C-band Cryogenic bi-periodic accelerating structure with TM02 mode

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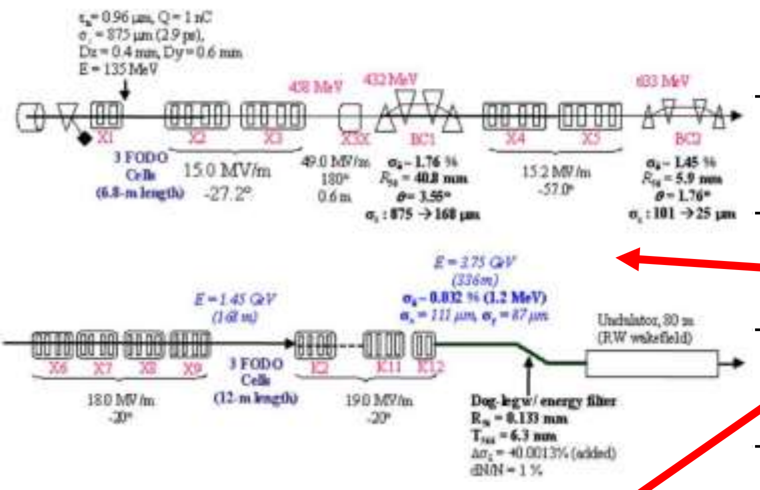
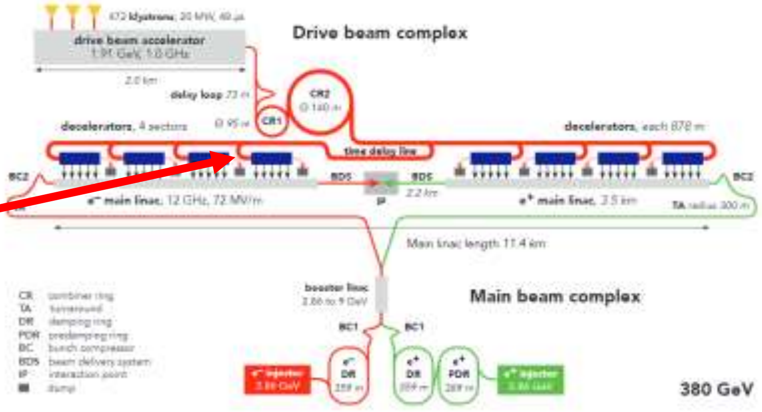
Outlines

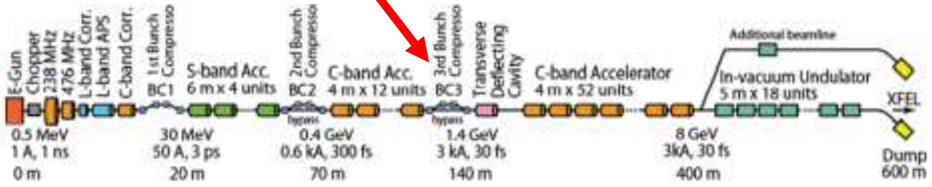
- Background
- RF design of bi-periodic structure
- Multi-objective optimization applied on accelerating cavity
- RF design of the complete accelerating structure
- Thermodynamic analysis and cryogenic system

Background: Energy and length of linacs

Name	Energy (GeV)	Length	Energy/100m
LCLS	14.35	923m	1.55 GeV
PAL XFEL	3.75	336m	1.12 GeV
SwissFEL	5.8	428m	1.36 GeV
CLIC	190.0	3500m	5.43 GeV
SACLA	8.0	400m	2.00 GeV





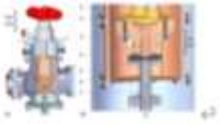


Background: Development of accelerating gradient

- The gradient has been rising.
- Limited by the development of the power source.

- Today has reached a bottleneck
- Because of the high breakdown rate.

- Thus the cryogenic accelerating structure is born.

	X-band 45K E_{ave} = 250MV/m E_{max} = 507MV/m
	S-band 20K E_{max} = 250MV/m
	C-band 20K E_{ave} = 75.5MV/m

cryogenic accelerating structure

Mark I
6MeV

SLAC
10GeV
3km

SwissFEL
26MV/m
C-band

LCLS
37MV/m
S-band

CLIC
72, 100MV/m
X-band

X-band
~100MV/m
Microwave structures

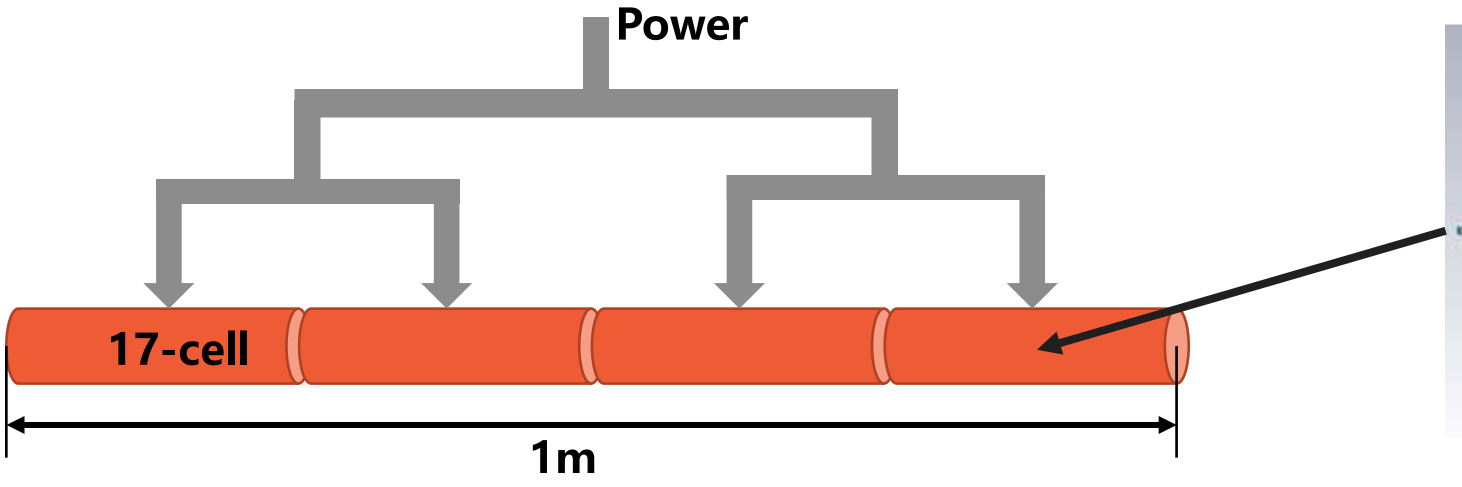
Normal conducting

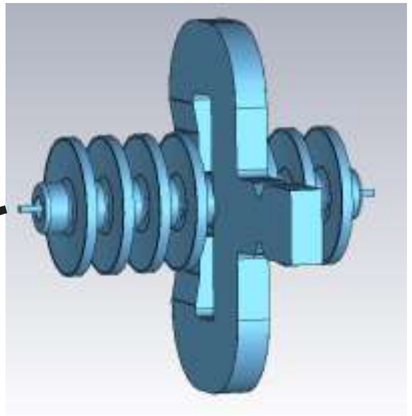
Cryogenic

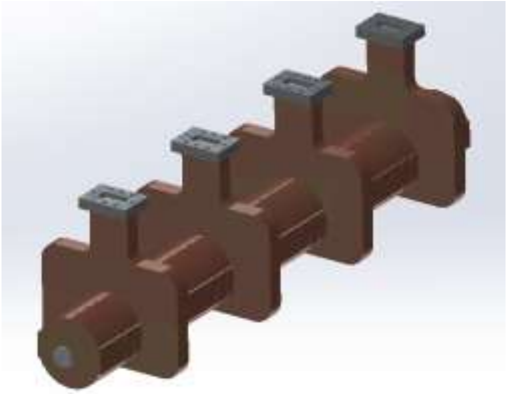
Structure

- A cryogenic standing wave accelerating structure
- Length : 1m
- Four identical accelerating sections.
- Each section consists of 9 accelerating cavities and 8 coupling cavities, which are fed from the middle cavity in a double-fed way.

Parameter	Value	Unit
RF frequency	5712	MHz
Working temperature	40	K
Surface resistance@20K	0.005	Ω
Surface resistance@273.15K	0.0188	Ω
The target E_{acc}(SW)	65/80	MV/m
Type of Structure	Bi-periodic	
Operating Mode	SW / $\frac{\pi}{2}$	
Material	Copper	
RRR	300	
Coolant	Liquid helium	







Bi-periodic cell

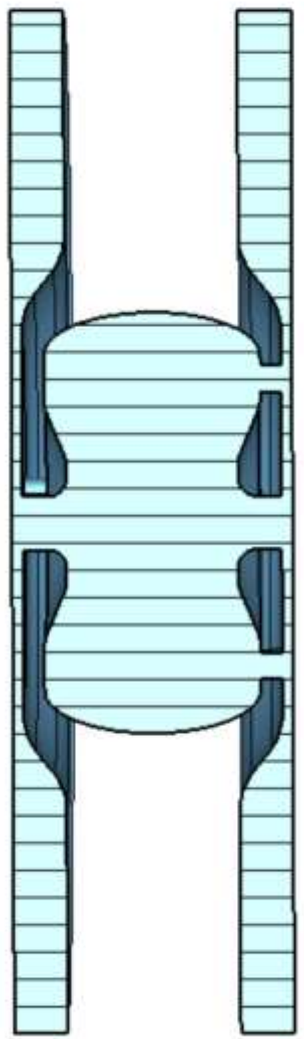
Magnetically coupled

High shunt impedance

Larger coupling cavity

TM02 mode

Special-shaped coupling cavity



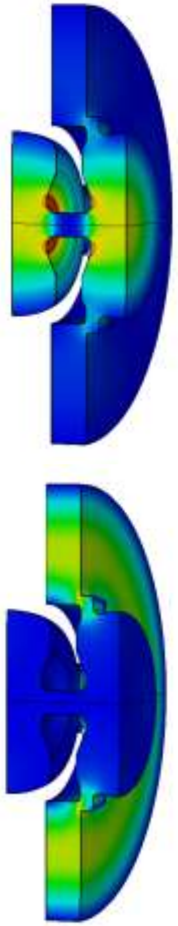
Iris size does not affect coupling

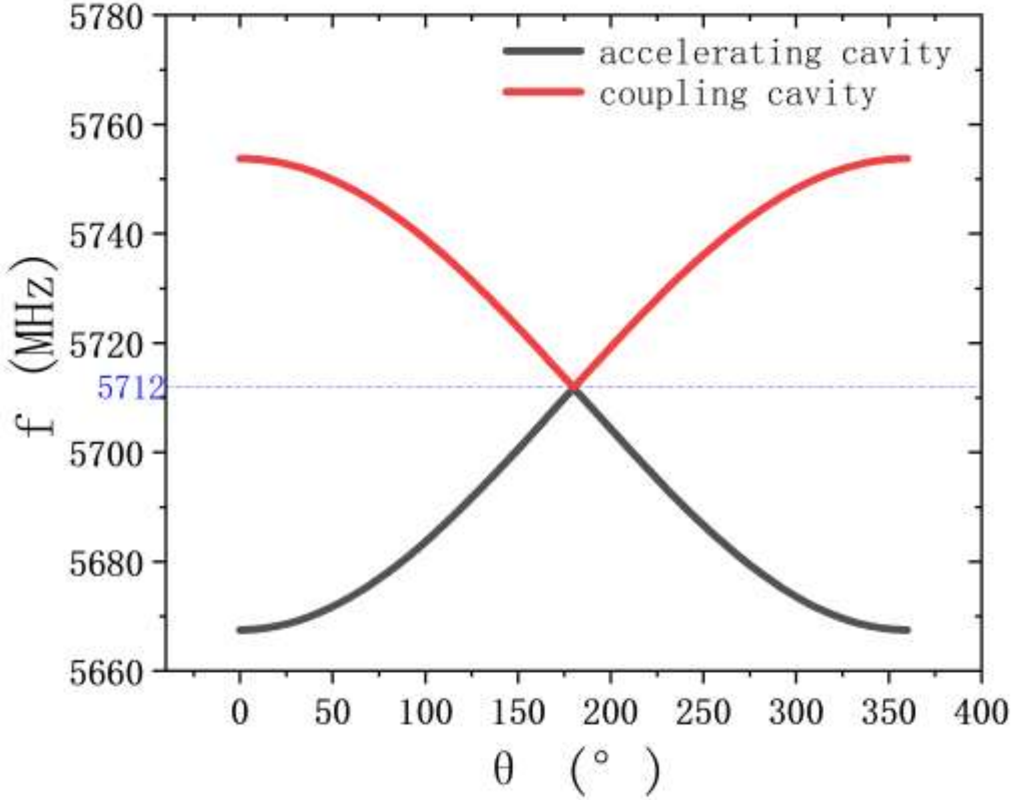
Higher efficiency

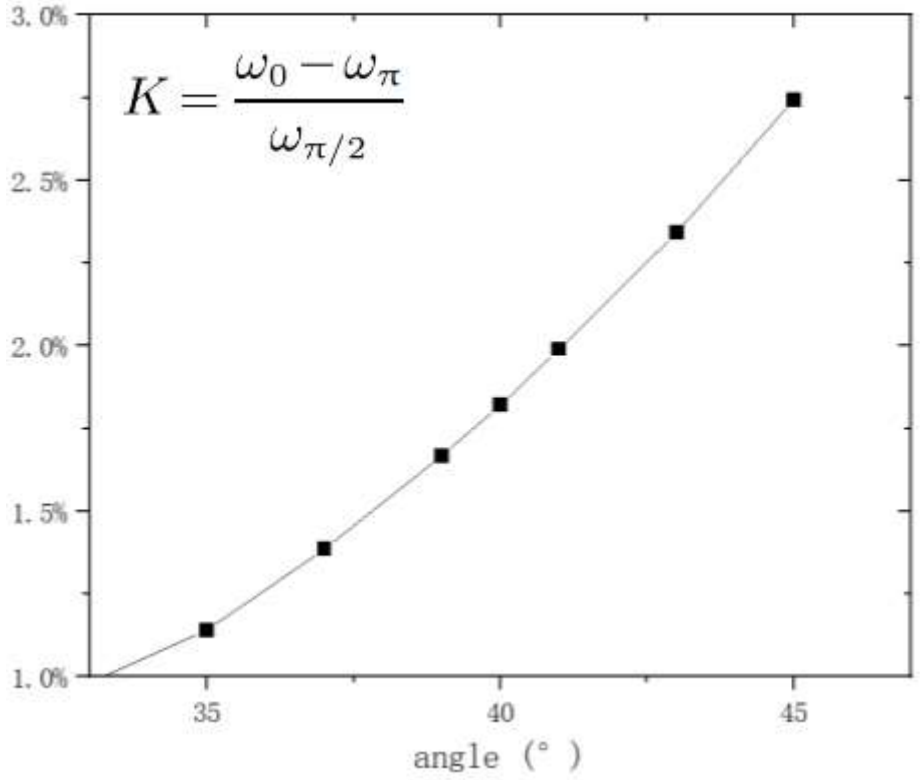
Stability

Tunable

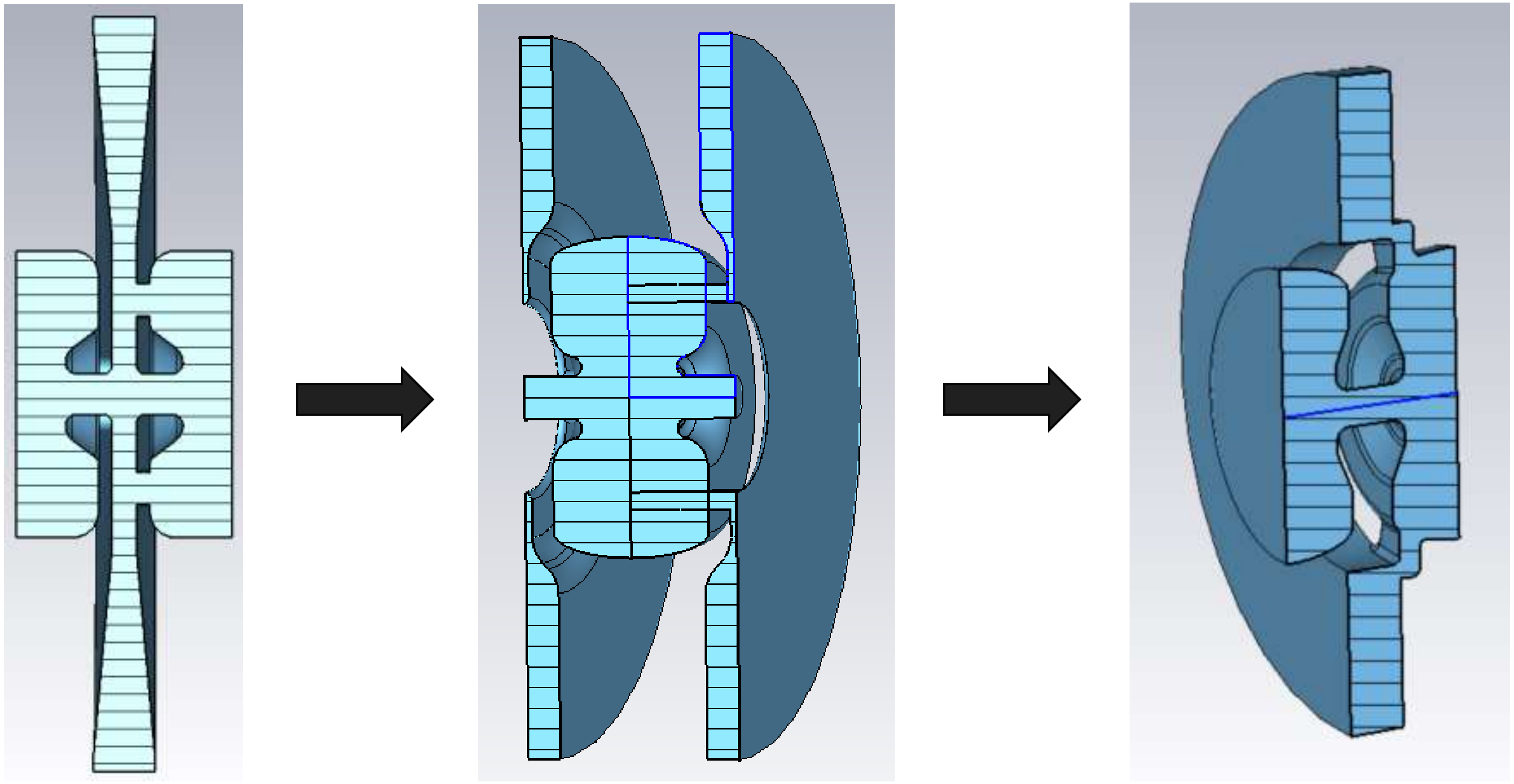
Dispersion curve & Coupling coefficient





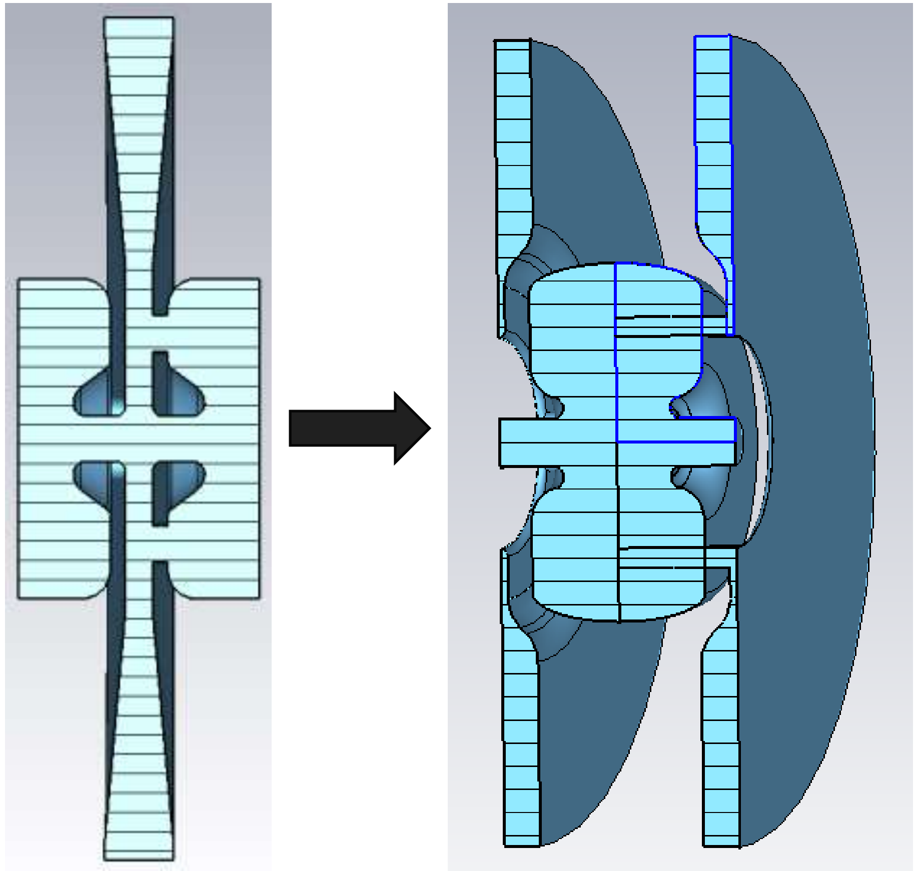


Iteration of coupling cell

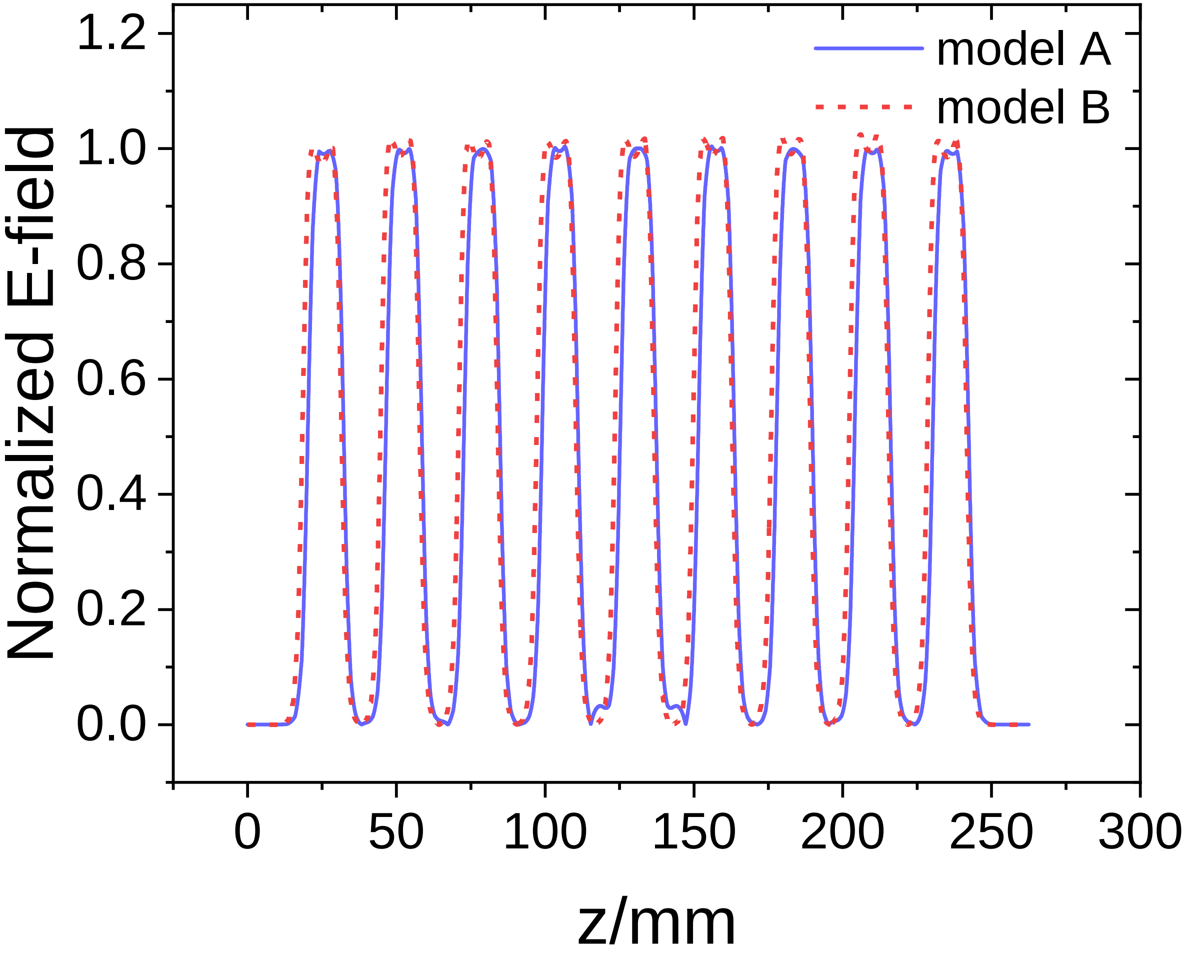


A B C

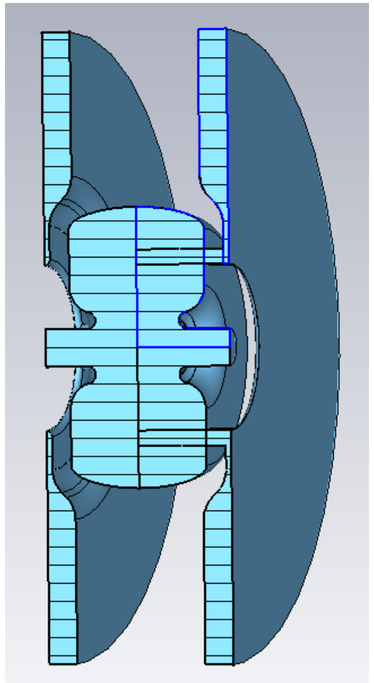
Iteration of coupling cell



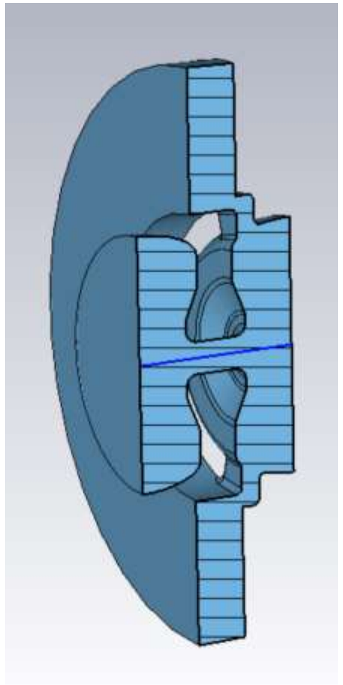
A B



Iteration of coupling cell



B



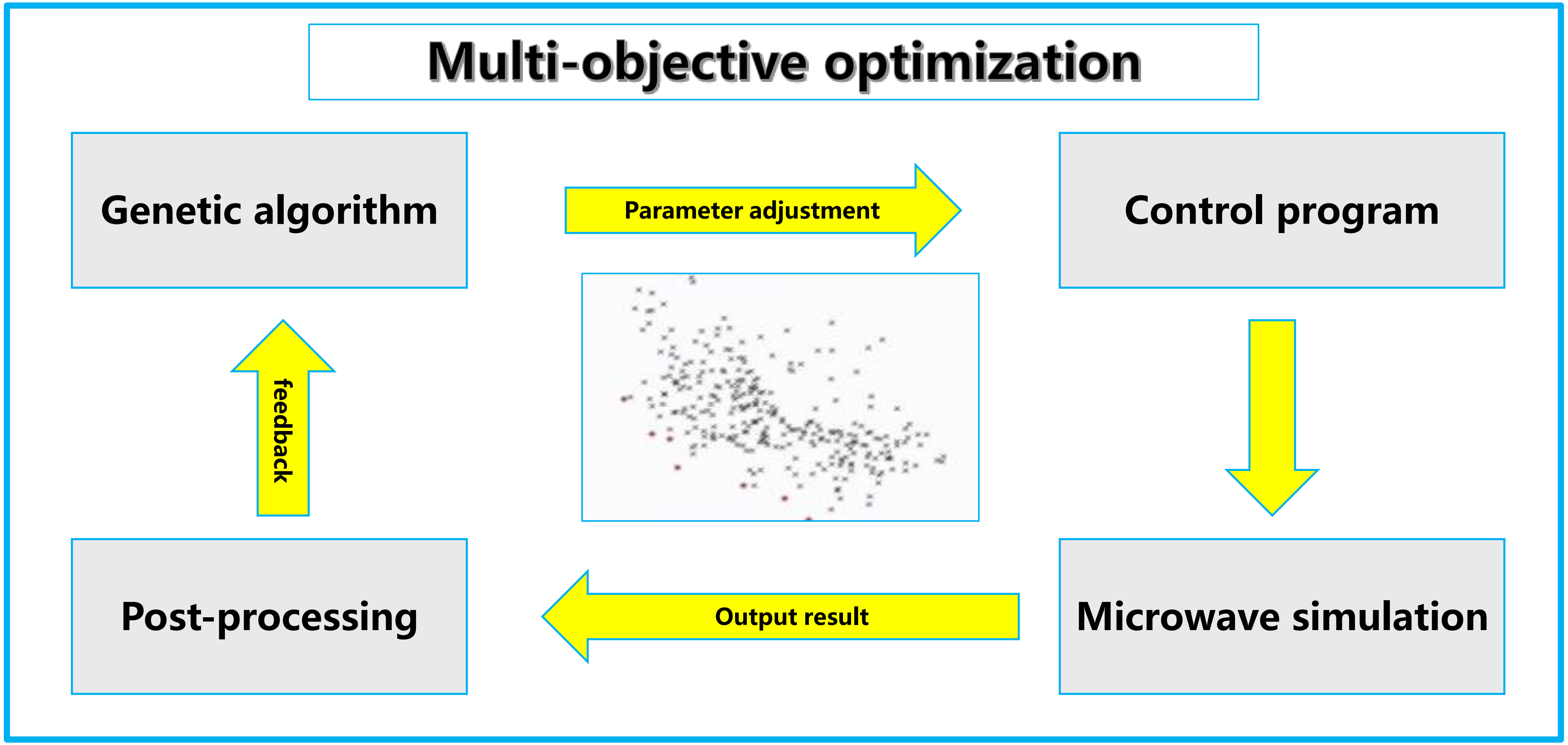
C

The thin middle part of the coupling cavity is completely removed.

The position of the coupling slot was changed.

The length of the accelerating cavity can be designed to be longer, taking into account the thickness of the disc.

Multi-objective optimization



Objectives

Modified Poynting vector

$$S_c = ||\mathrm{Re}(\bar{S})|| + g_c \cdot ||\mathrm{Im}(\bar{S})||$$

The force on metal surface

$$\sigma = \frac{\epsilon_0 (\beta E)^2 - \mu_0 (H)^2}{2} + ZGb\rho = \sigma_L + ZGb\rho$$

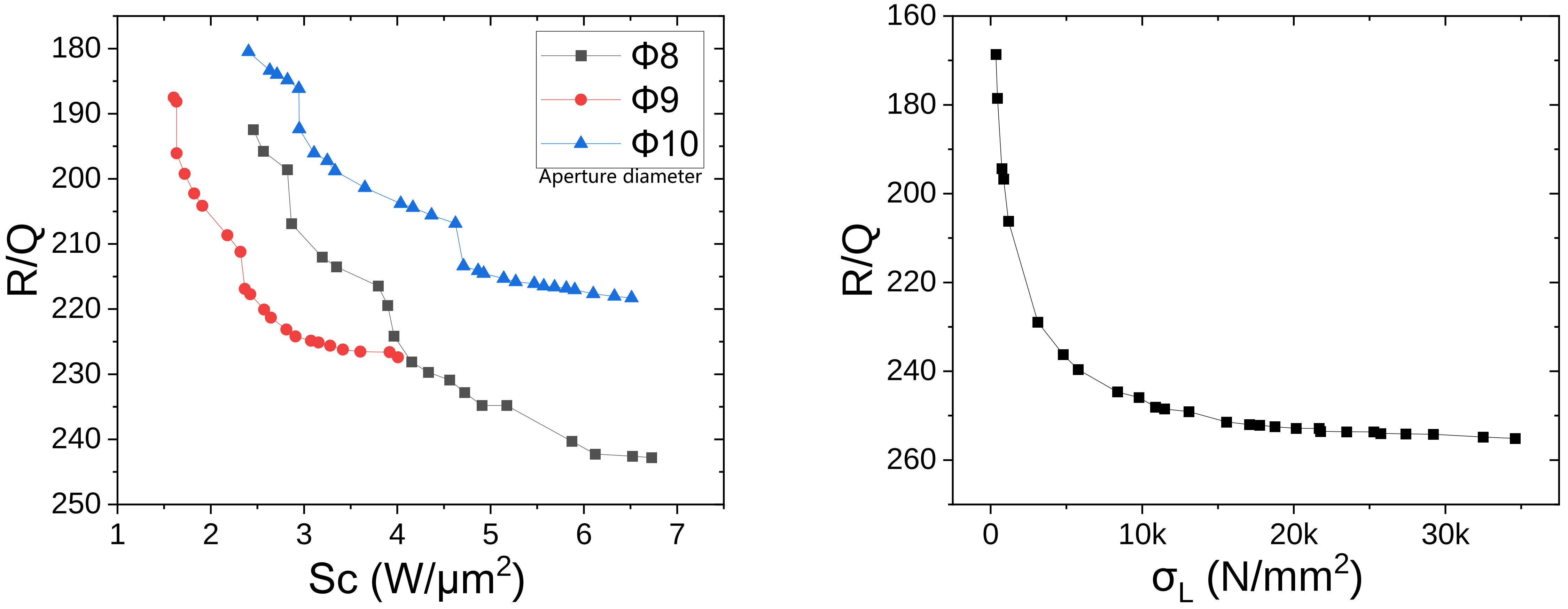
conflicting

$$\frac{R}{Q}$$

The requirements for any rf accelerating structure are, typically, a high shunt impedance, a high accelerating gradient, and low surface fields to avoid rf breakdown and heating effects.

These objectives are normally conflicting.

Pareto front



Cell

There are six parameters, which can be reduced to three.

$$x_2 = x_3$$

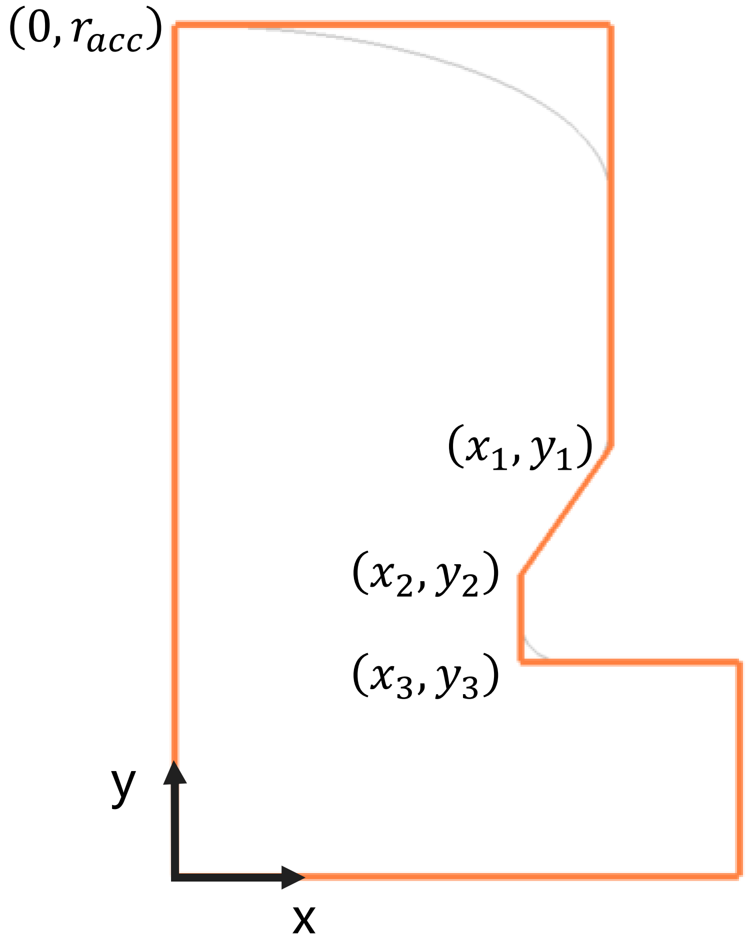
$$y_3 = \frac{\emptyset}{2} : the\ parameter\ related\ to\ aperture$$

$$x_1 : the\ parameter\ related\ to\ disk\ thickness$$

After a long optimization process, we found that the points on the pareto front have the following characteristics:

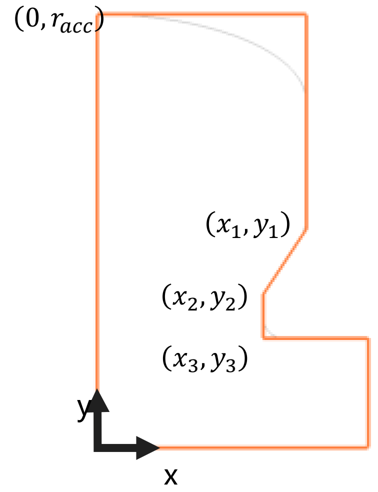
1. x1 is close to the upper limit
2. y3 is close to the lower limit

Limited by the strength of copper, the thickness of the disk can not be too thin.
The smaller the tube aperture is, the stronger the wake field is.
Set these two parameters to our acceptable upper and lower limits.



$$x_1, x_2, y_1, y_2$$

The fillets of the nose

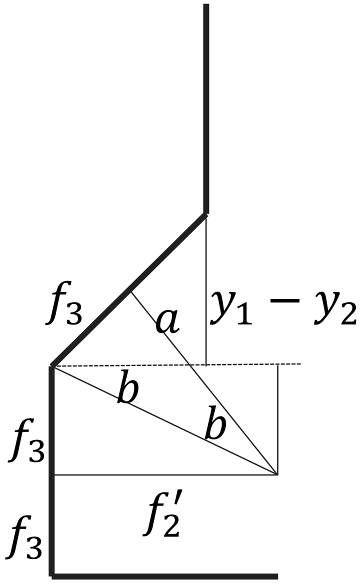


- Add Fillets at these three points.
- The smaller the fillets, the higher the surface field.
- The maximum fillets can be obtained.
- Change with the six parameters.

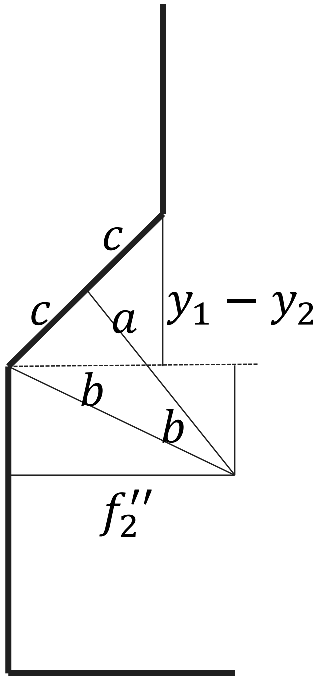
① $\begin{cases} f_3 = \dfrac{y_2 - y_1}{2} \\ a^2 + {f_3}^2 = b^2 \\ \dfrac{a}{f_3} = \dfrac{y_1 - y_2}{x_1 - x_2} \\ f_2' = a + b \end{cases}$

② $\begin{cases} a^2 + c^2 = b^2 \\ \dfrac{a}{c} = \dfrac{y_1 - y_2}{x_1 - x_2} \\ (x_1 - x_2)^2 + (y_1 - y_2)^2 = (2c)^2 \\ f_2'' = a + b \end{cases}$

$$f_2 = min(f_2', f_2'')$$

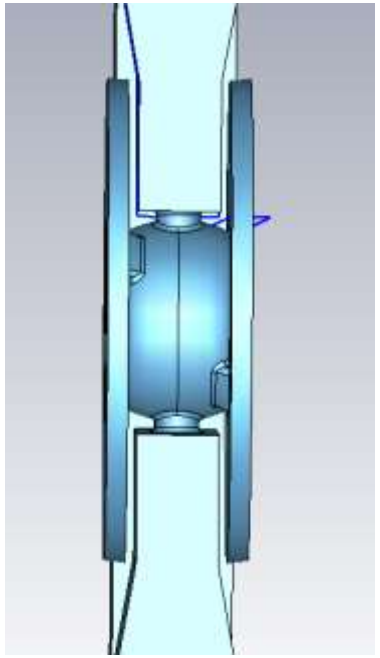


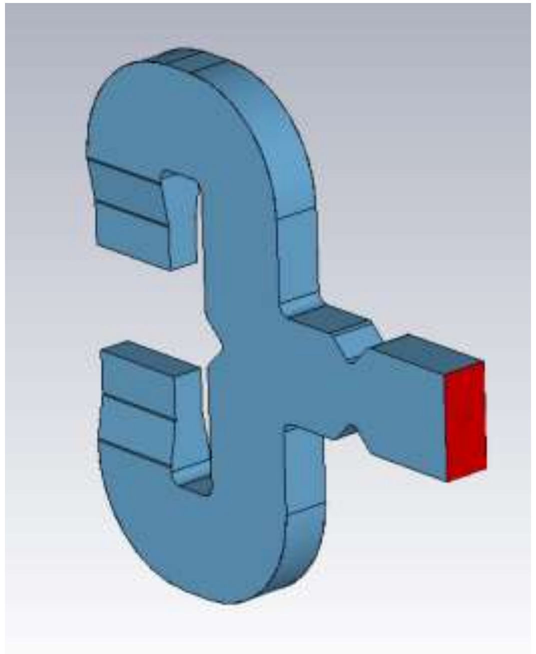
①

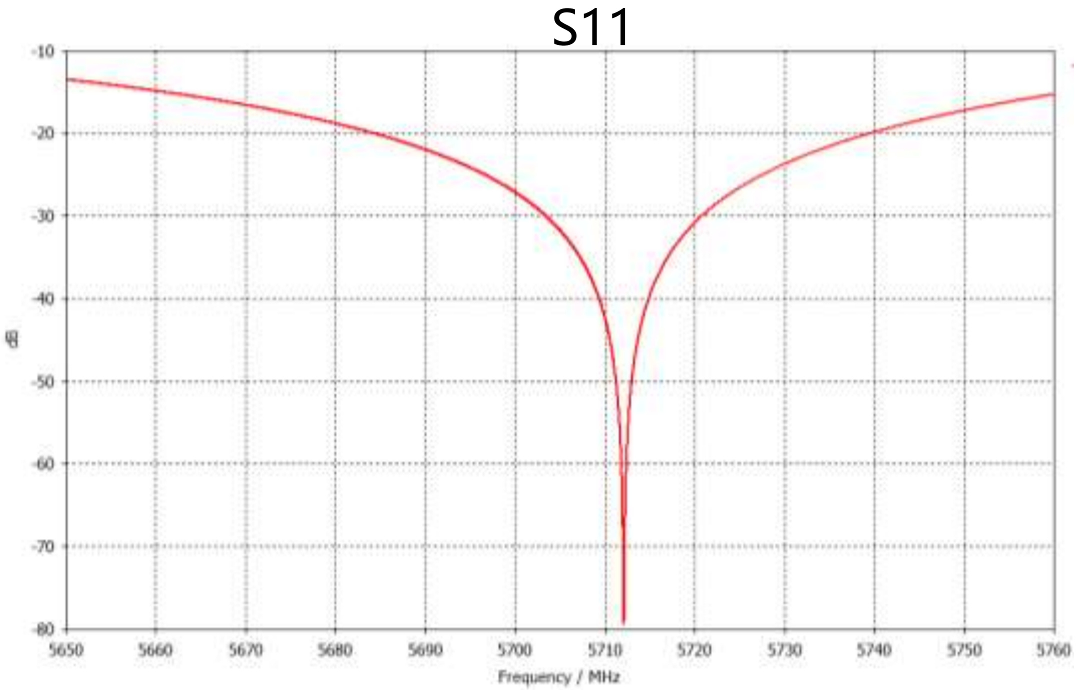


②

Coupler



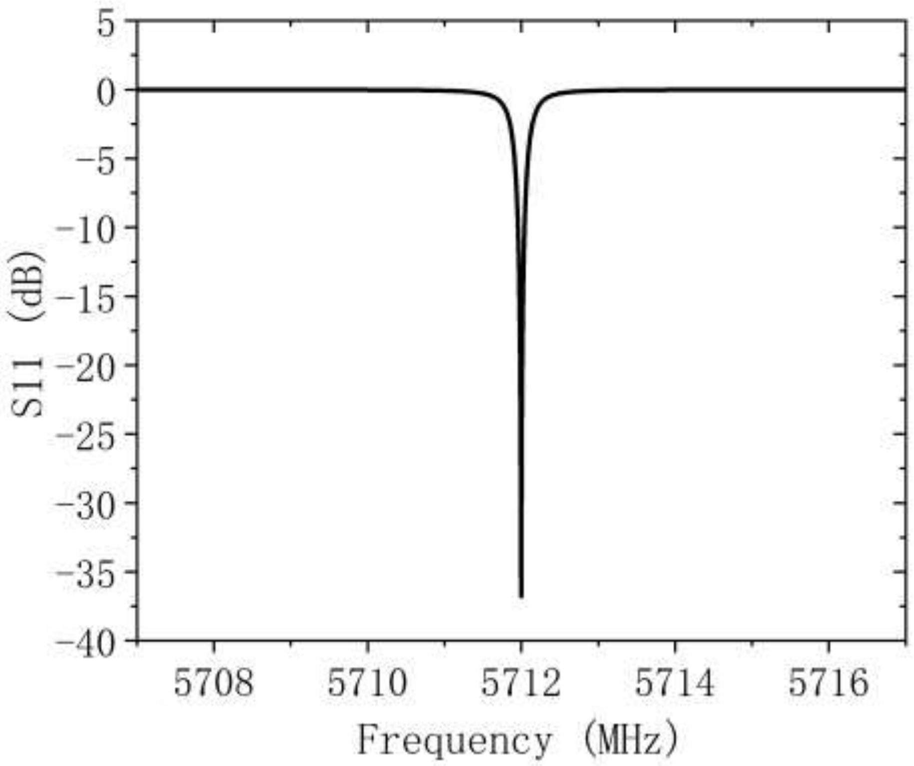


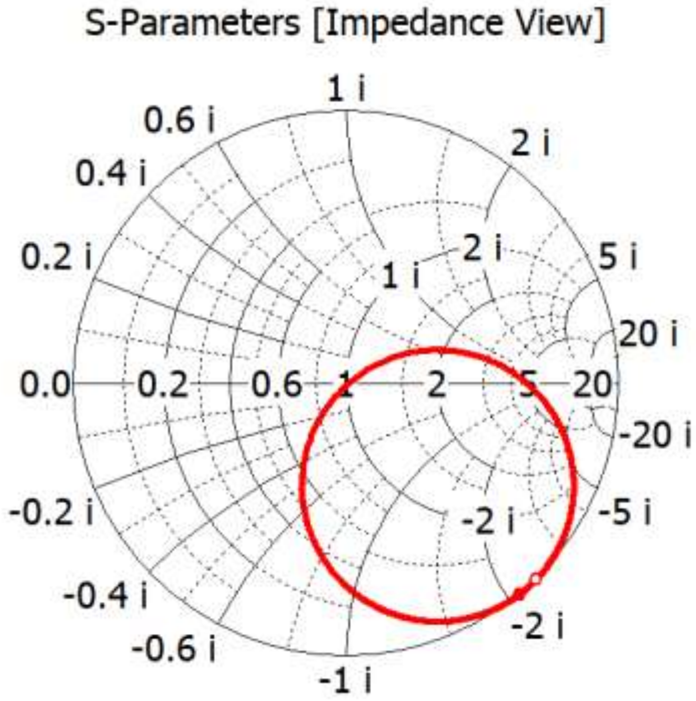


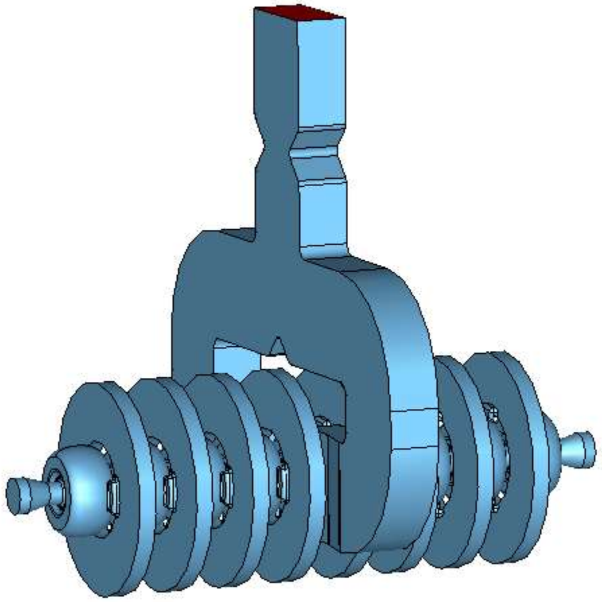
- A doubly-fed coupler is designed to ensure the symmetry of the field.
- It consists of a T-shaped waveguide and two transition segments from standard waveguides to non-standard waveguides.

Field distribution

Then we completed the design and optimization of the 17-cell structure.

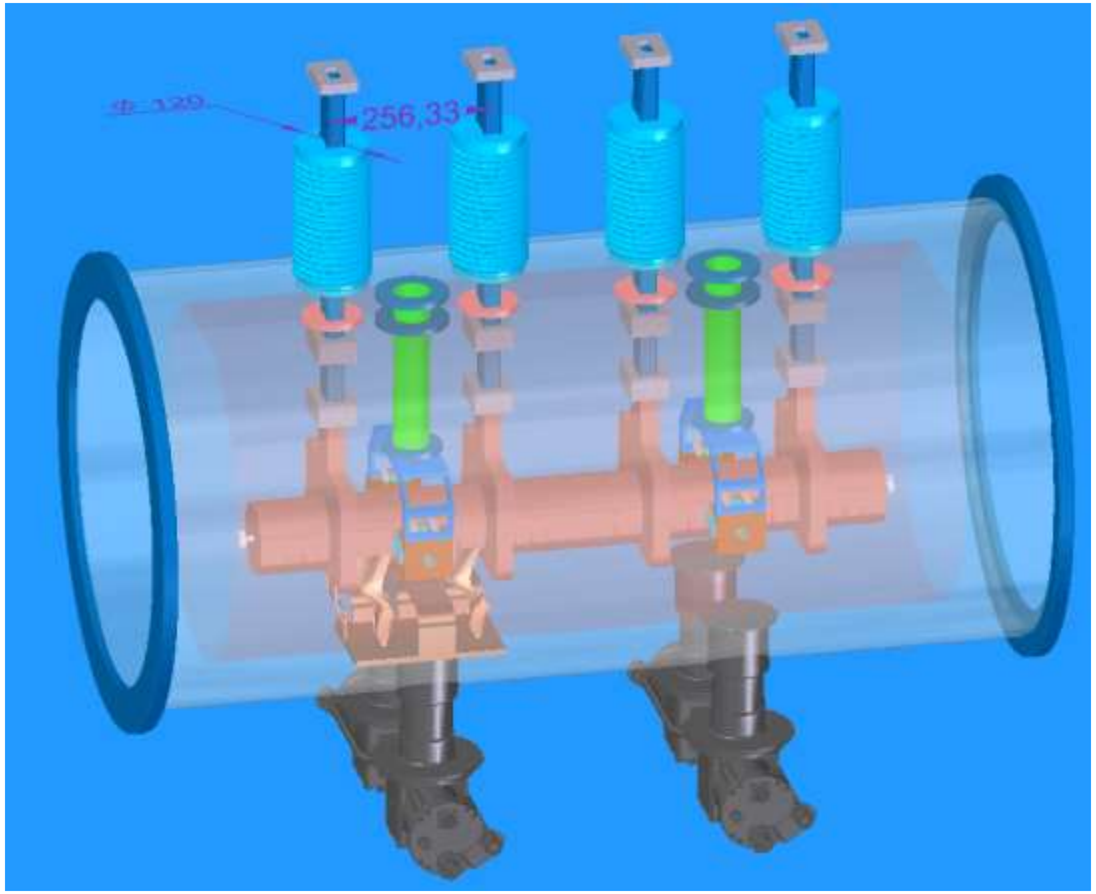


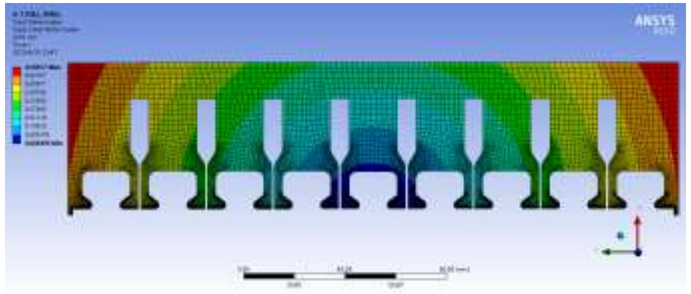


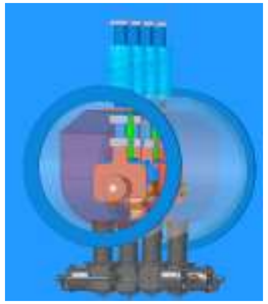


Cryo-module

- Cooler, cold head conduction cooling method
- The structure dynamic thermal load is 80W@40K.
- Static thermal load 20W@40K.
- Plus 50%, total thermal load 150W@40K
- The number of cold head is 4.
- The length and thickness of the cooling belt of the structure are calculated according to 75W@30K







Summary

- A bi-periodic structure is designed, and TM02 is innovatively adopted as the mode in the coupling cavity.
- The shape of the coupling cavity has been modified twice.
- The shape of the accelerating cavity is optimized using multi-objective genetic algorithm.
- Such a structure has the advantages of low sensitivity, good heat dissipation, and tunability.
- The 1m long accelerating structure and the cryo-module is completed.
- In the future we will finish machining and carry out experiments.

Thanks!