a limit

$$\boxed{E_{peak}, B_{peak}}$$

# Electromagnetic design

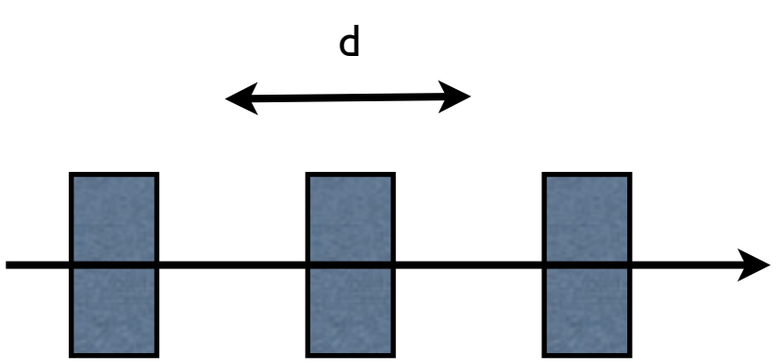
- Beam dynamics study determines the approximate no. of cavities and the accelerating gradients. For example, SCL12 needs ~120 HWR with the accelerating voltage ~1.3 MV.
- The frequency roughly determines the heigh of the cavities




$$Z_I = Z_0 \frac{Z_L + iZ_0 \tan k(z_l - z_i)}{Z_0 + iZ_L \tan k(z_l - z_i)},$$

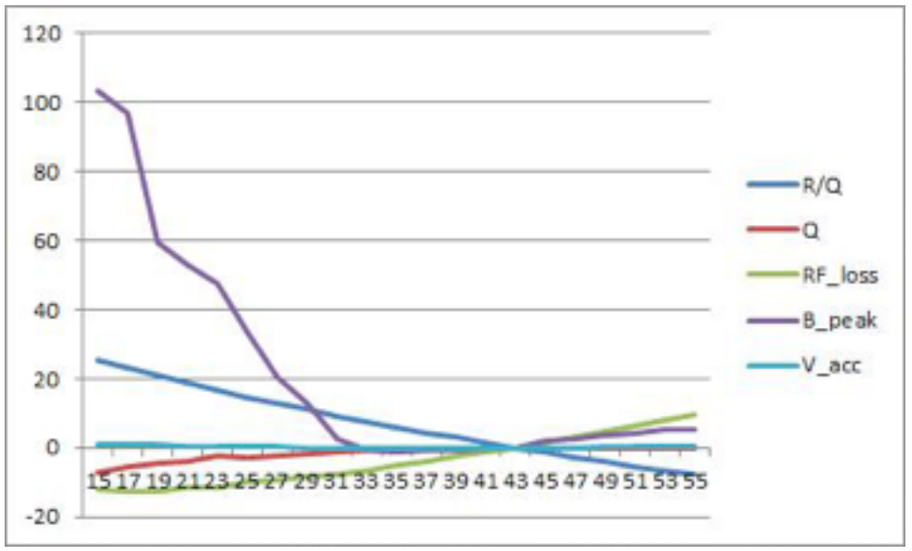
$$H_{cav} = \frac{\lambda}{2}$$

- Beta and the frequency roughly determines the gap to gap distance of the cavities

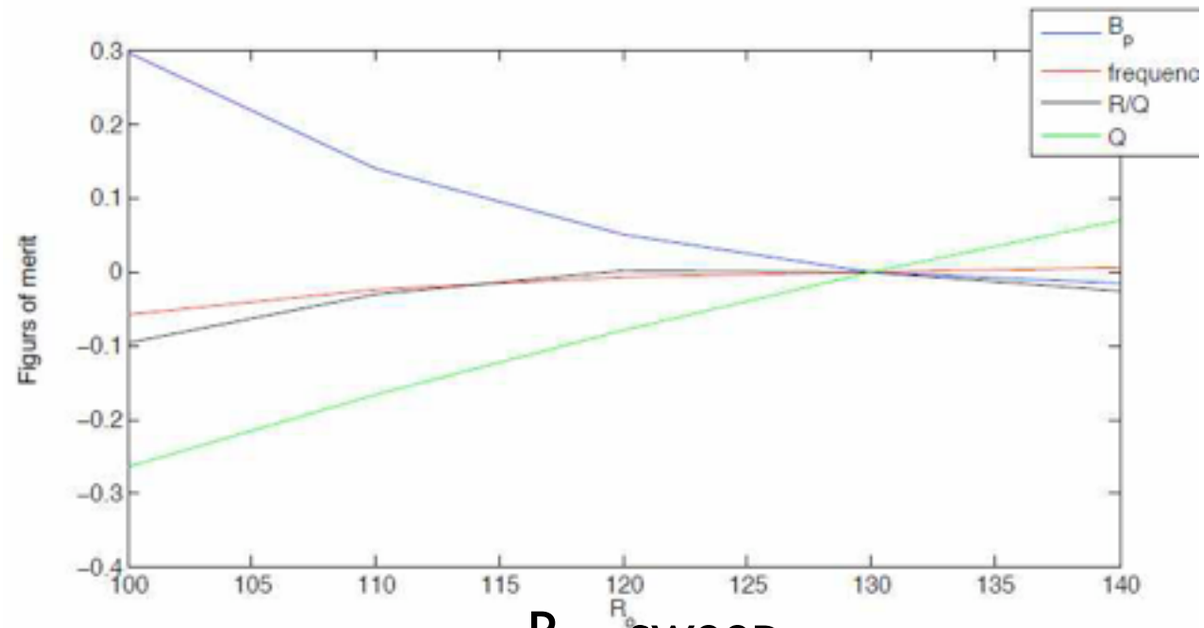



$$d = \frac{\beta\lambda}{2}$$

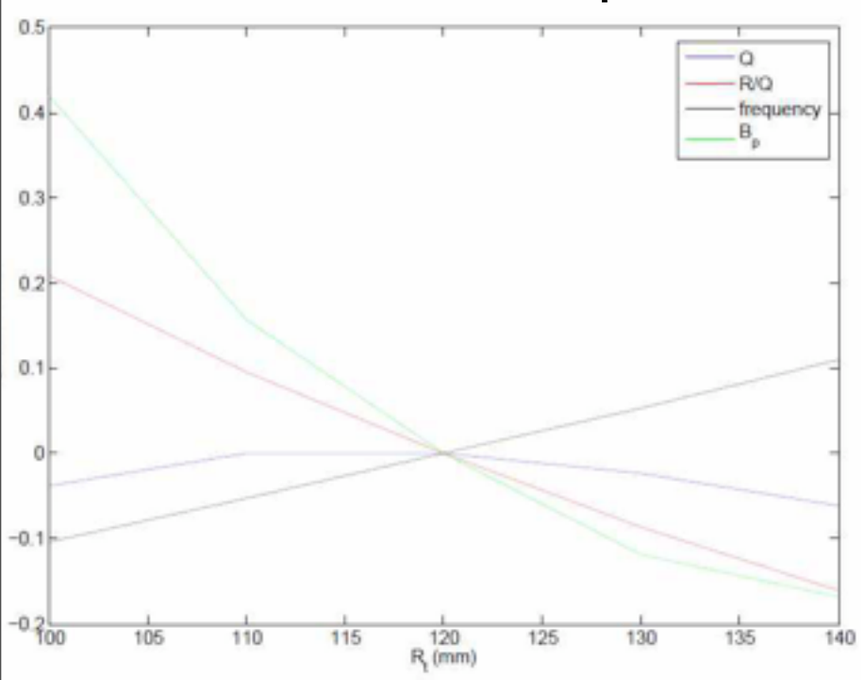
- EM design is done by 3D FEA (Finite element analysis) code that optimizes the figures of merit while sweeping the design parameters



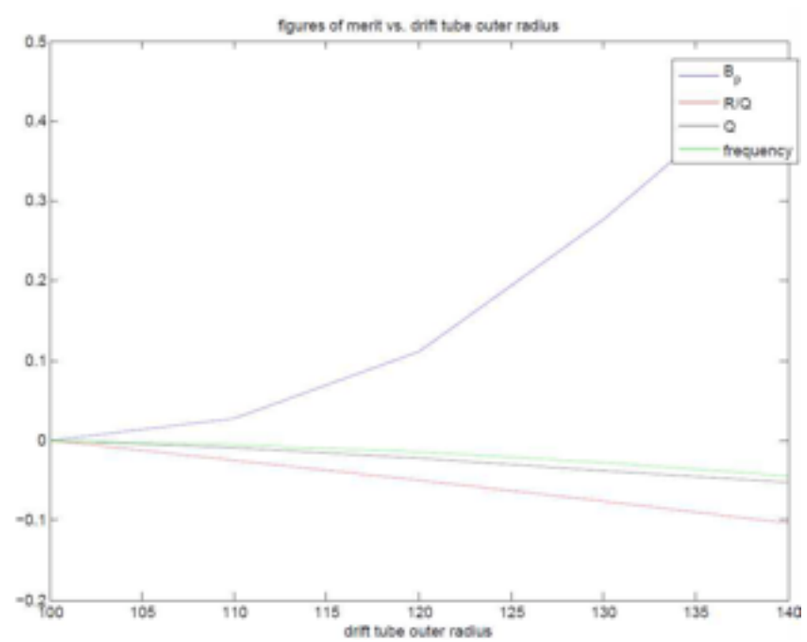

$R_{bottom}$ sweep



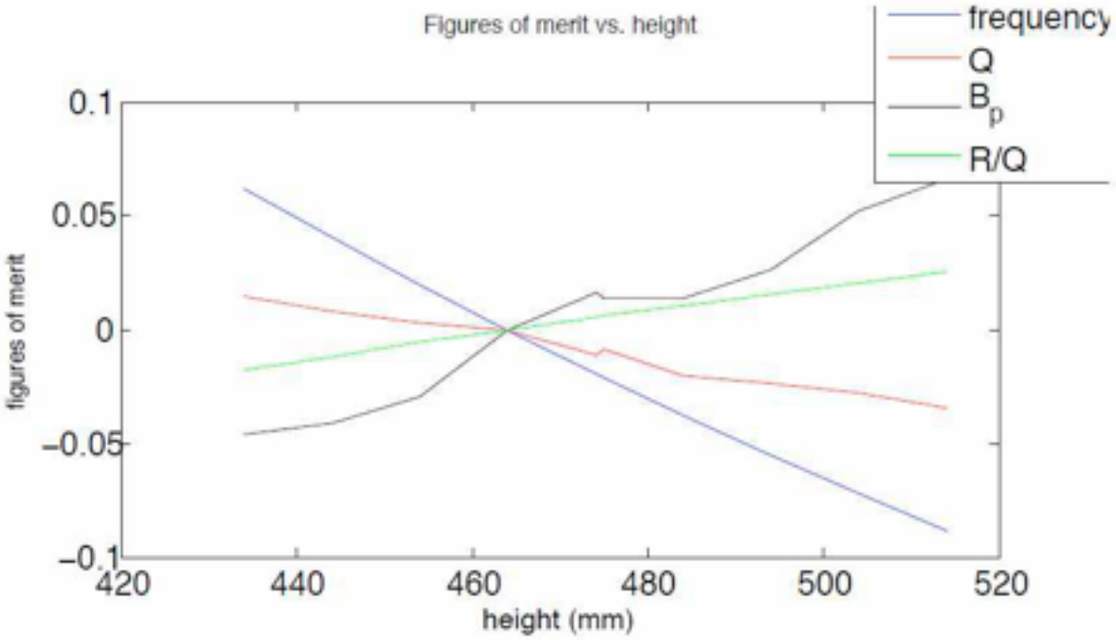

$R_{out}$ sweep



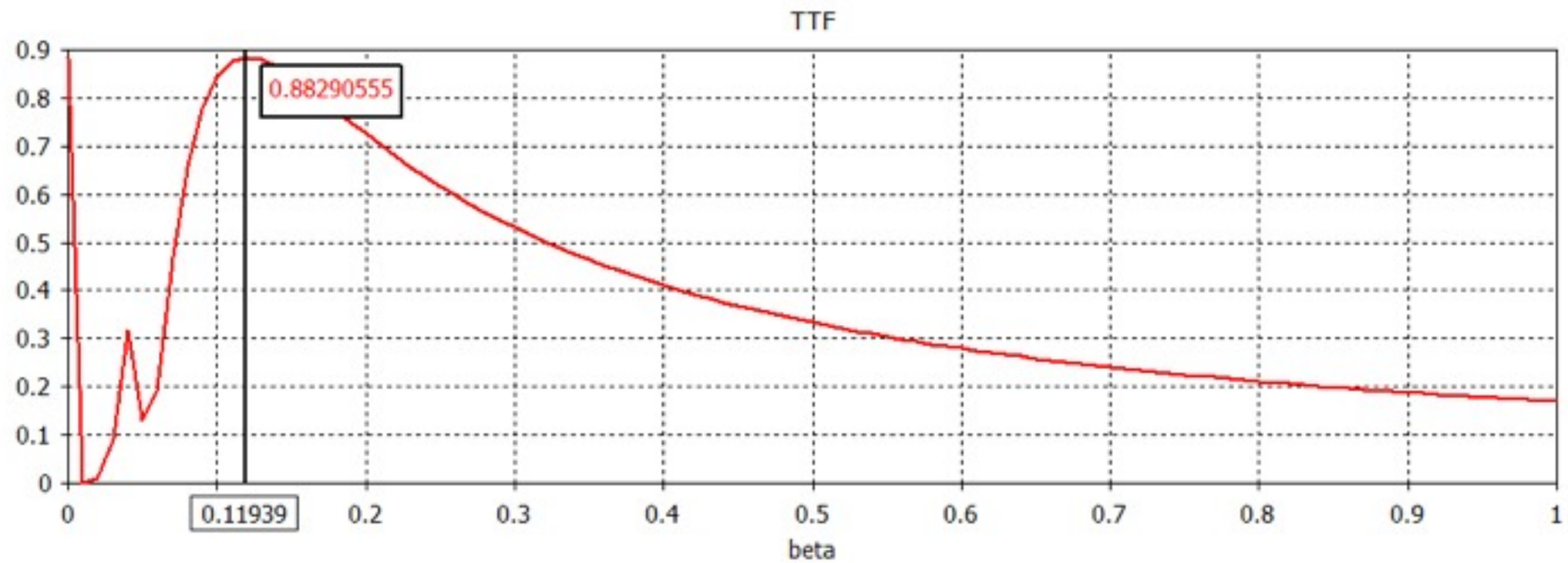

$R_{top}$ sweep




$R_{ring}$ sweep

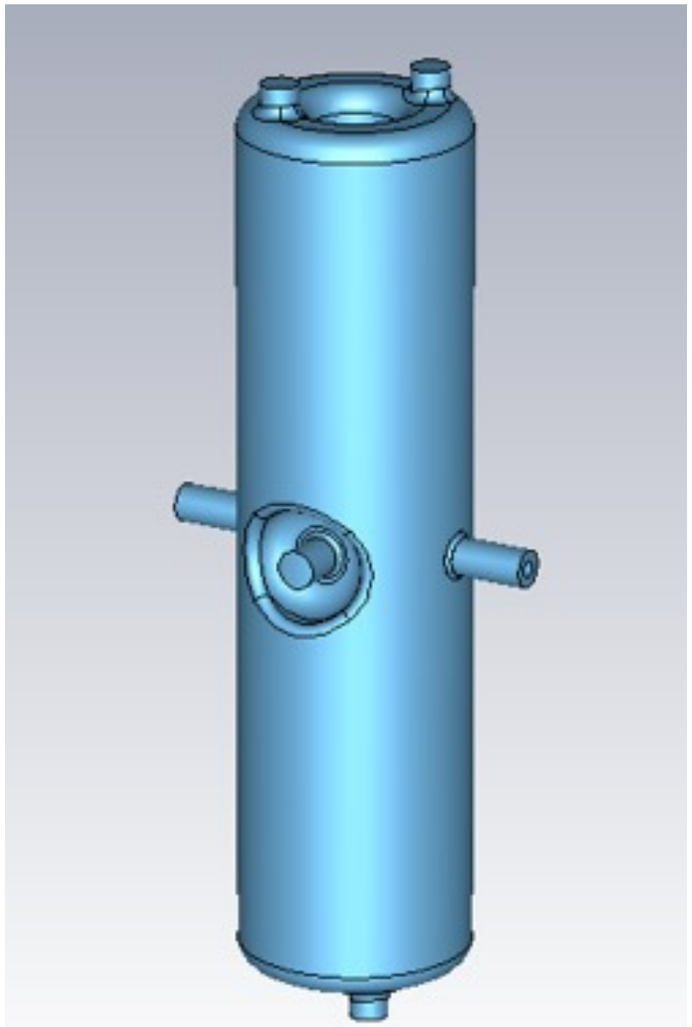



$H_{cav}$ sweep




TTF vs. beta

# Final specification of the HWR

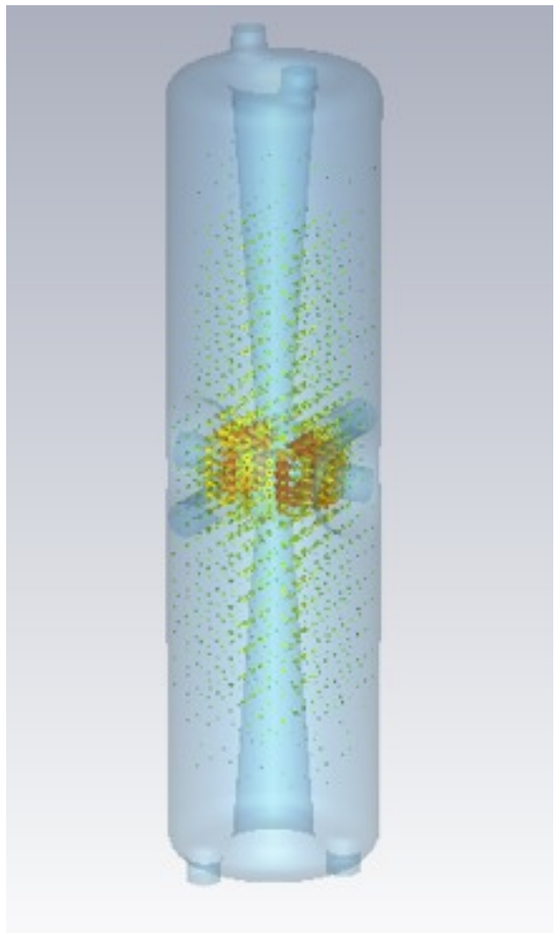


Perspective view of the HWR

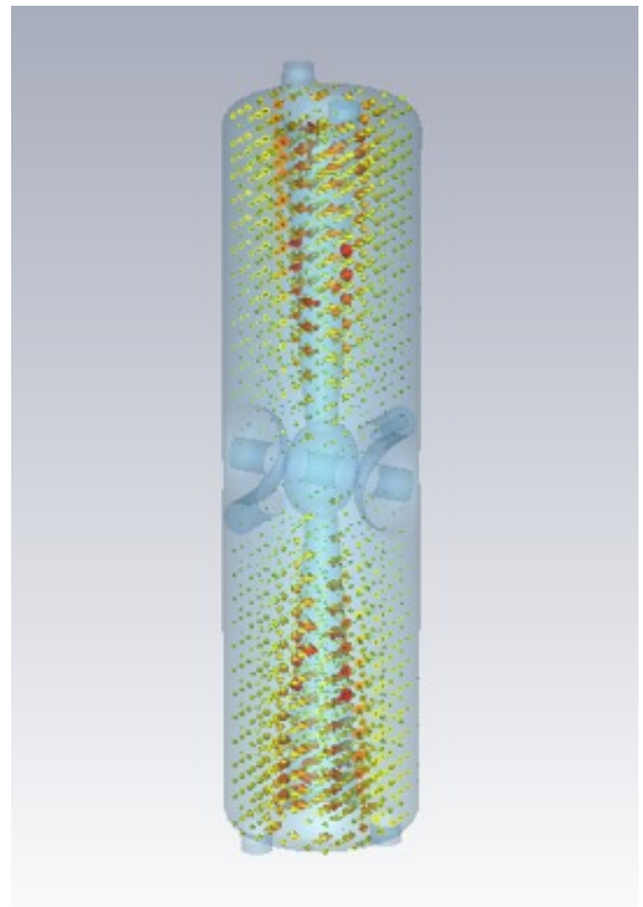
| design parameter | value (mm) |
|---|---|
| $H_{cav}$ | 920 |
| $R_{outer}$ | 120 |
| d | 100 |
| g | 35 |
| $R_{top}$ | 45 |
| $R_{bottom}$ | 21 |
| $R_{ring}$ | 60 |
| $R_{nose}$ | 60 |

Design parameters of the HWR

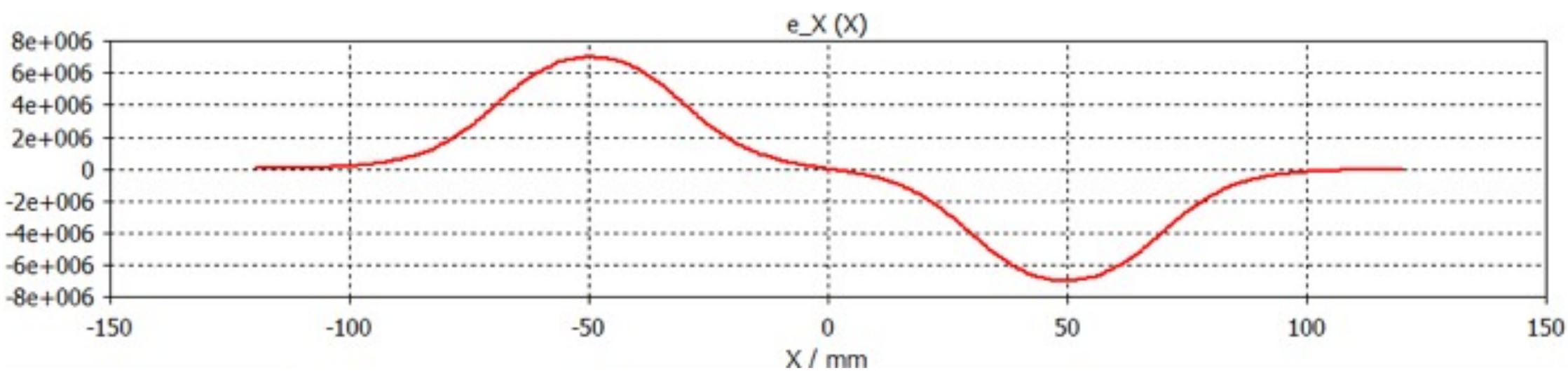
# Electromagnetic fields of the HWR



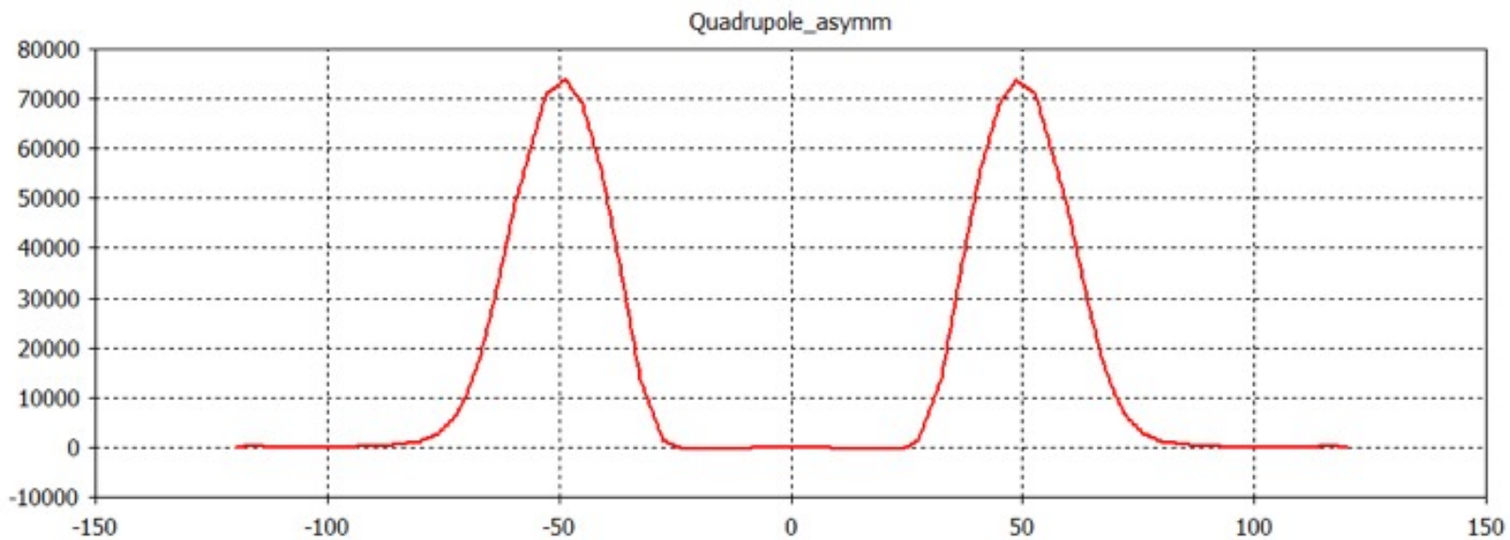
Electric field distribution



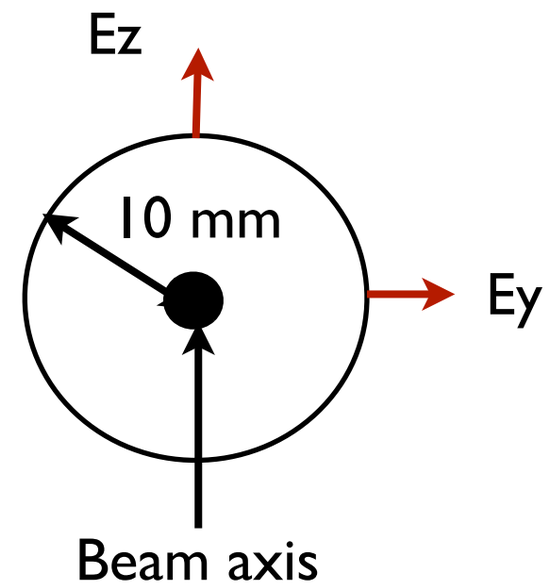
Magnetic field distribution




Longitudinal field distribution of the HWR




E-field difference vs. longitudinal distance along the beam axis

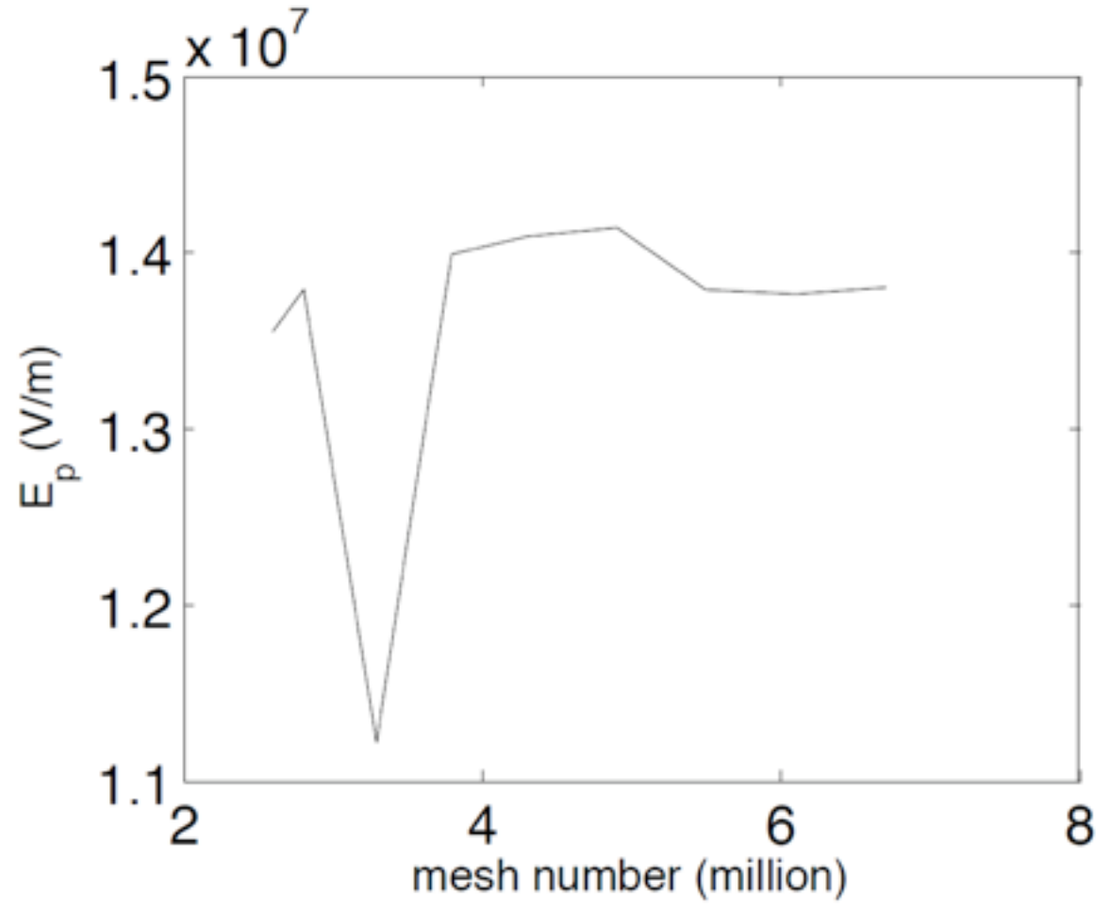



- Asymmetry of the transverse (quadrupole) compoent of the E-field was investigated by obtaining $E_z$-$E_y$ at 10mm away from the beam axis, which must be zero if the transeverse field were symmetric. The difference is about 1% of the longitudinal component.

# Optimal figures of merit of the HWR

| figures of merit | value |
|---|---|
| $Q_0$ | 4.10E+09 |
| $R/Q_0$ | 316.2 Ohm |
| TTF | 0.89 |
| $E_p$ | 35 MV/m |
| $B_p$ | 52.2 mT |
| $V_{acc}$ | 1.4 MV |
| $P_w$ | 1.5 W |

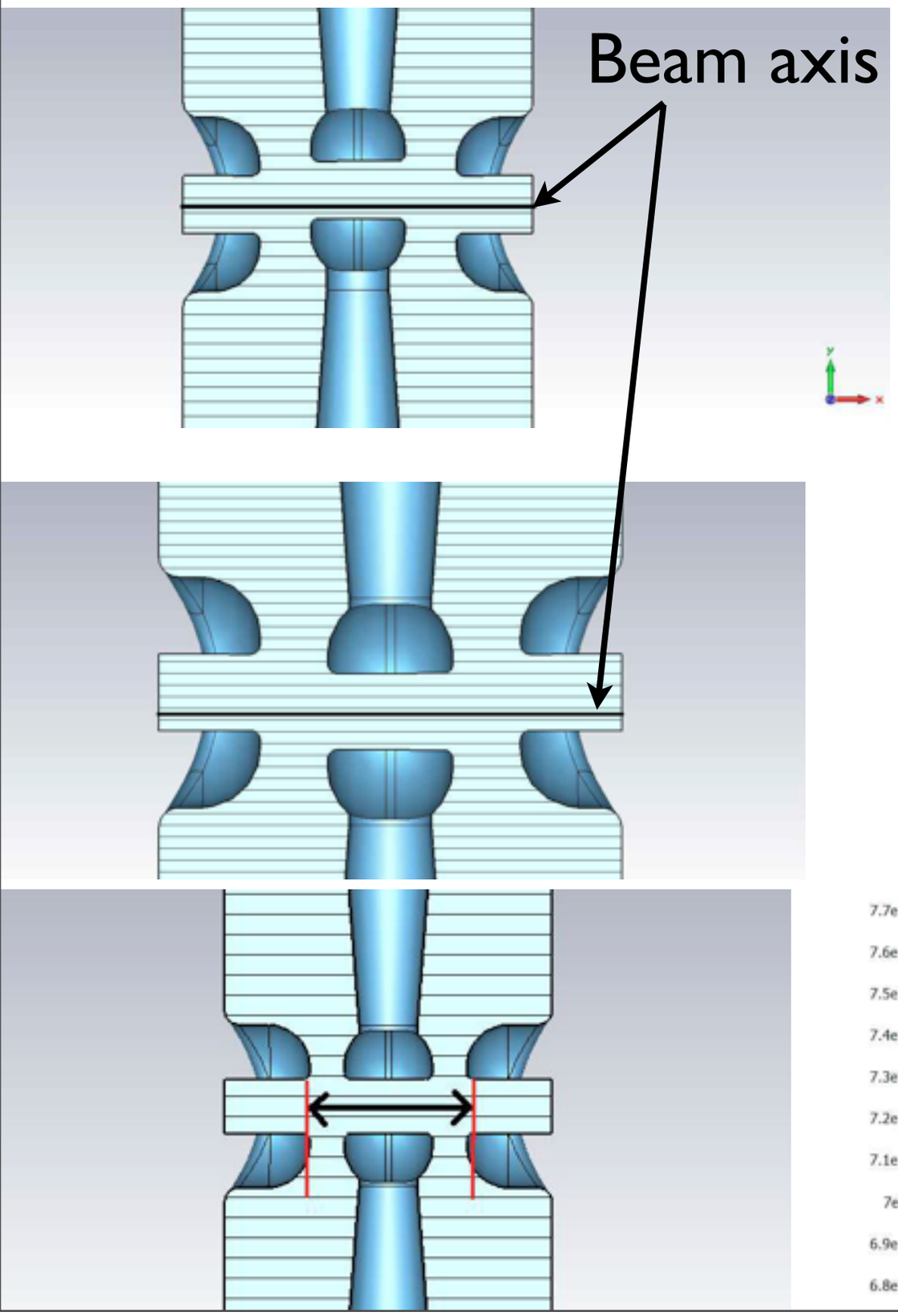
Figures of merit (HWR)

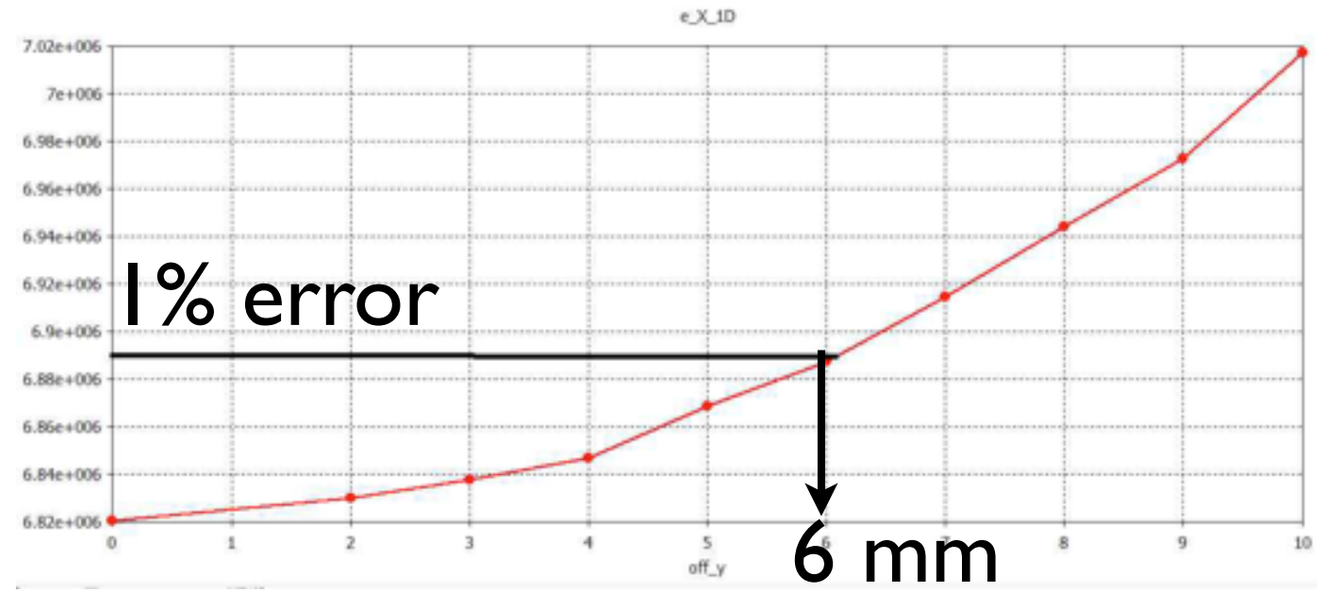


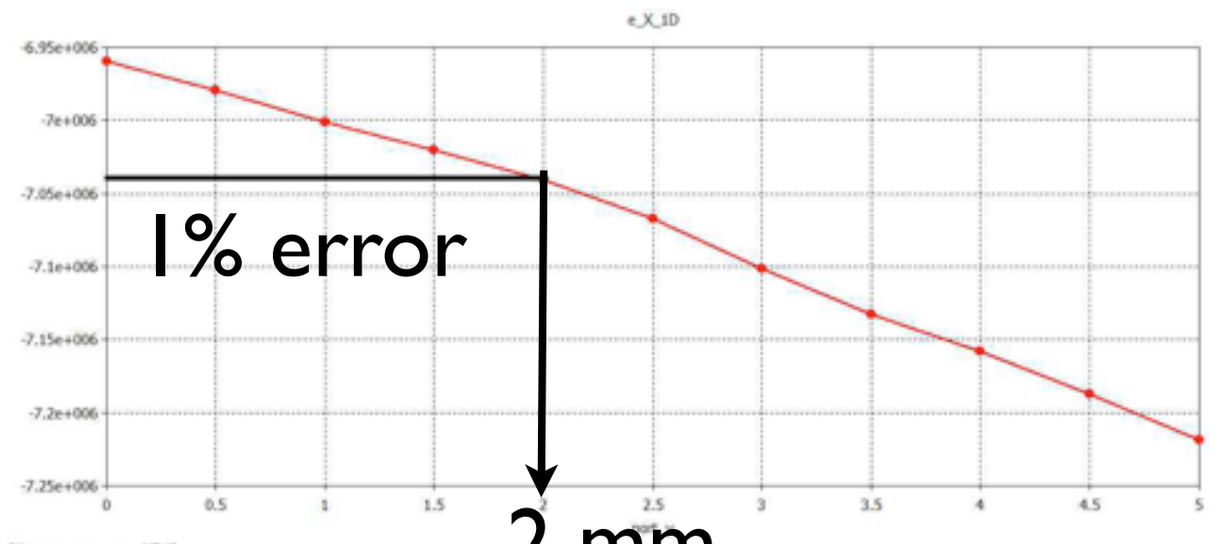

The peak field values are sensitive to the meshing and thus determined by a largeer number of the meshes with the use of 3 symmetry planes.

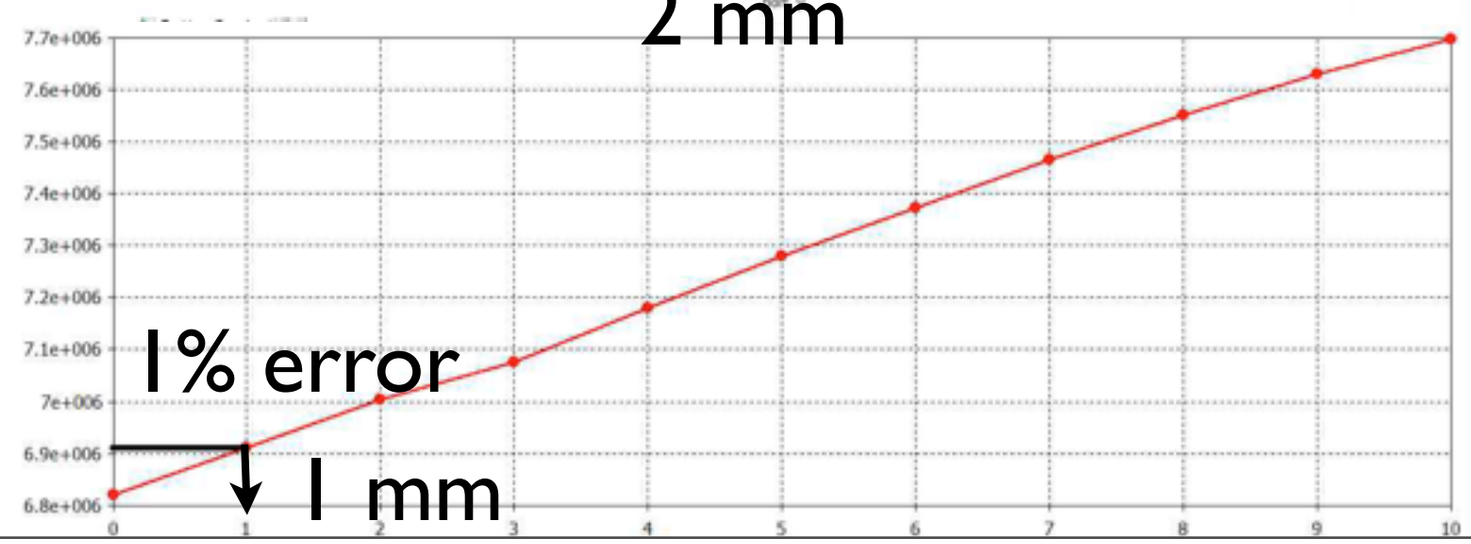
# Error study

Axial component of the accelerating gradient



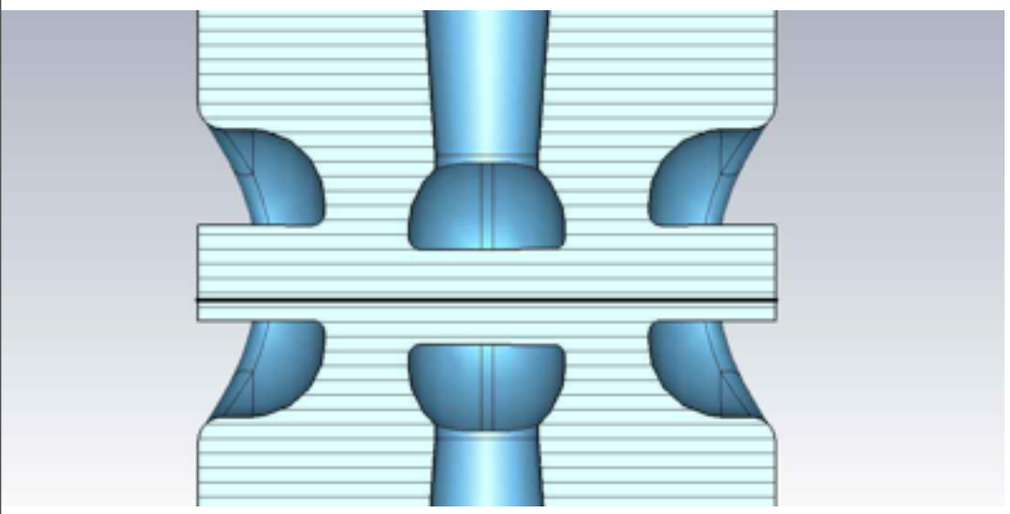



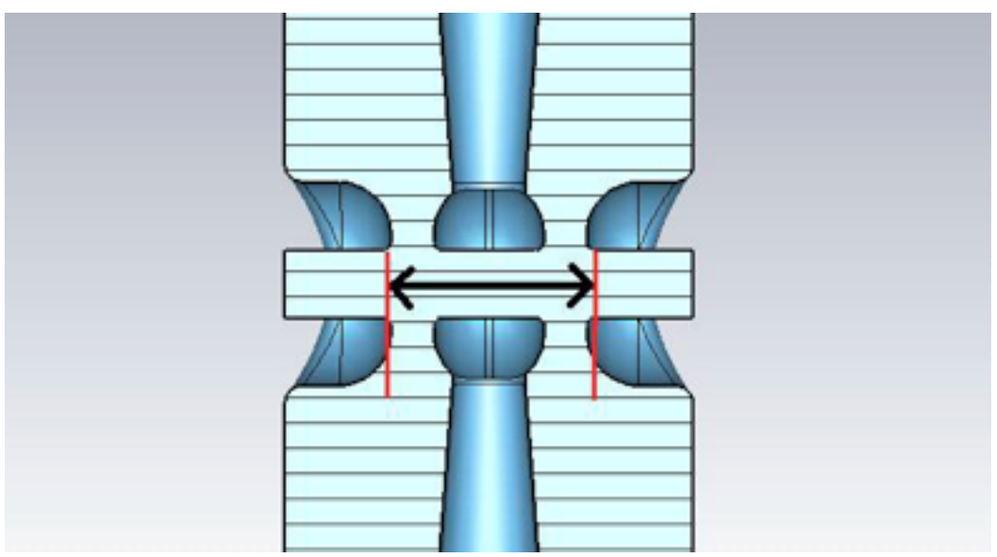



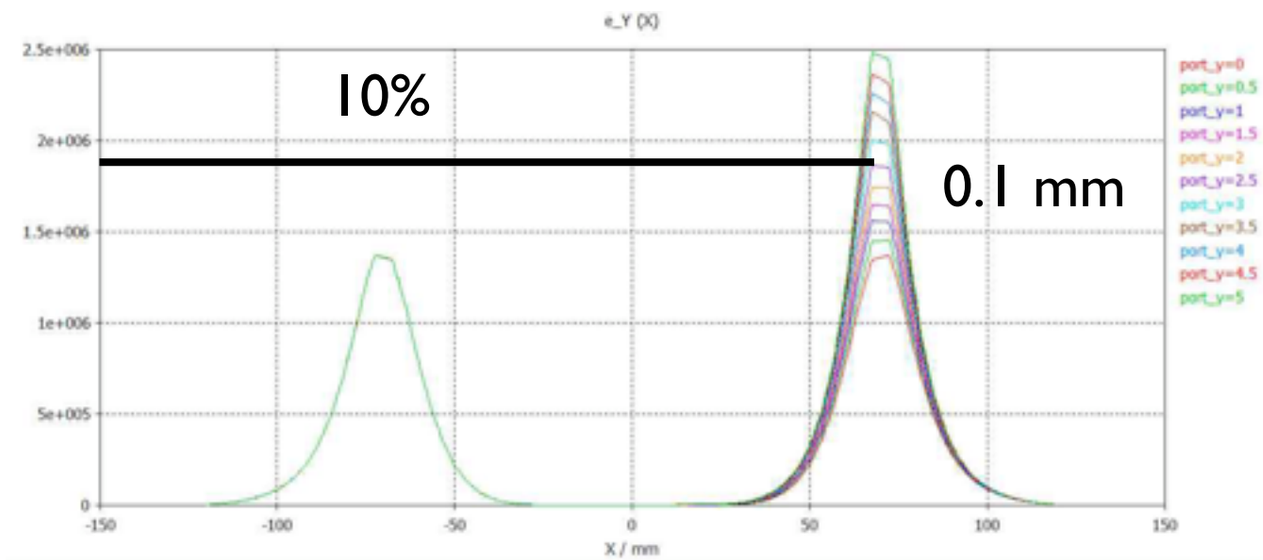



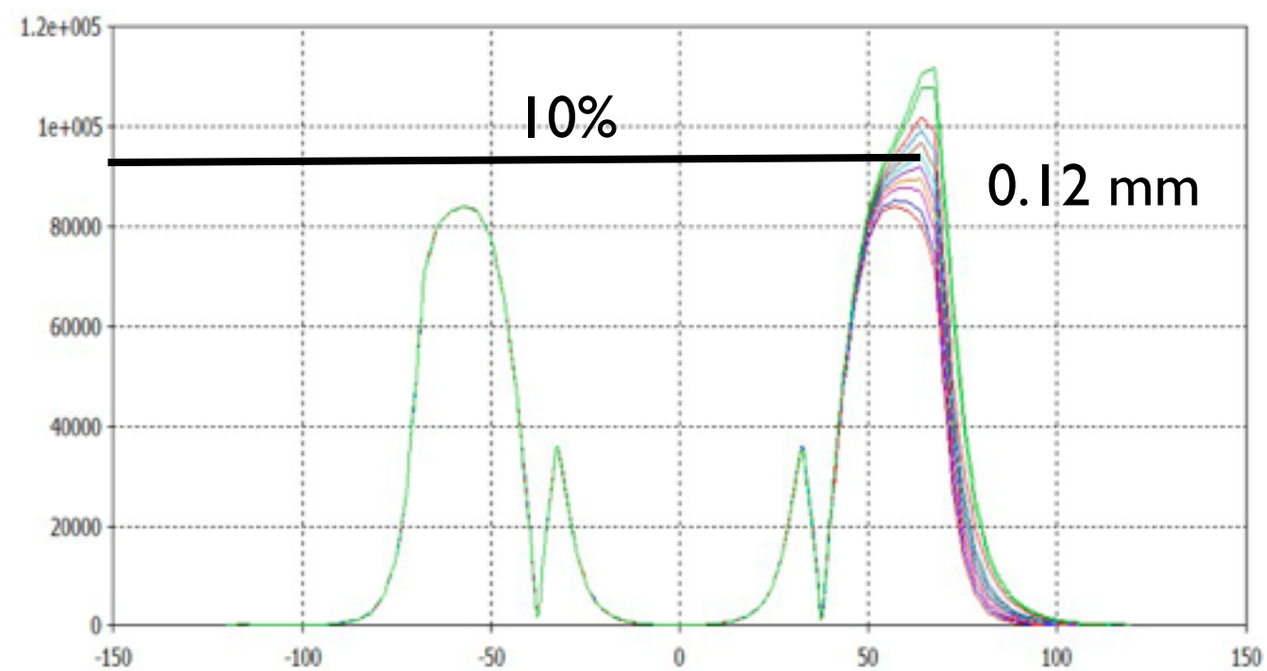
Only one gap (RHS) is deformed

Transverse(Vertical) component of the accelerating gradient

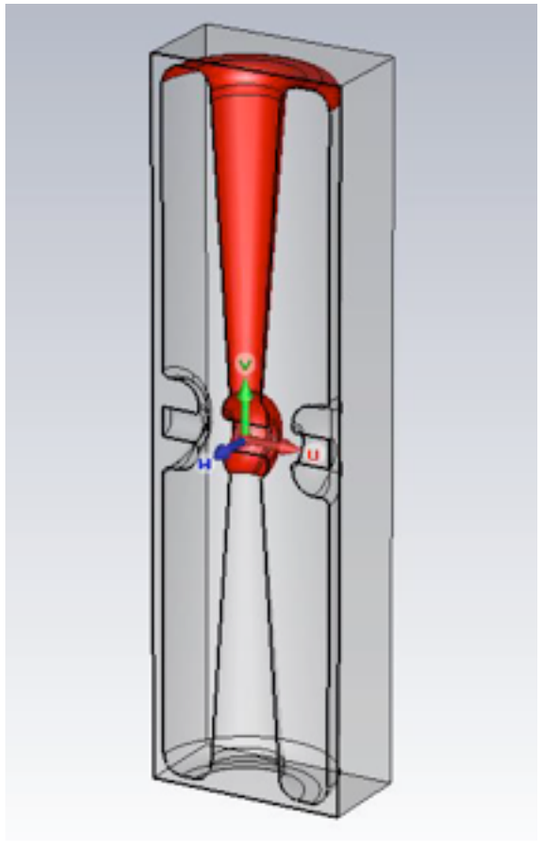




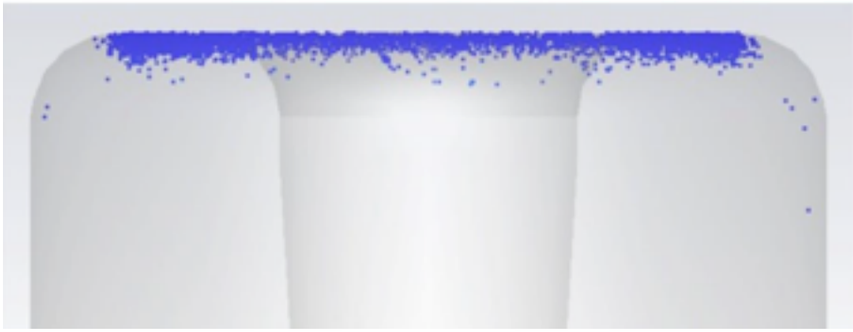


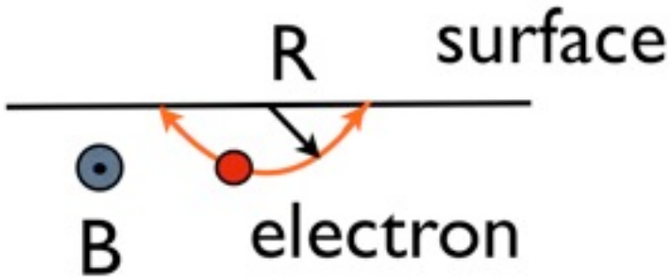
# Multipaction



Electron source

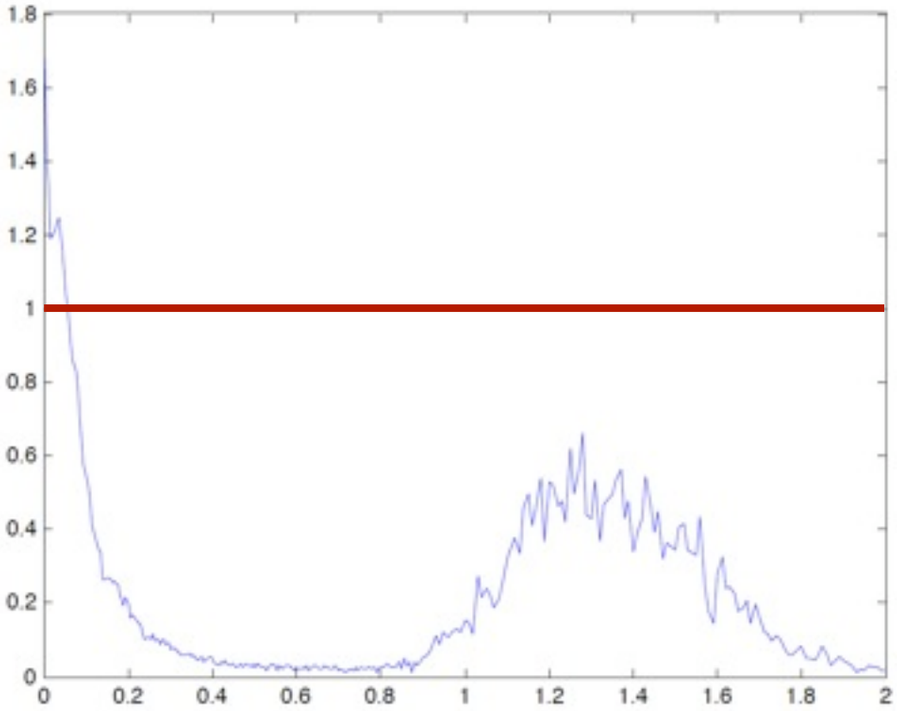


Multipacting electrons




Schematic of the multipaction

- The enlarging the flat region may spread the electrons disrupting the resonance
- Increased $R_{top}$ from 50 mmto 45mm.




Multipacting factor vs. gradient scale factor

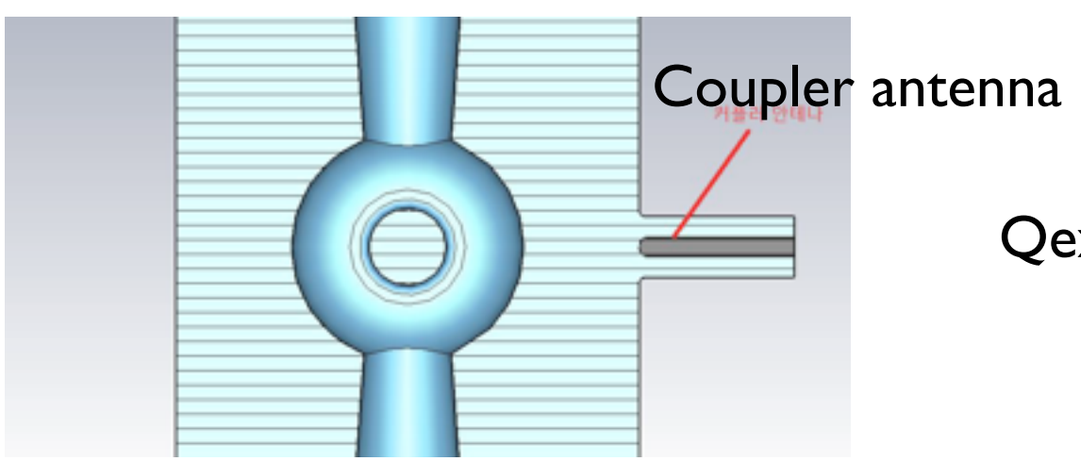
# Interface to the Coupler

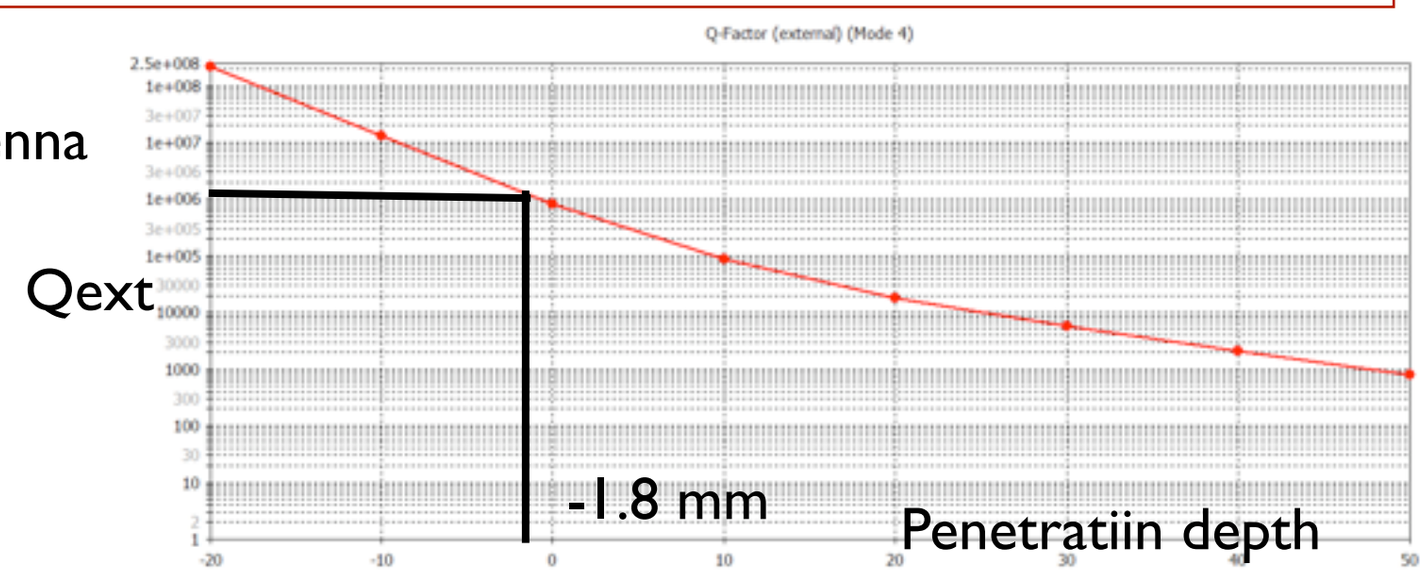
In over-coupling, the power needed to maintain the constant accelerating voltage is given by

$$P = \frac{V_{acc}^2}{4\frac{R}{Q}Q_{ext}}\left[\left(1+\frac{R}{Q}Q_{ext}\frac{I_b}{V_{acc}}\cos\phi_b\right)^2 + \left(2Q_{ext}\frac{\Delta f}{f_0}+\frac{R}{Q}Q_{ext}\frac{I_b}{V_{acc}}\sin\phi_b\right)^2\right].$$

where $I_b$ is the beam current, $\phi_b$ is the accelerating phase.

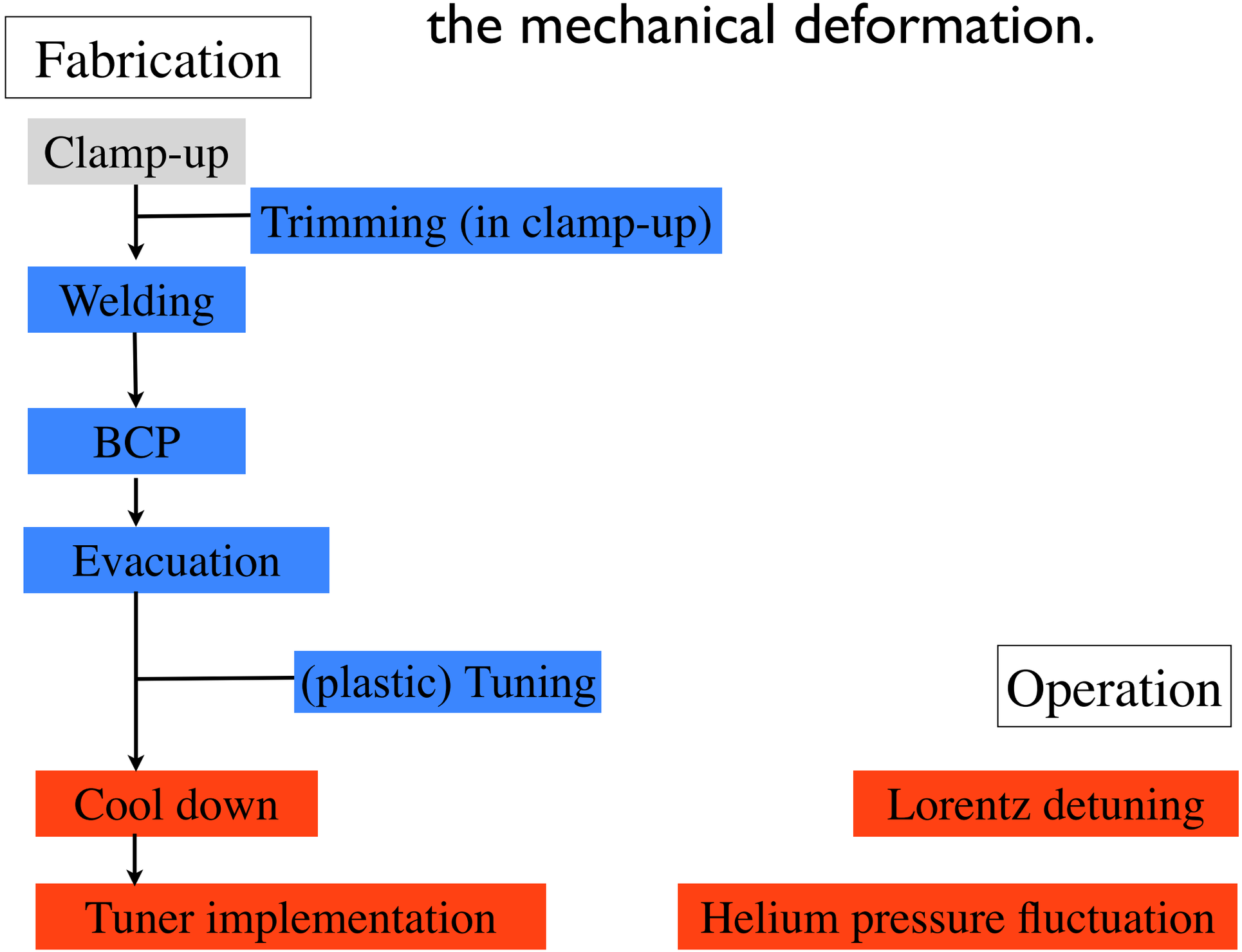
With the bandwidth $2\Delta f$=80 Hz, $R/Q_0$=317, $Q_{ext}$=2.03e6, $I_b$~0.7 mA, and $\phi_b$, the power is computed as P=1.5 kW



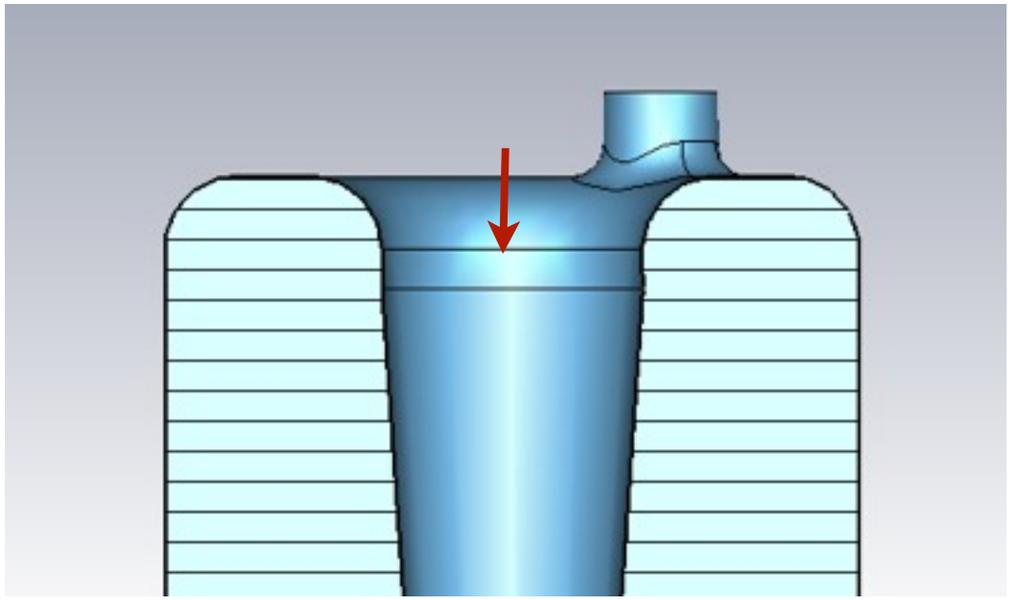



# Mechanical design

- As a RF device with a narrow bandwidth, SC is very sensitive to the mechanical deformation.

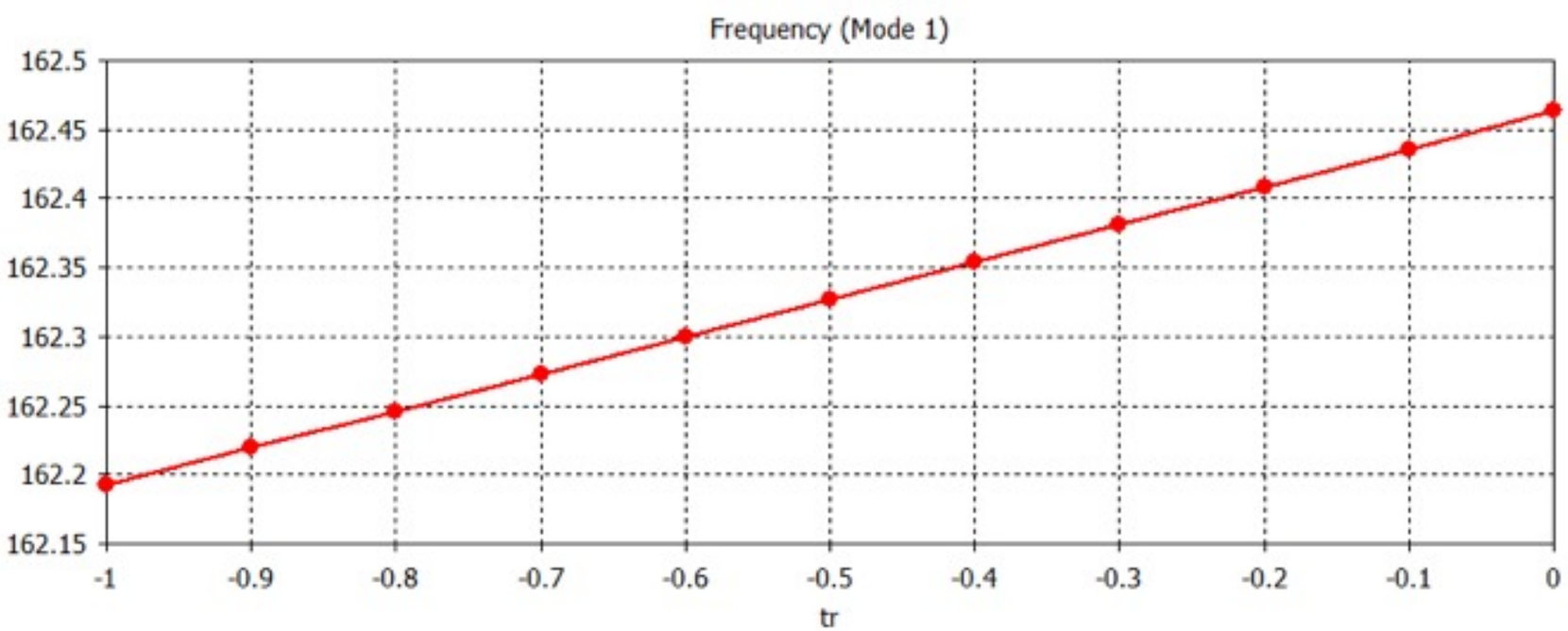


# Trimming/welding shrinkage



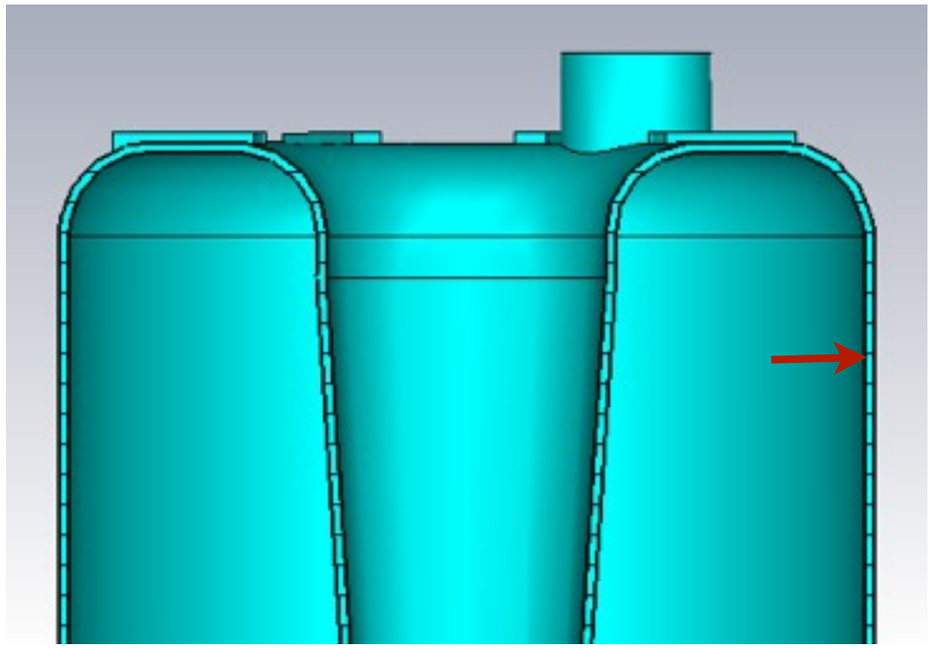
- Frequency shift rate=272 kHz/2mm

Trimming of the straight section



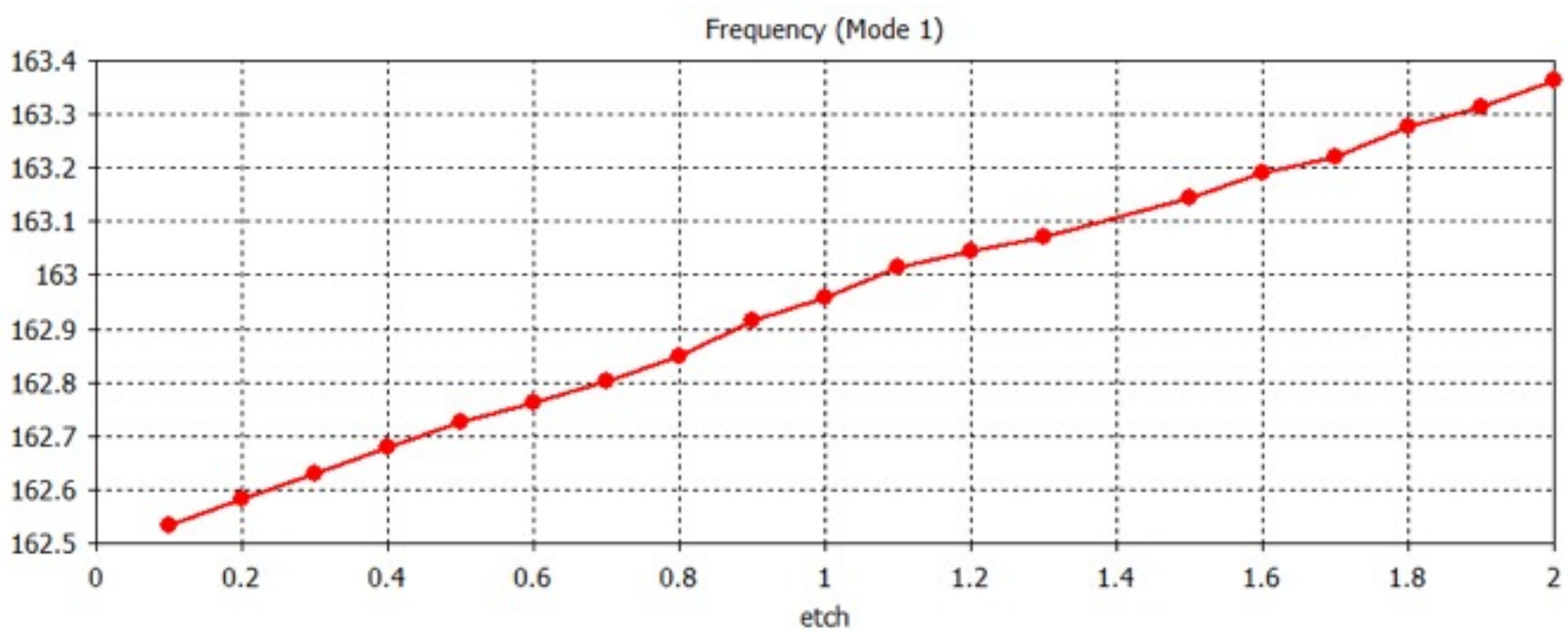

Frequency vs. trimming

# Polishing



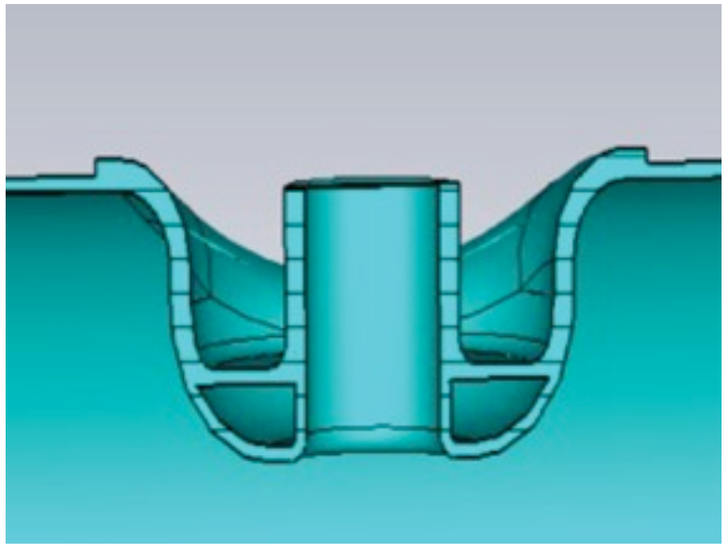
- frequency shift rate=48.4 kHz/0.1mm
- The polishing is done by 0.15mm

Polishing the inner surface

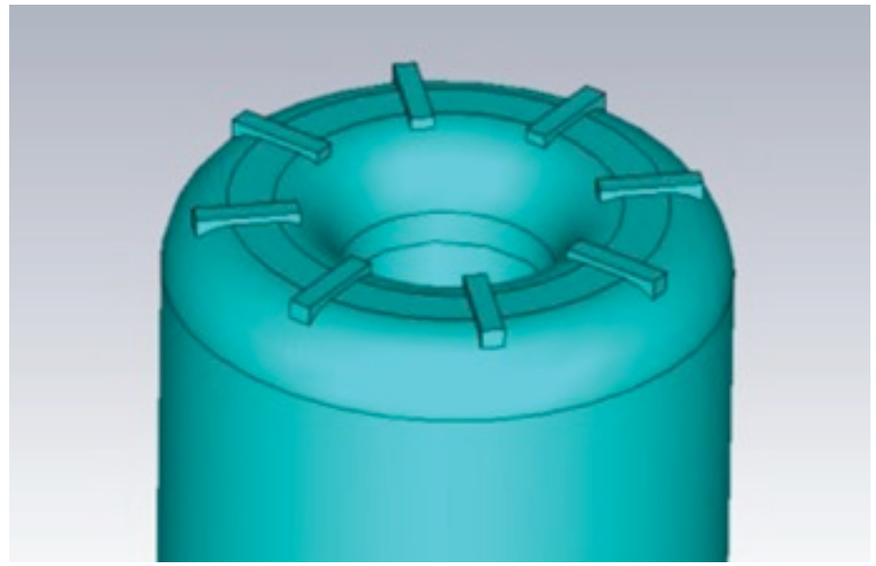



Frequency vs. etch depth

# Pressure sensitivity

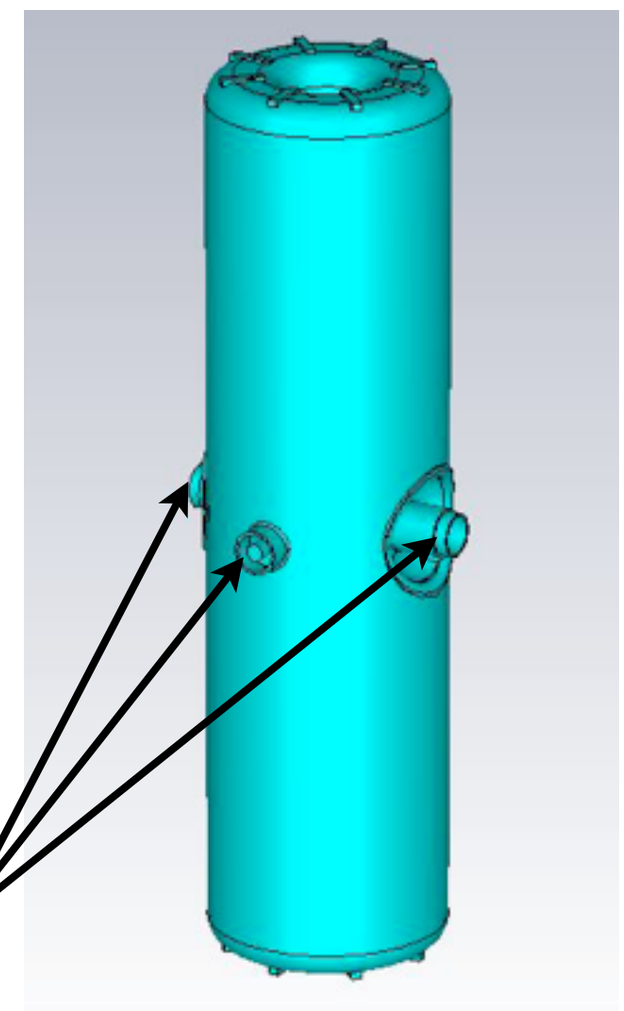


The doubler



The gussets

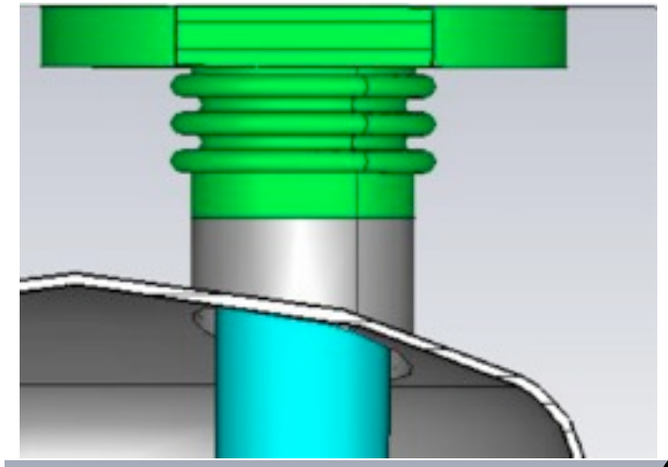
The stiffeners were introduced and optimized for the minimum deformation against the pressure.



Frequency shift :0.27kHz/bar

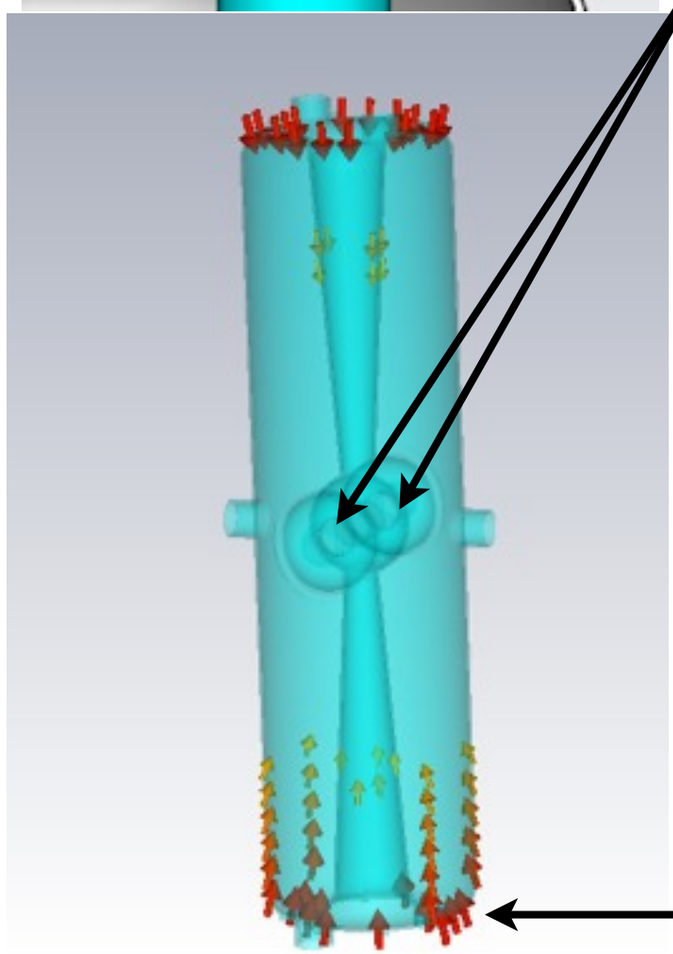
B.C: fixed ports

# Cool down



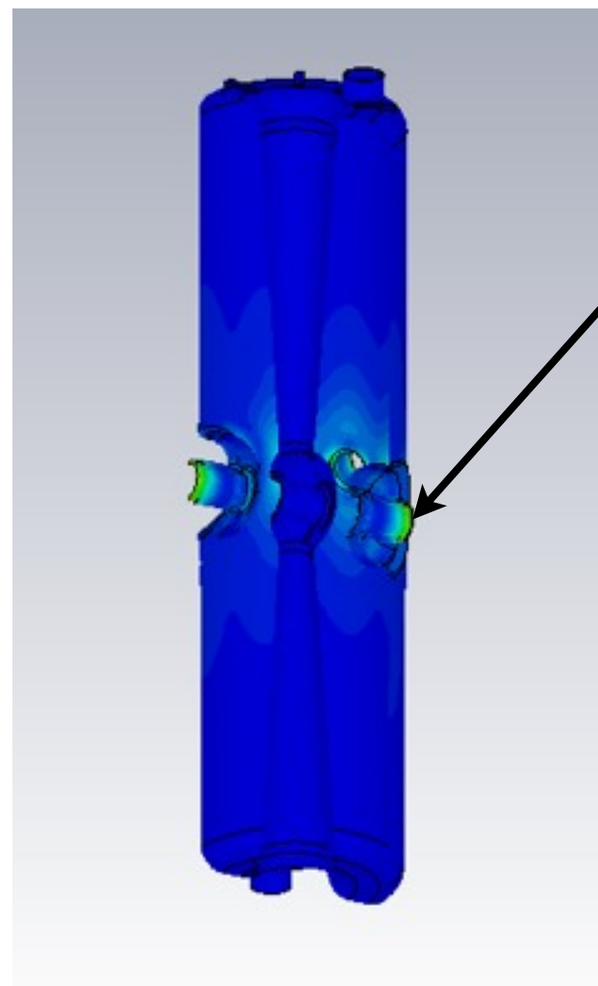
To overcome the thermal contraction difference between cavity (Nb) and the helium vessel (SS 304L), the bellows were introduced.

As an approximation, fixed b.c applied.



Maximum deformation of 1.1mm @ toroids

The deformation due to cooldown from room temp. to 2K

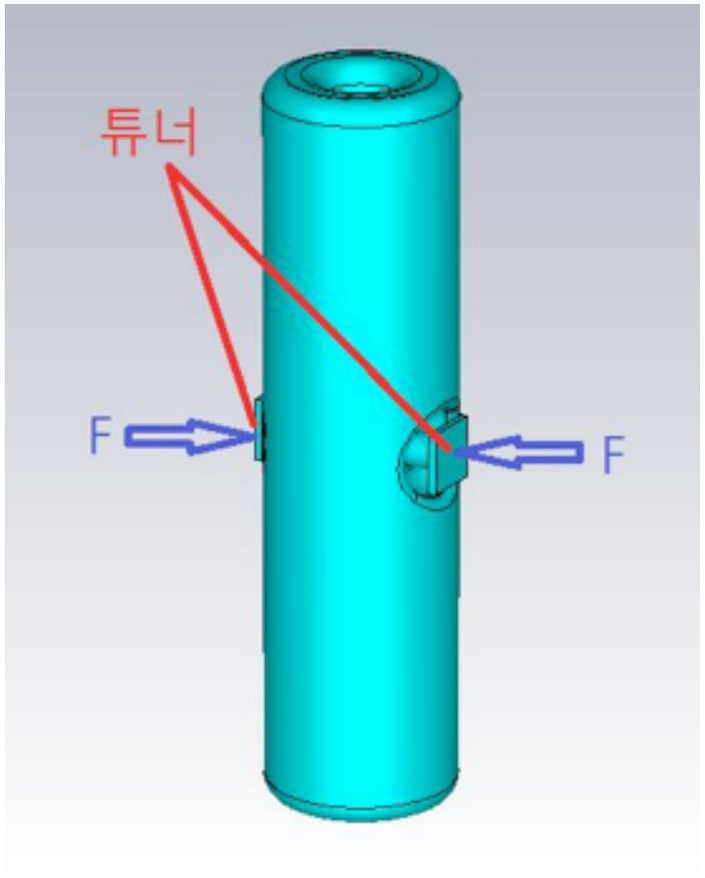


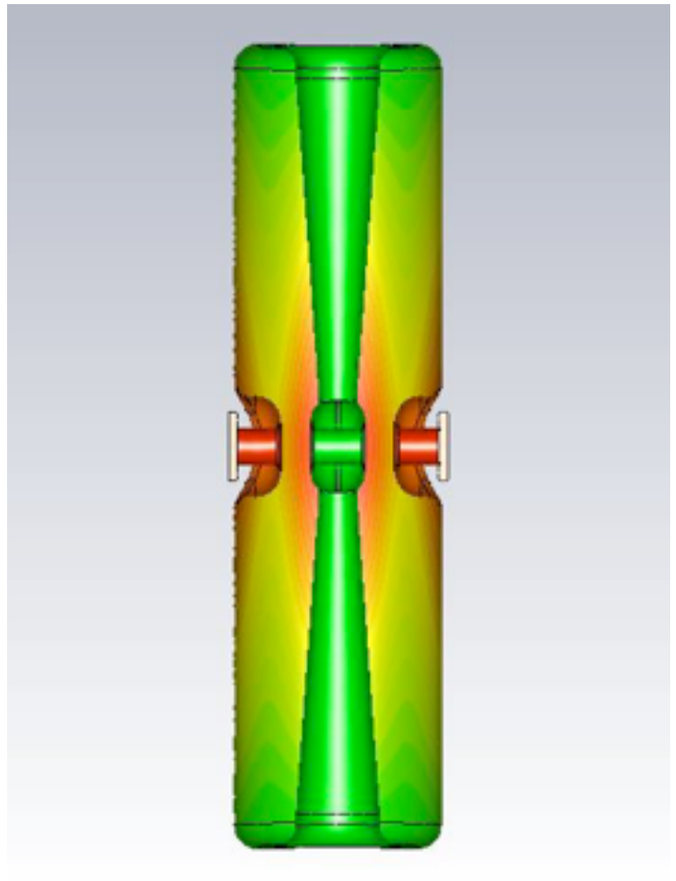
Maximum stress of 533MPa @ beam ports

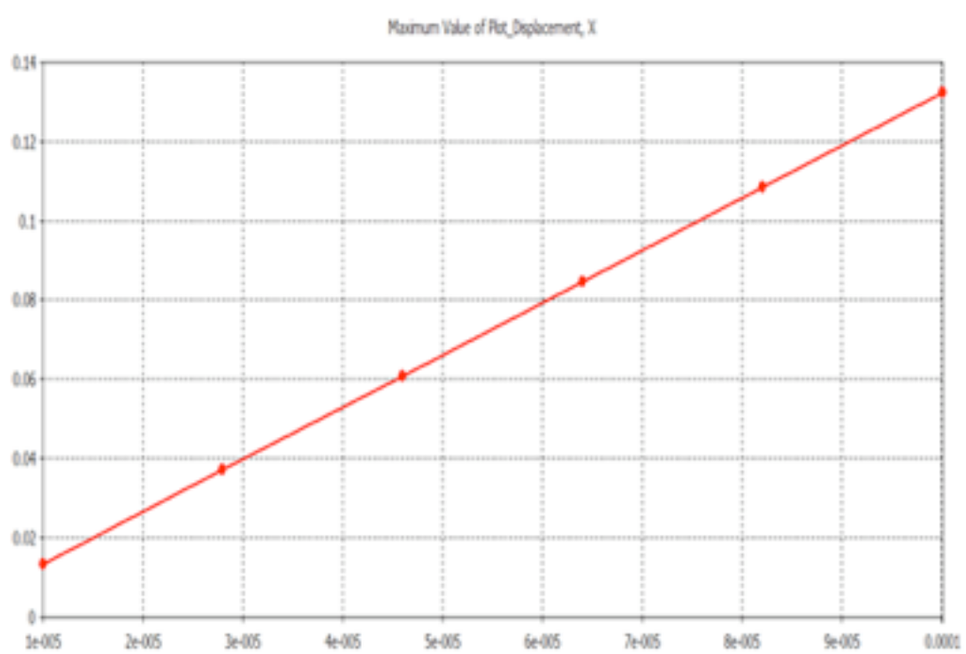
The first principal stress due to cooldown from room temp. to 2K

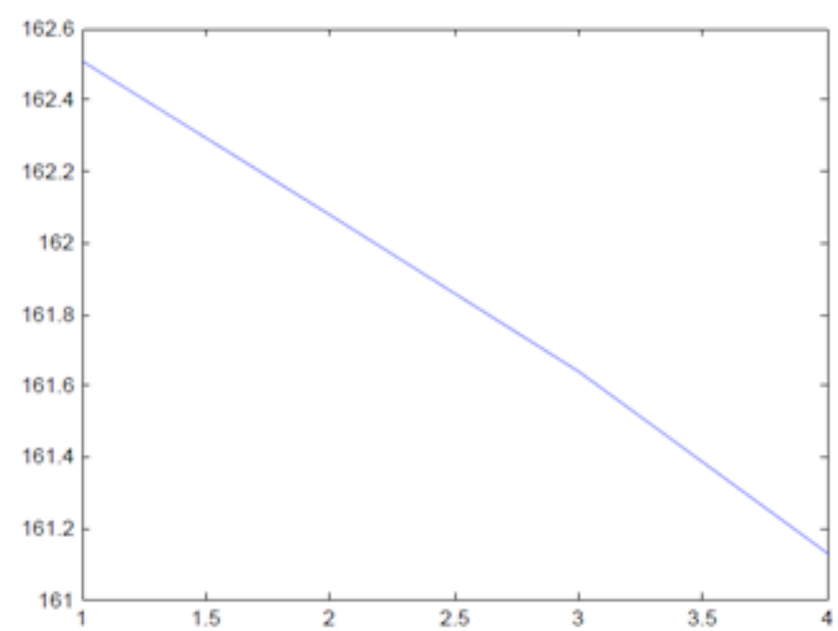
Frequency shift: 2.7kHz

# Interface to the tuning system



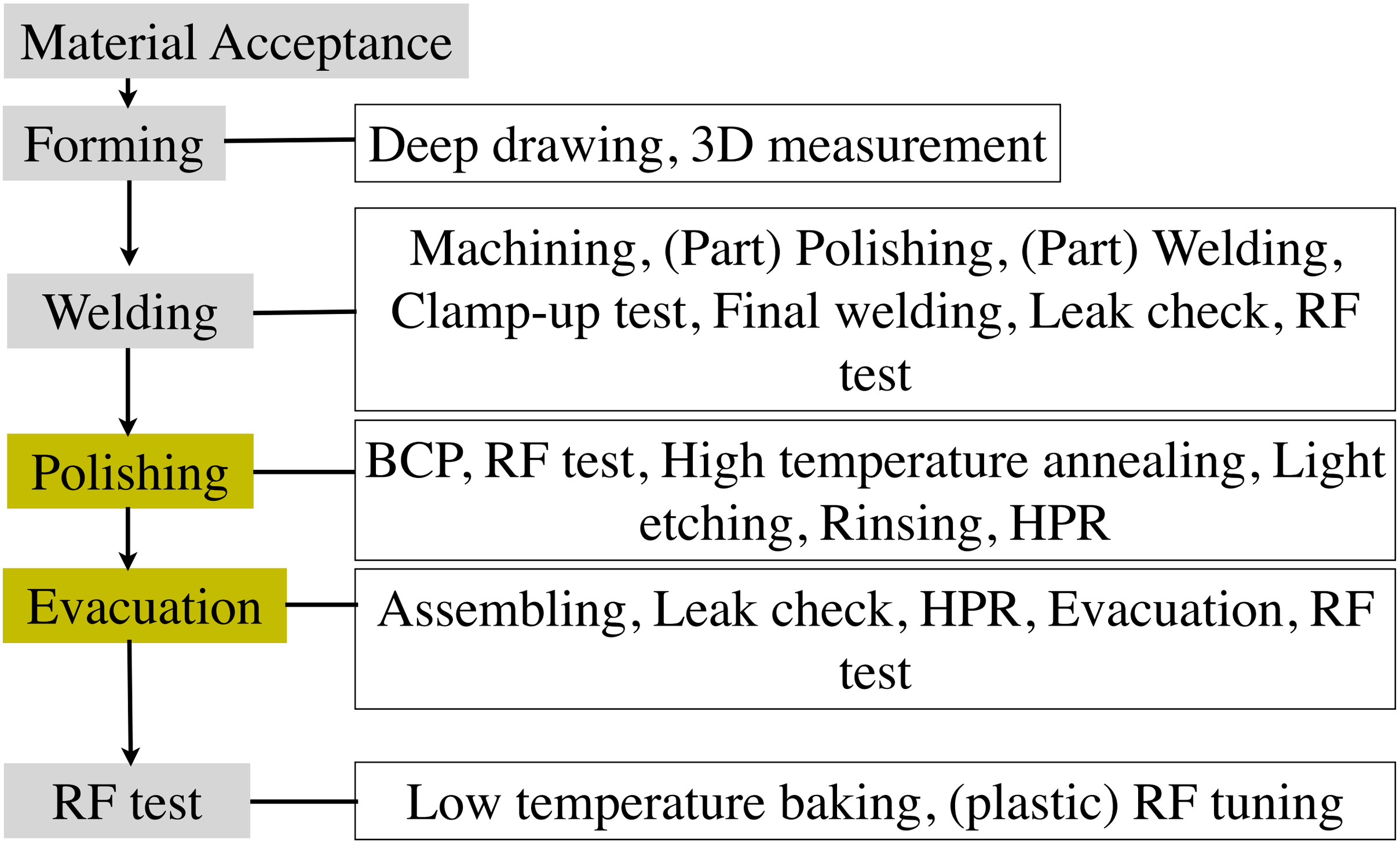





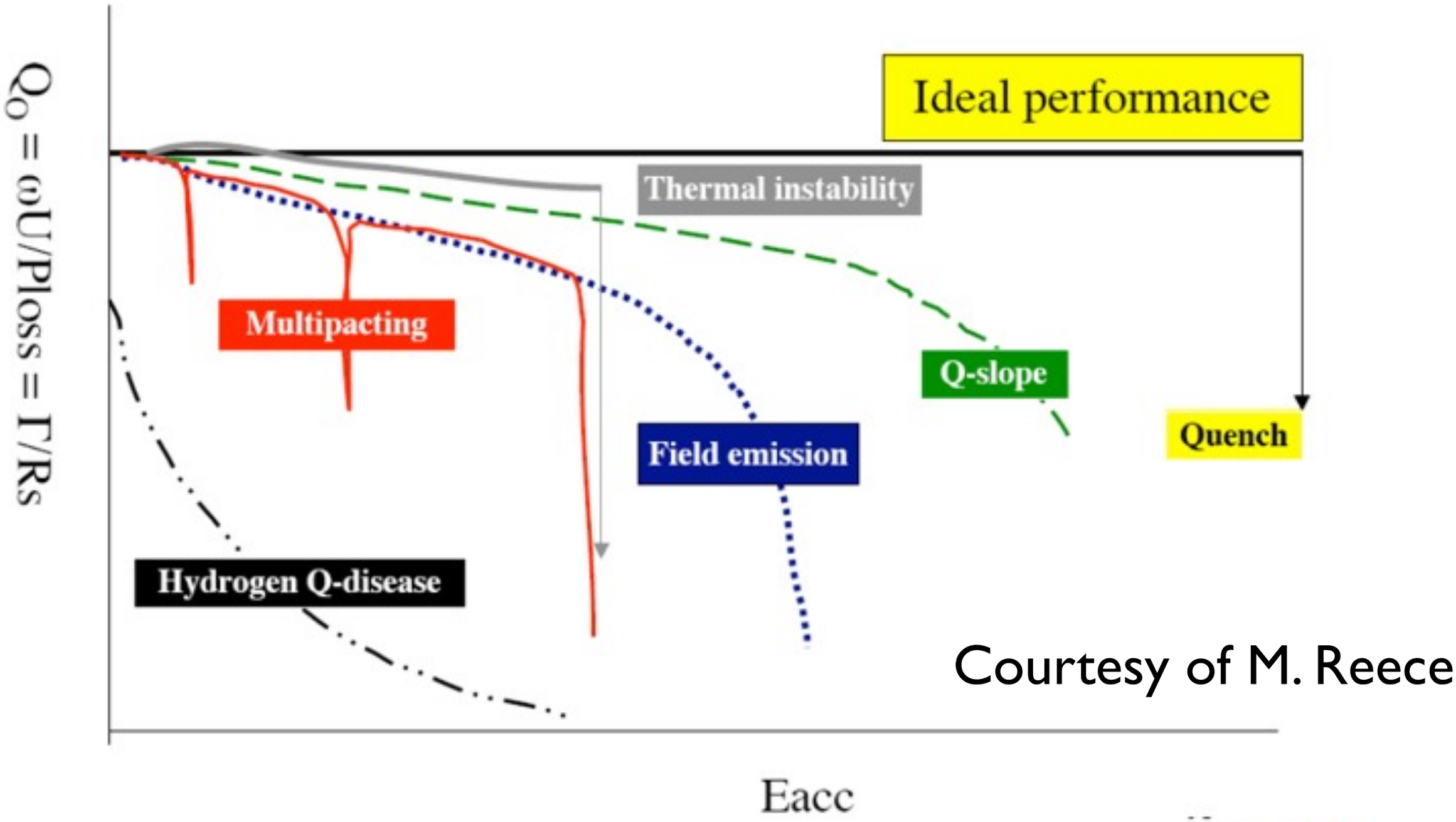



# 3. Fabrication of the HWR

# Fabrication procedure



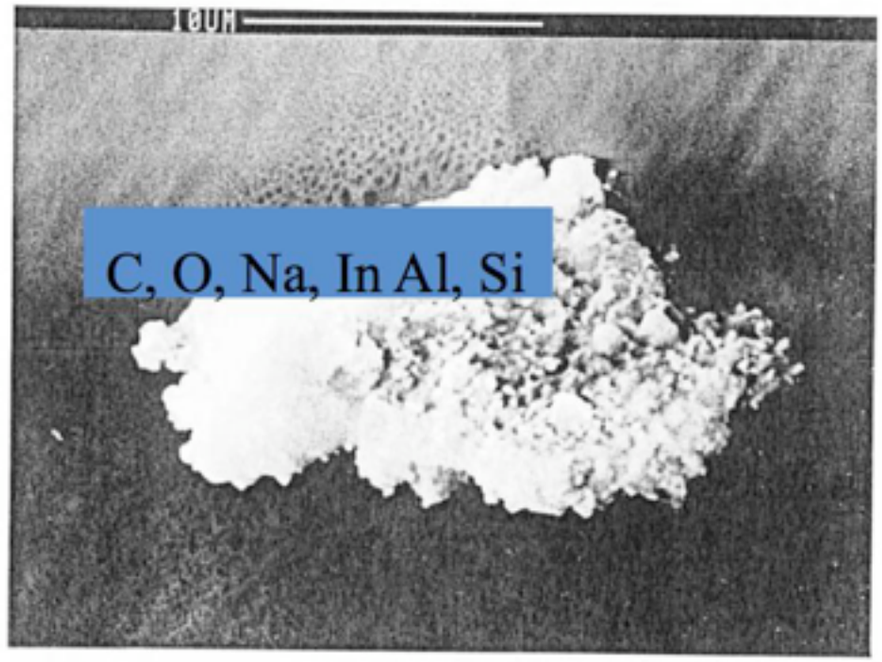
# Anomalous behavior of the cavity



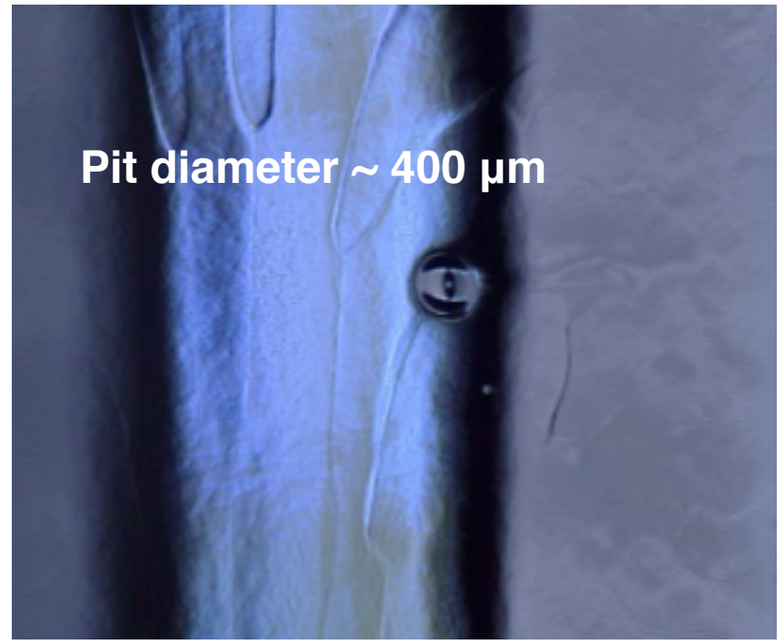

- The origins of these anomalous behaviors trace mostly back to the fabrication imperfections.

Courtesy R.L. Geng

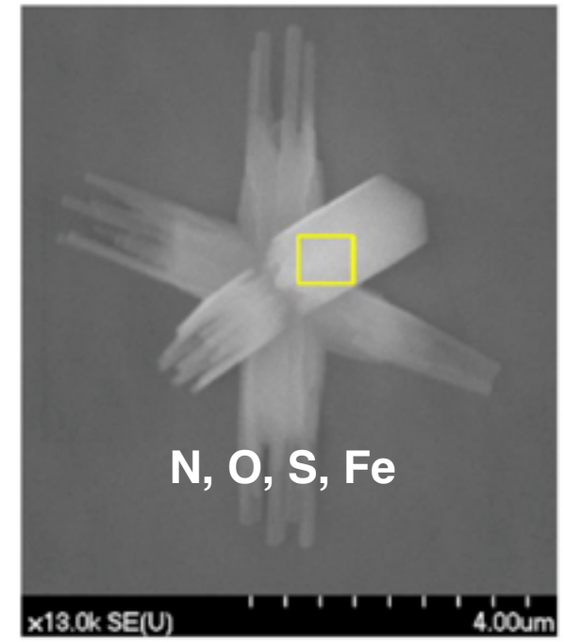
# The field emitters




Microscopic particles

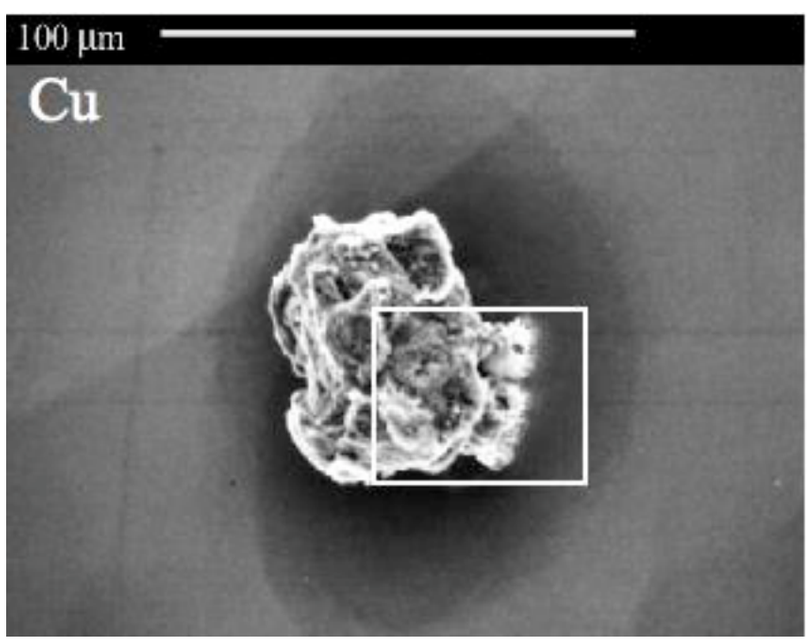



Geometrical defects

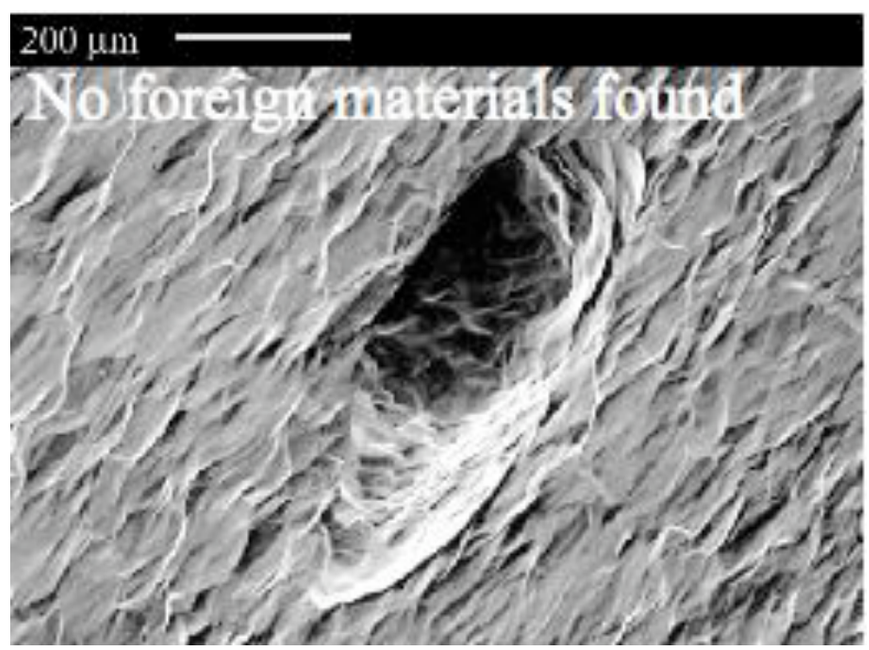



Chemical contaminant

# The quenchers




Normal conducting impurity

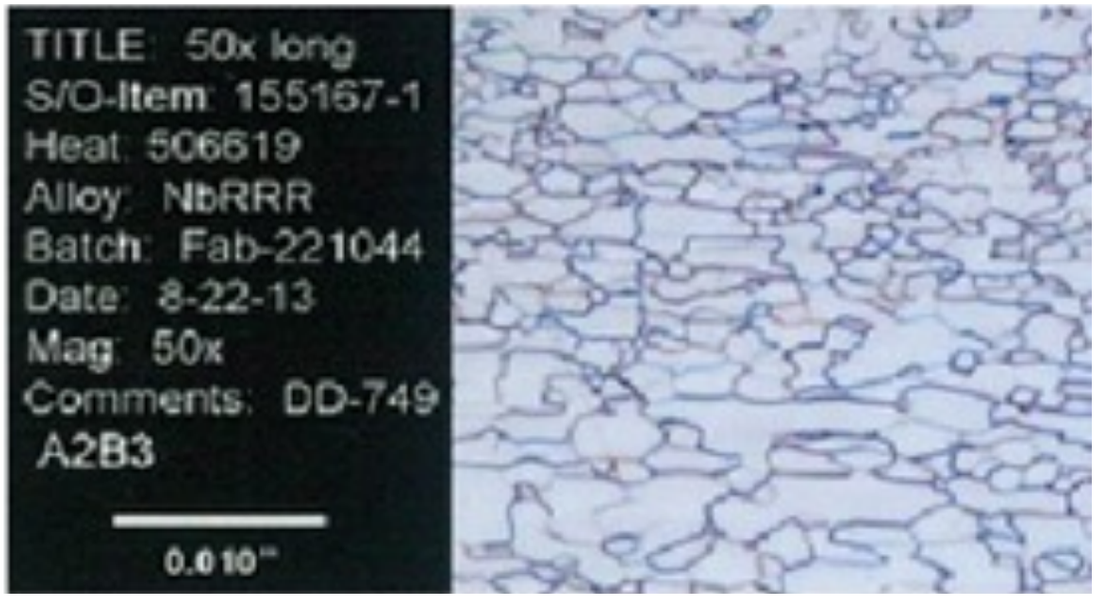



Geometrical defects (pit)

# Inspection

| | |
|---|---|
| Grain size | <4 ASTM |
| RRR | >300 |
| Recrystallization | 100 |

Specifications of Nb



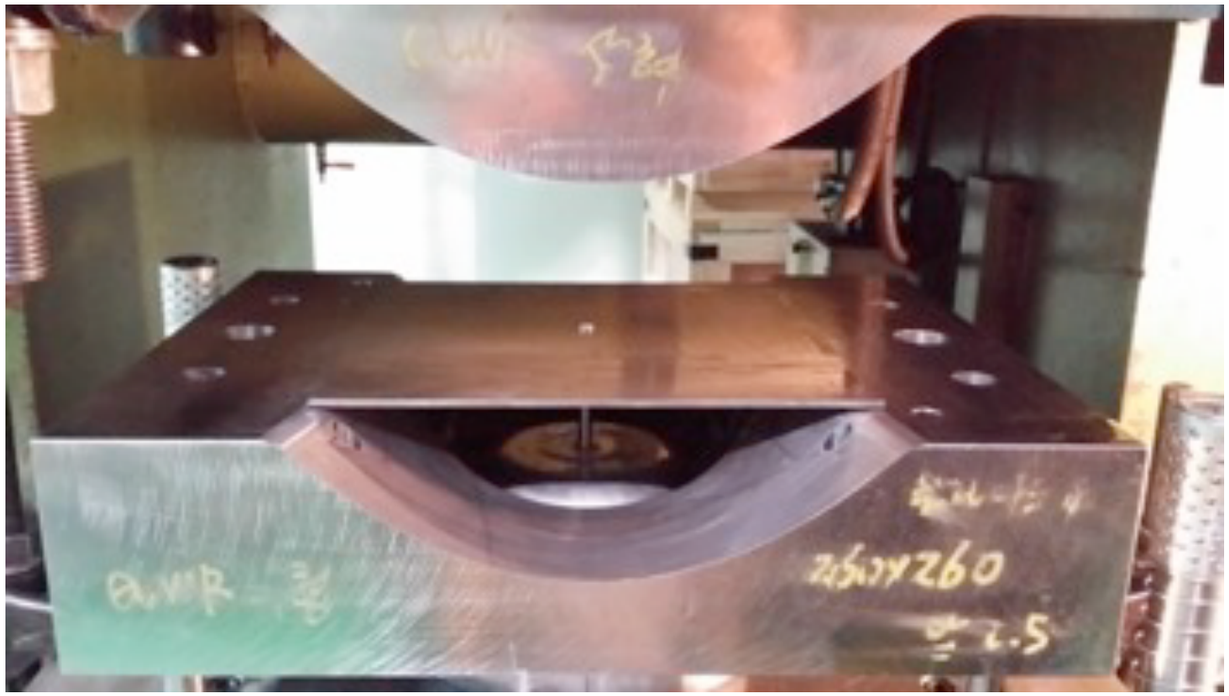

Grain structure of Nb

DI (deionized) water dipping

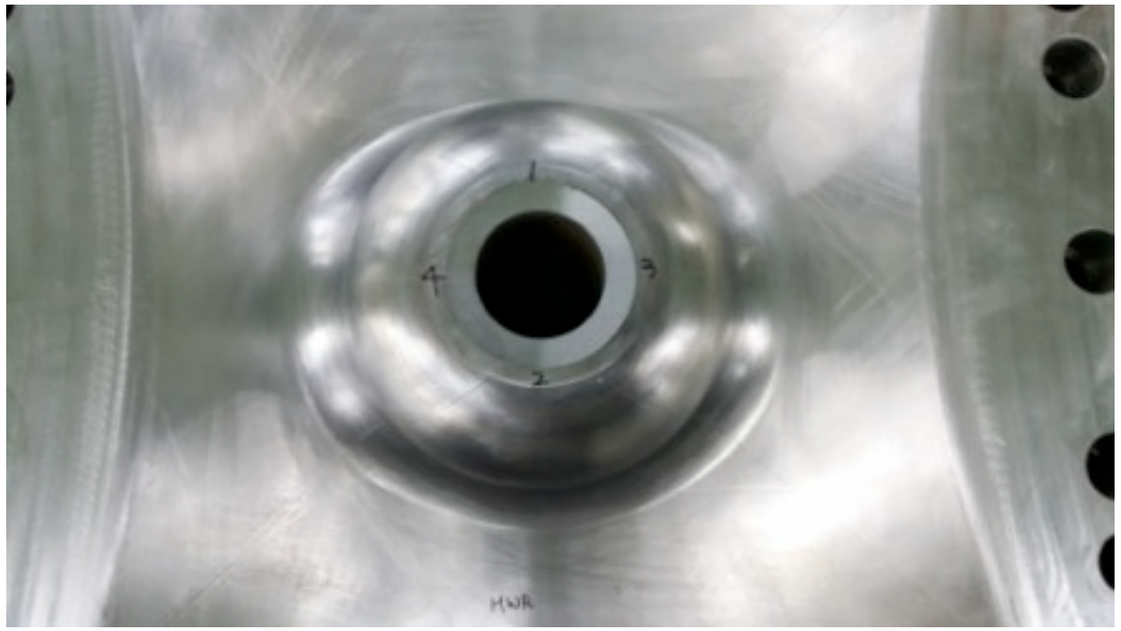
Rust

# Forming

Pressing the outer conductor



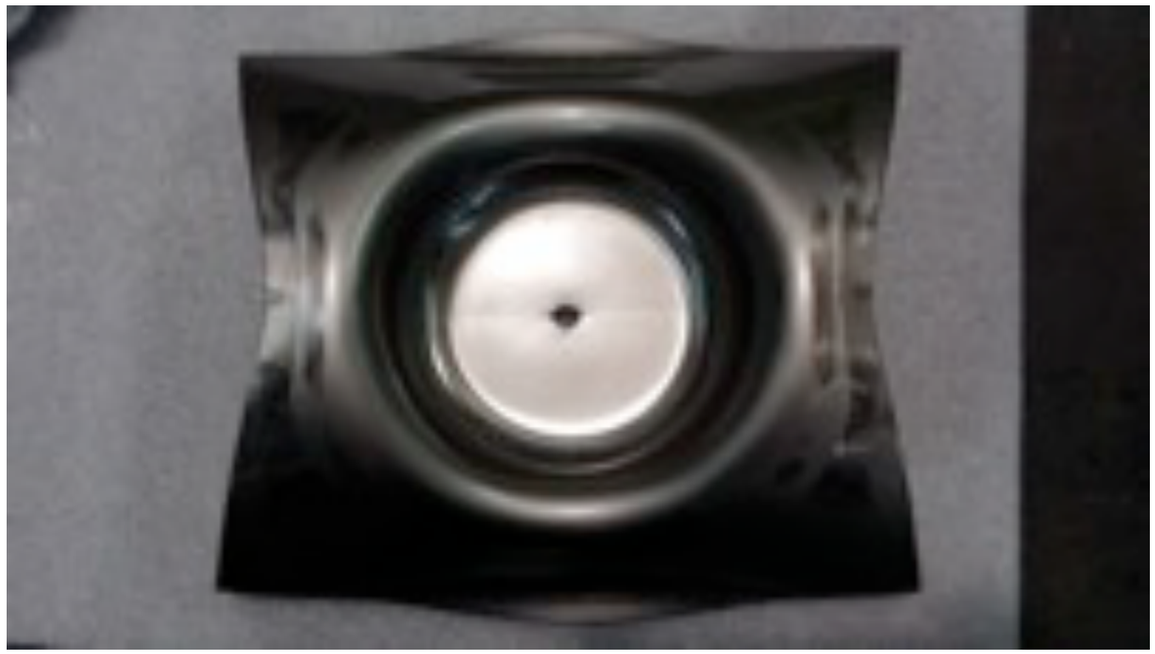
Pressing the re-entrant nose



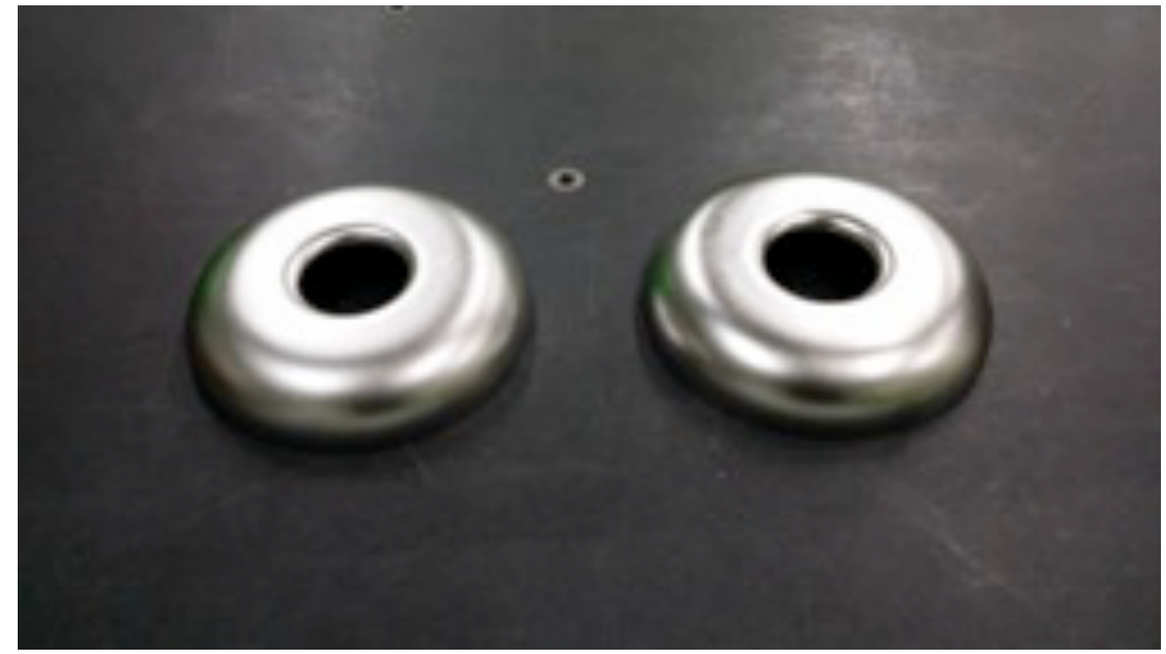
Press jig for re-entrant nose

Pressing jig for the upper toroid

# Formed parts of the cavities



Re-entrant nose

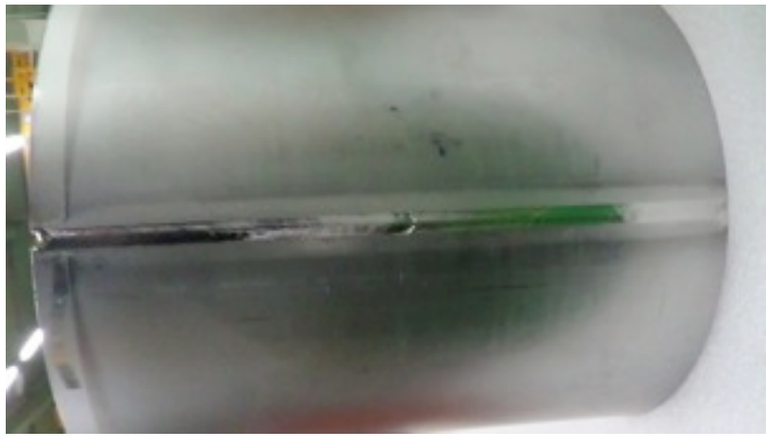


Ring

Inner conductor

Outer conductor

# EBW (Electron beam welding)



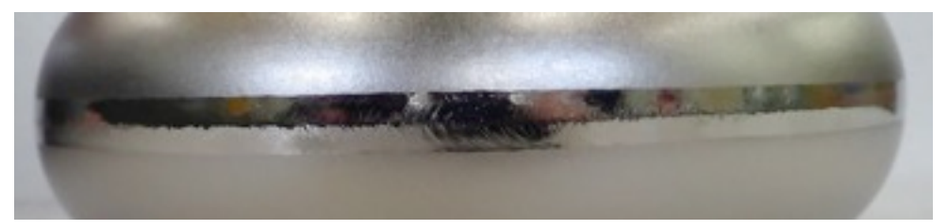
Frontbead of the outer housing

Backbead of the outer housing

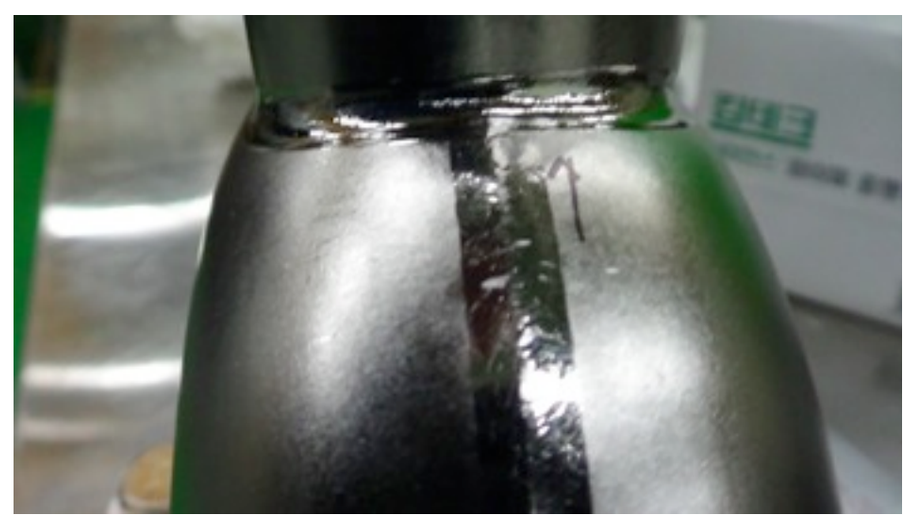
The ring fixed in welding jig

| Voltage | Beam Size | Frequency | Focus | Distance | Feed rate |
|---|---|---|---|---|---|
| 120 kV | 1 × 0.5 | 4999 Hz | −120 mA | 641 mm | 5 mm/s |
| Current of welding | | | | | |
| Ø138 Radian (21 mA → 20.5 mA) | | | | | |

Welding condition for the ring welding

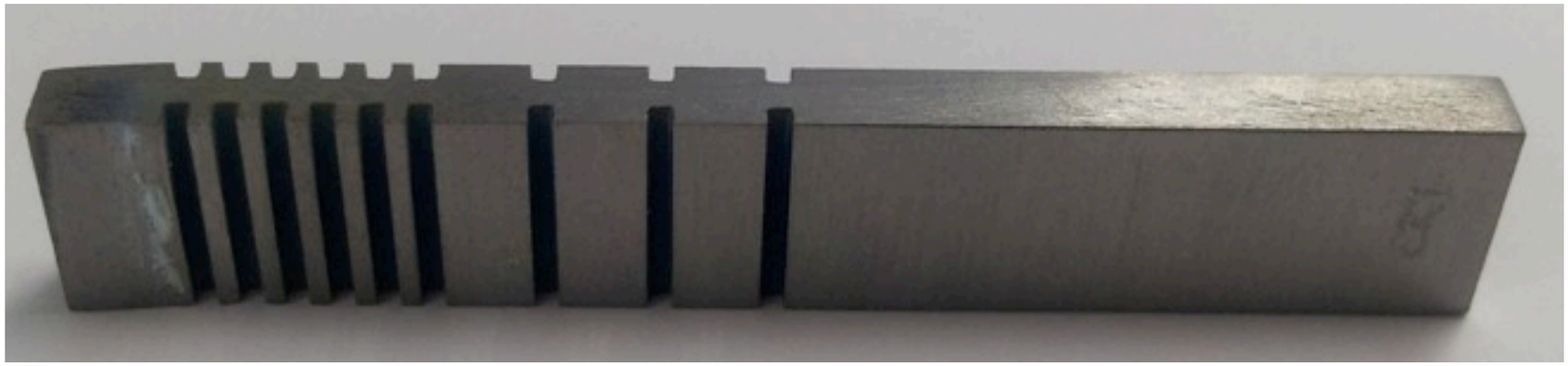


Frontbead of the ring



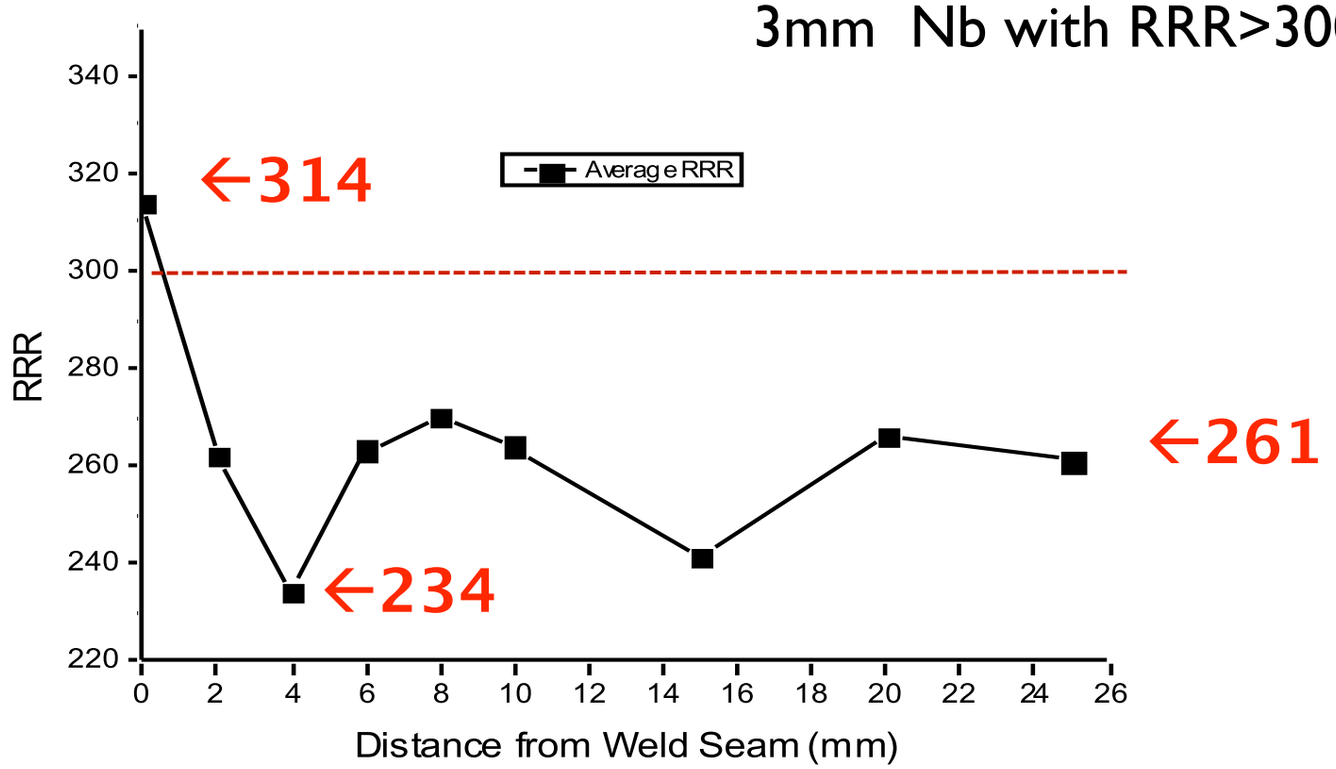
Frontbead of the ring

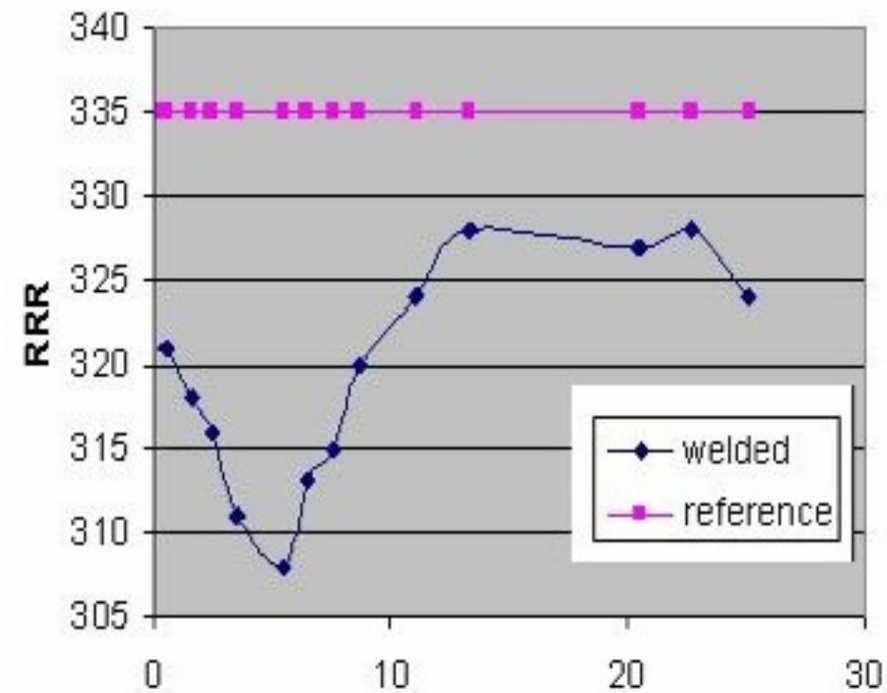
# RRR test after welding



Welding at 2x10e-6 Torr

3mm Nb with RRR>300



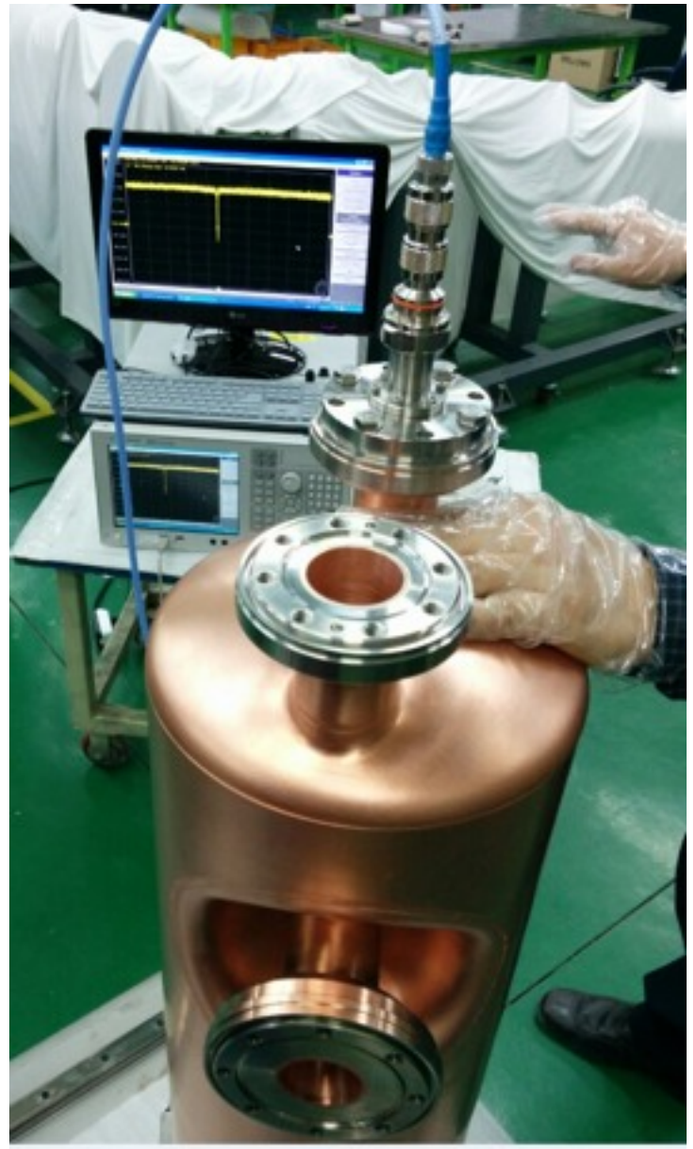




→9% Reduction at $2x10^{-5}$ [At lowest alue]
→5% Reduction [Avg value]

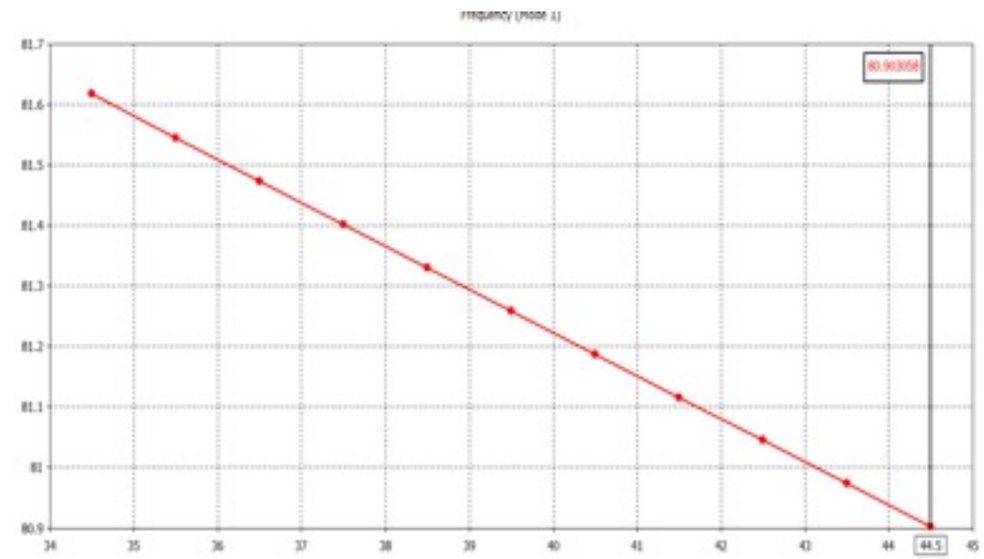
→ 22% Reduction [At lowest value]
→ 13% Reduction [Avg value]

# Clamp-up test of Copeer QWR

Clamp-up w/o indium wire



Resonant frequency measurement




Frequency (Mhz) vs. cavity height(mm)

Frequency shift=-71kHz/mm
(Simulation)

| Before trimming | 80.734 MHz |
|---|---|
| After trimming (6.5 mm) | 81.272 MHz |
| After Upper end welding | 81.363 MHz |
| After Lower end welding | 81.32 MHz |

Frequency shift=-83kHz/mm
(Experiment)

# BCP (Buffered chemical polishing)

- Standard chemical composition

$HF:HNO_3:H_3PO_4=1:1:2$ (volume)

- Etching rate=1 micron/min @ 20C

Spoke before BCP

Spoke after BCP

- We plan to polish the surface by 20 μm before the welding, 150 μm for bulk polishing and again 10 μm for the light etching.

# 4. Test in preparation.....

# Bakcups

# Lorentz detuning

Brazed ports