X-band novel open cavity for SLED-type rf pulse compressors

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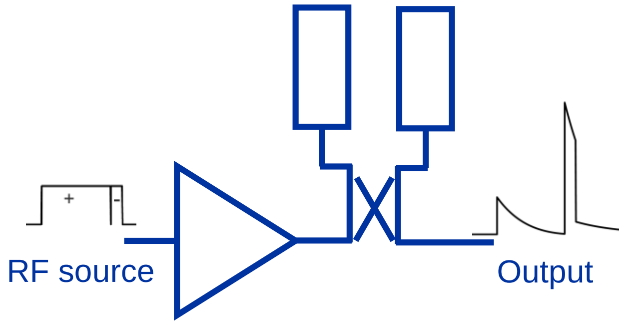
Outline

1. Overview of existing pulse compressors
2. Introduction to bowl-shape open cavity
3. Correction cavity design
4. Storage cavity design
5. Conclusion and future work

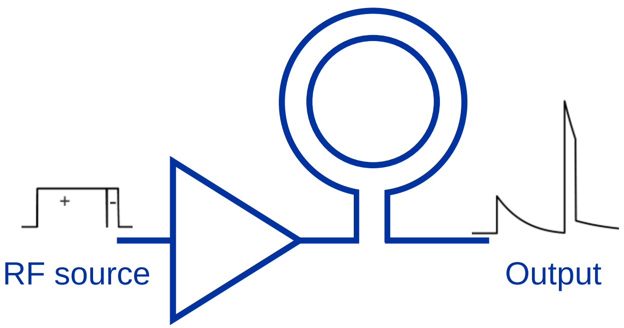
Overview of X-band passive pulse compressors

SLED-type pulse compressors with resonant cavities

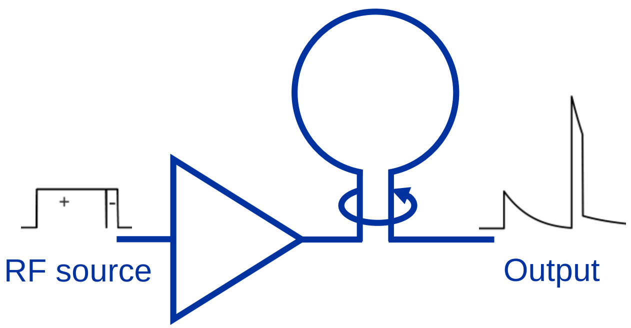
Cylinder cavities



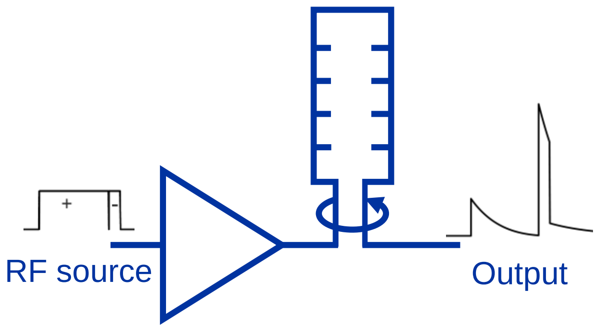
Barrel open cavity



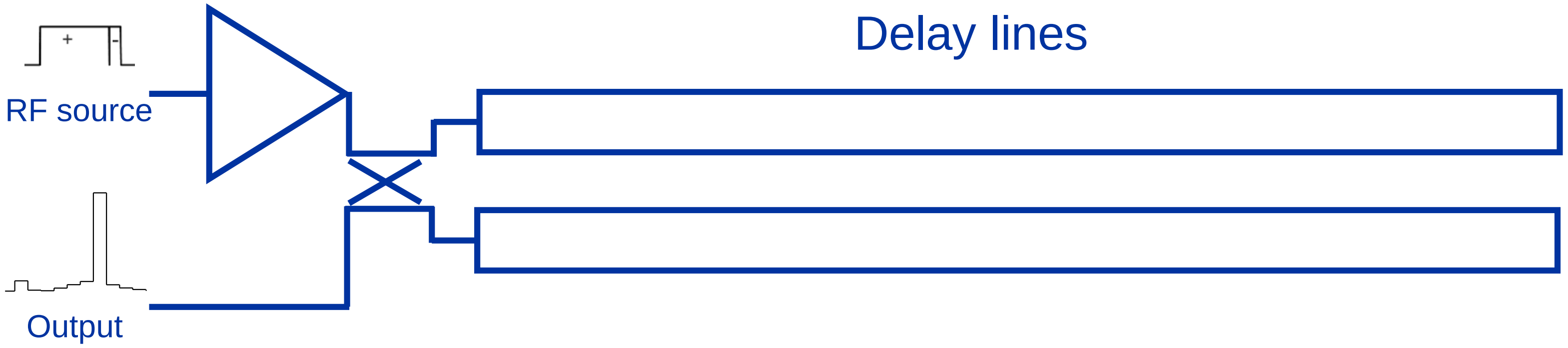
Spherical cavity



Corrugated cavity



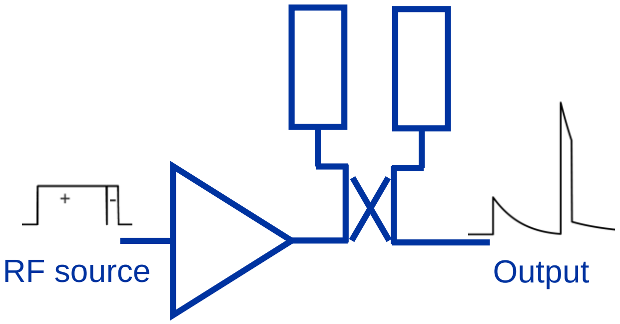
SLEDII type pulse compressor with delay lines



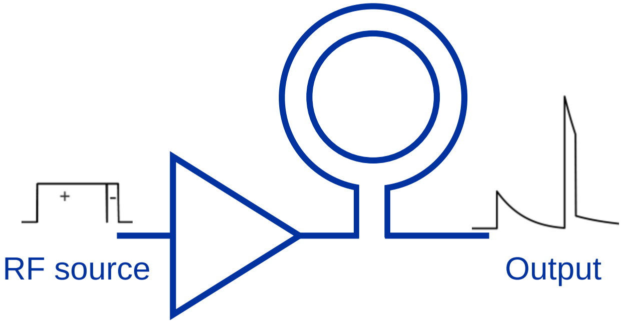
SLEDII type pulse compressors in my eyes

SLED-type pulse compressors with resonant cavities

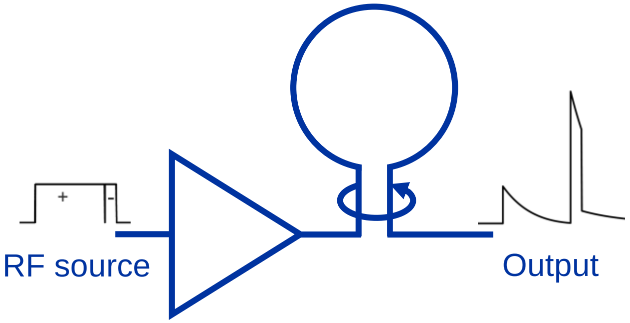
Cylinder cavities



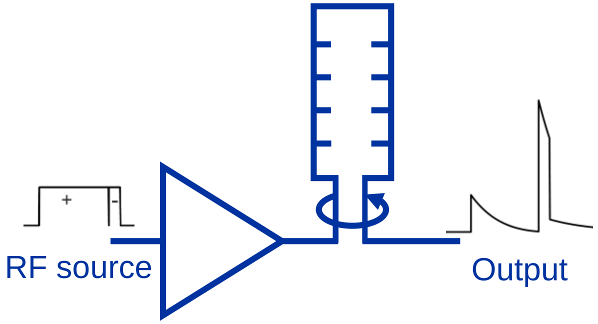
Barrel open cavity



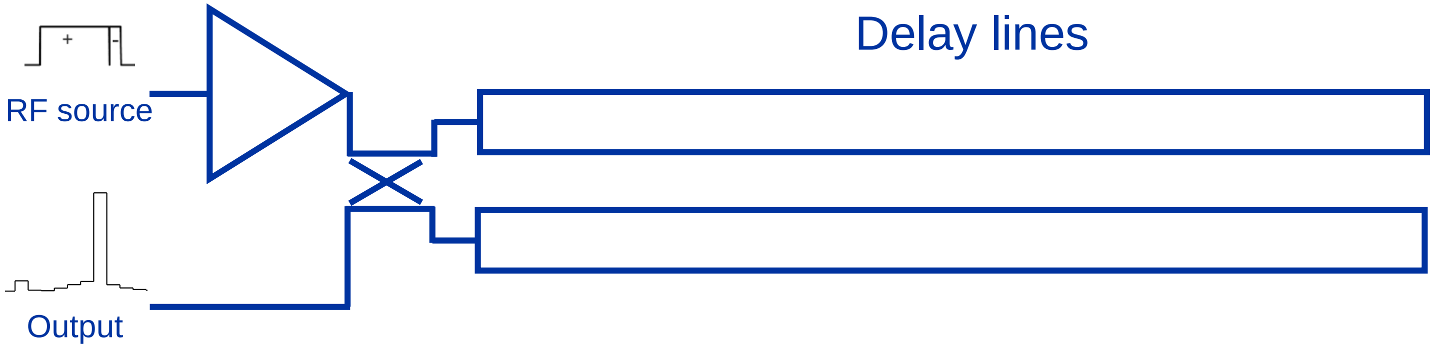
Spherical cavity



Corrugated cavity



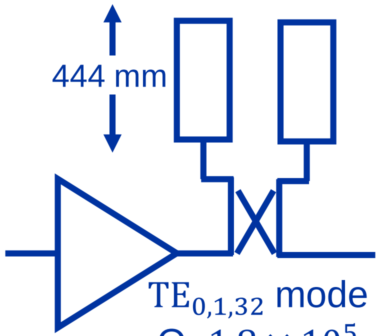
SLEDII type pulse compressor with delay lines



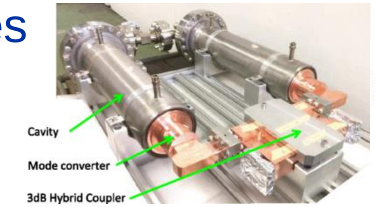
- Flat-top in the compressed pulse
- Very long delay lines for long compressed pulse width

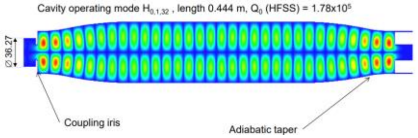
SLED-type pulse compressors in my eyes

Cylinder cavities



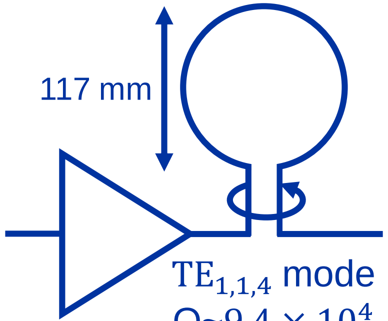
$TE_{0,1,32}$ mode
$Q{\sim}1.8 \times 10^5$



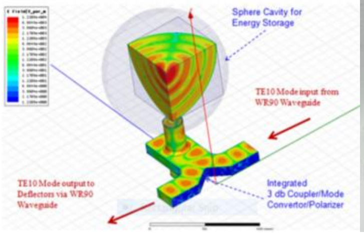


- ✓ Easy fabrication
- ✗ Not compact
  Dipole mode “breakdown”

Spherical cavity

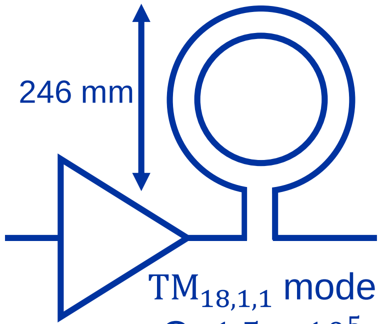


$TE_{1,1,4}$ mode
$Q{\sim}9.4 \times 10^4$

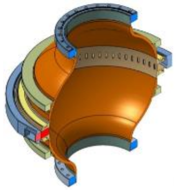


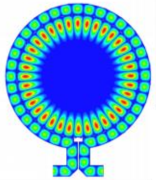
- ✓ Very compact
  Relatively easy fabrication
- ✗ Relatively low Q
  Dense mode spectrum

Barrel open cavity



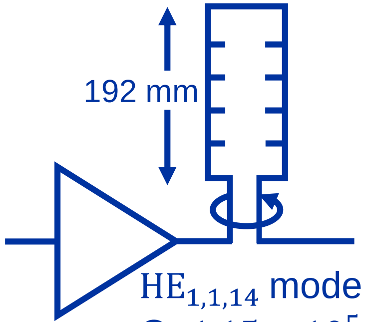
$TM_{18,1,1}$ mode
$Q{\sim}1.5 \times 10^5$



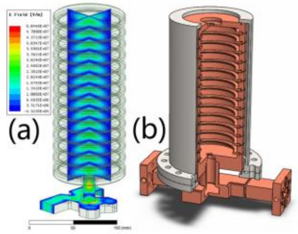


- ✓ Very stable performance
- ✗ Difficult fabrication
  Relatively not compact
  Additional loss in waveguides

Corrugated cavity



$HE_{1,1,14}$ mode
$Q{\sim}1.15 \times 10^5$



- ✓ Compact
- ✗ High magnetic field at coupling iris
  Many pieces for assembling

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Novel bowl-shape open cavity

SLED-type resonant cavity working at $\mathrm{TE}_{1,2,i}$ rotating quasi-spherical mode

index i depends on the radius of the cavity (R_{cav})

High quality factor with compact size

Q_0 ~ 240000 in $\mathrm{TE}_{1,2,13}$ mode with R_{cav}=16.5 cm

Open boundary at the top the cavity

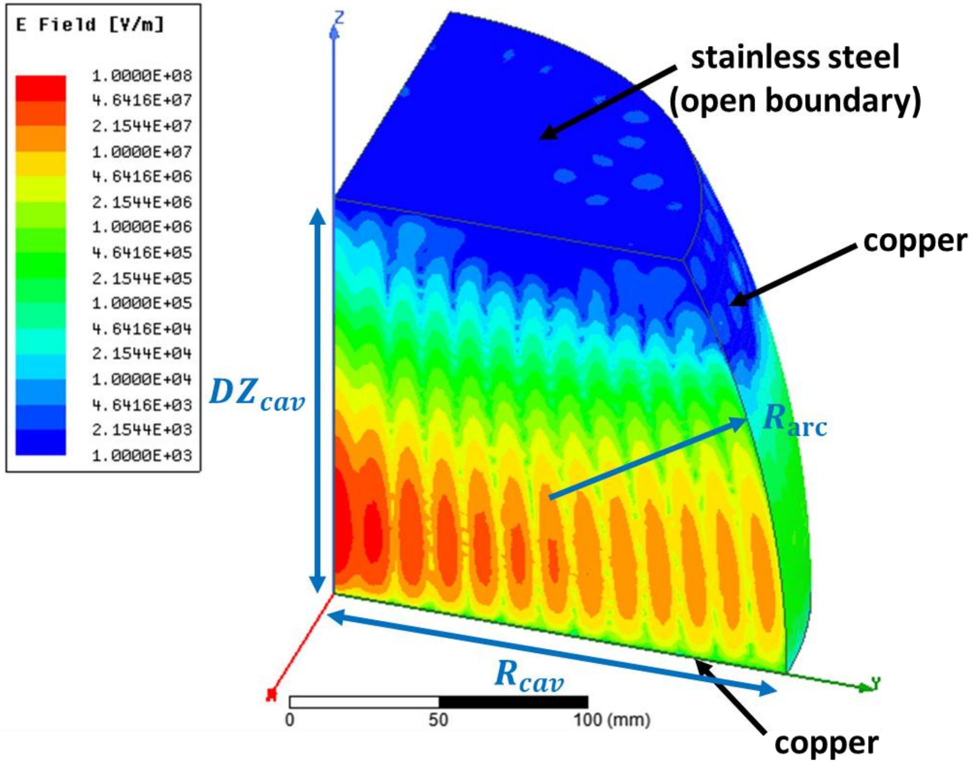
low field at the top area, connect to stainless steel flange (open boundary) and used for vacuum pumping

suppress many parasitic modes

Bowl shape symmetric geometry

machining by lathe with high accuracy and low cost

no brazing needed for the cavity fabrication

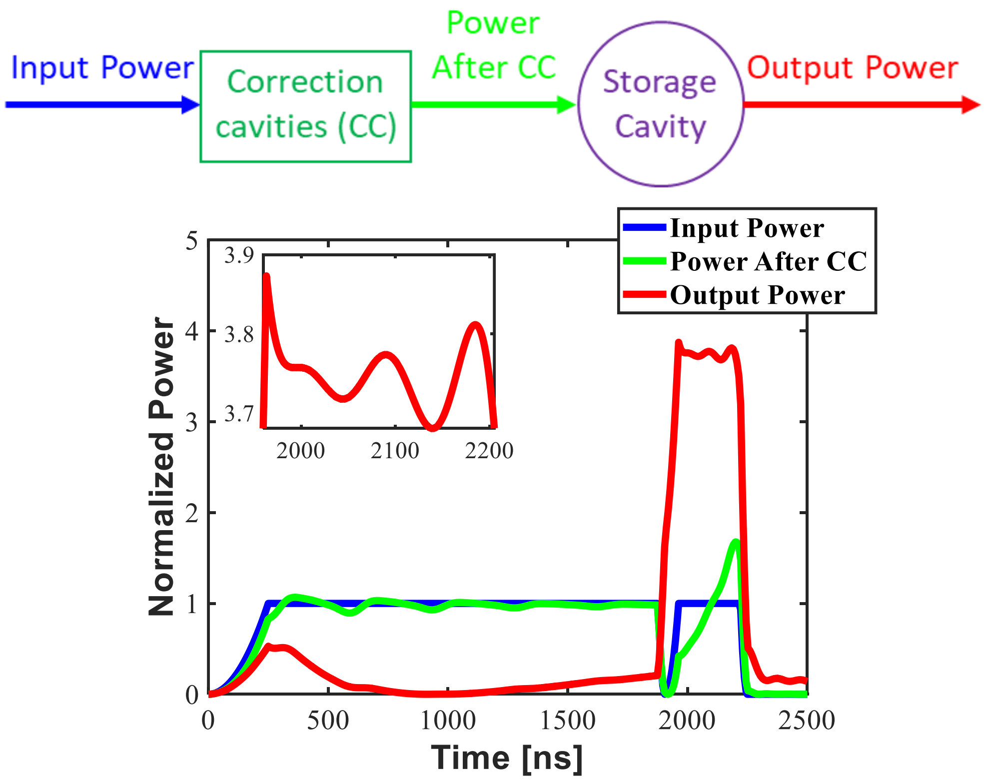


E-field in logarithmic scale

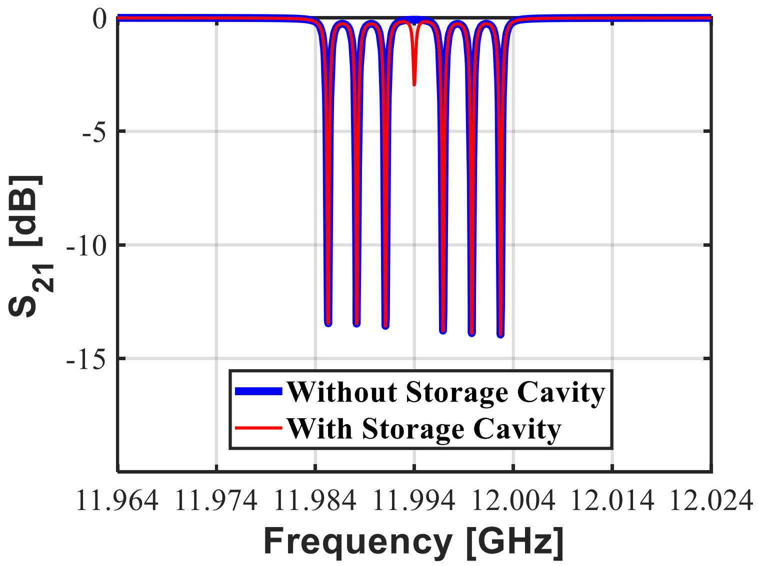
Requirement from CLIC rf pulse compression system

Firstly studied for CLIC rf pulse compression system [1]
Can also be applied to other pulse compression systems

	Correction cavity	Storage cavity
Required Q_0	60000	240000



6 correction cavities + 1 storage cavity



[1] C. Jin, I. Syrachev, CERN CLIC - Note No. 1166, 2020.

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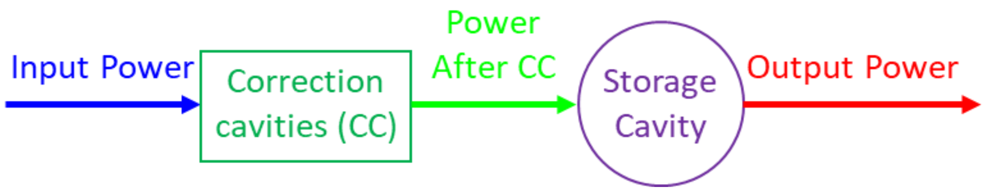
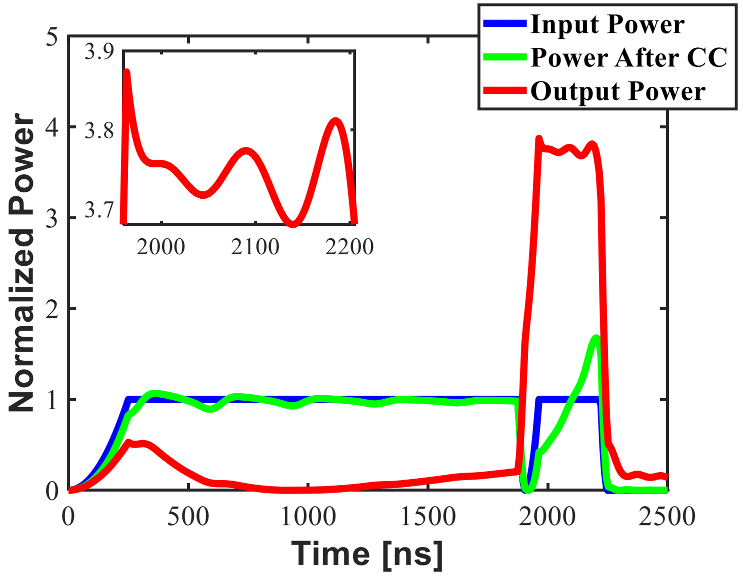
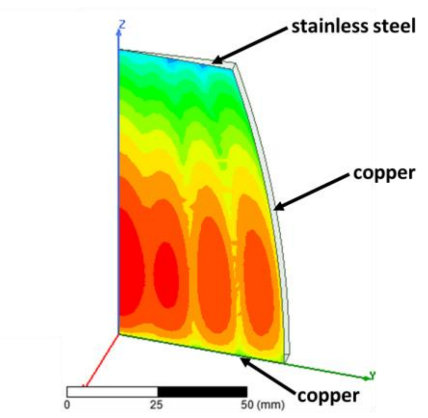


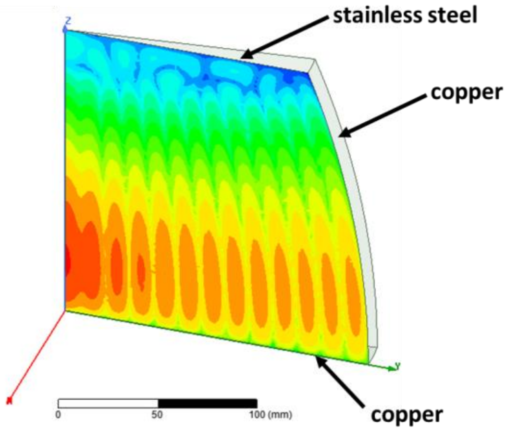


	Correction cavity	Storage cavity
Required Q_0	60000	240000
Mode selection	$TE_{1,2,4}$	$TE_{1,2,13}$
Mode Q_0	~74000	~240000

Correction cavity



Storage cavity



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Mode spectrum of correction cavity

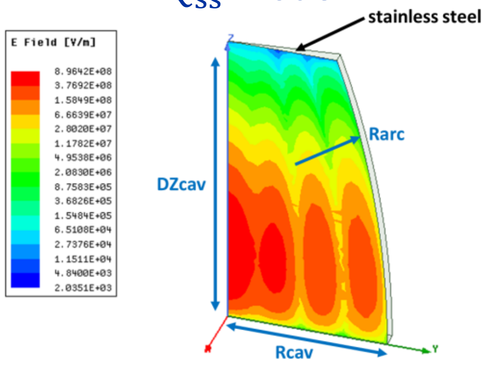
Many parasitic modes in high Q cavity

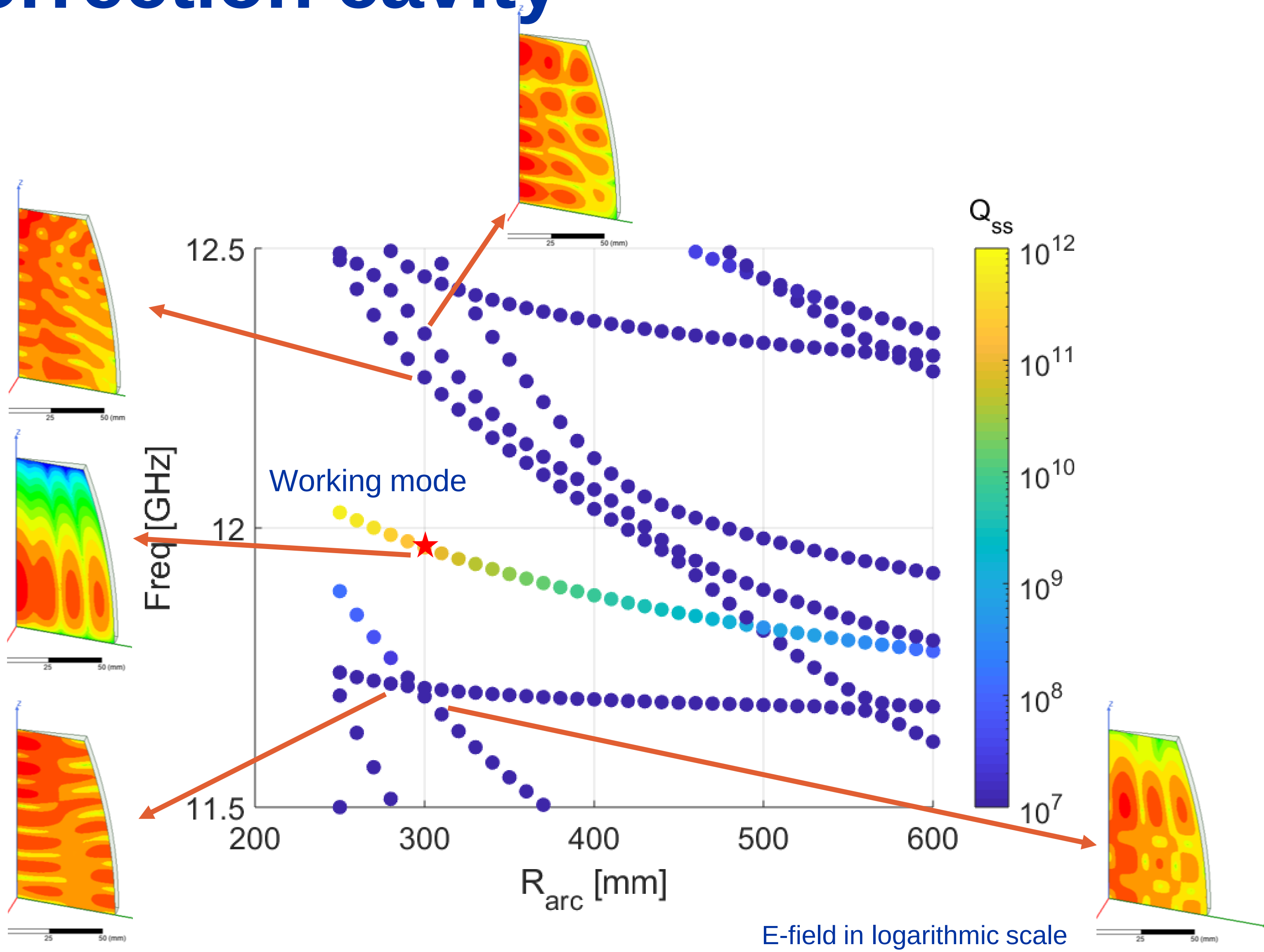
Chose R_{arc}=300 mm

large frequency (>200 MHz) separation from parasitic modes

high Q for working mode

Q_{ss} model





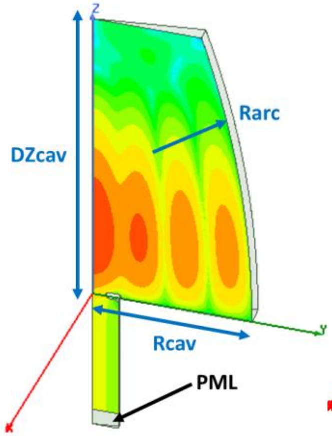
E-field in logarithmic scale

Coupling iris design for correction cavity

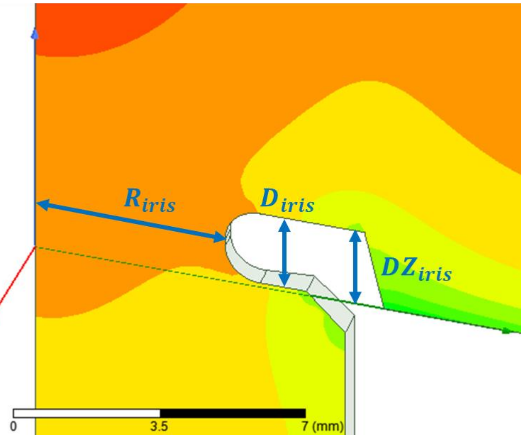
Optimize R_{iris} and DZ_{iris}

get required $\mathrm{Q}_{\mathrm{ext}}$ and minimize the loss in stainless steel
ensure the open boundary

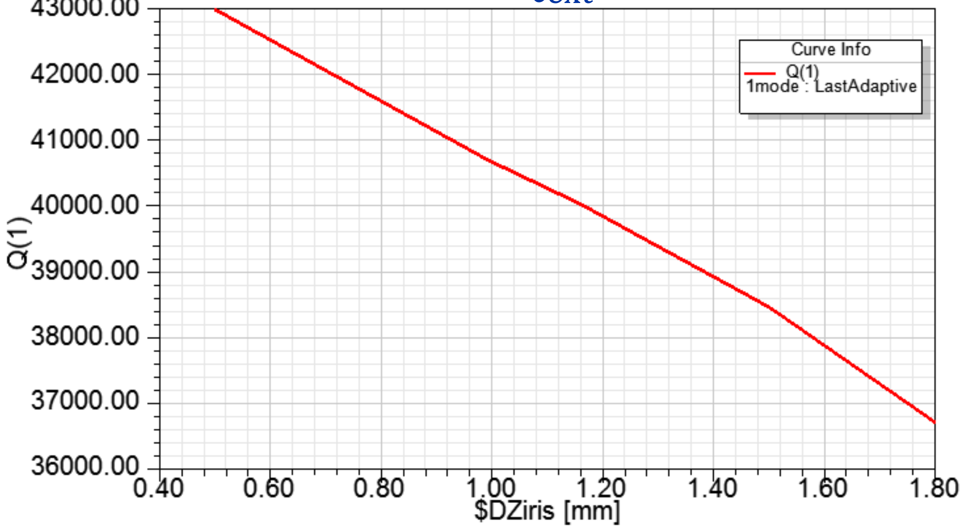
$\mathrm{Q}_{\mathrm{ext}}$ model



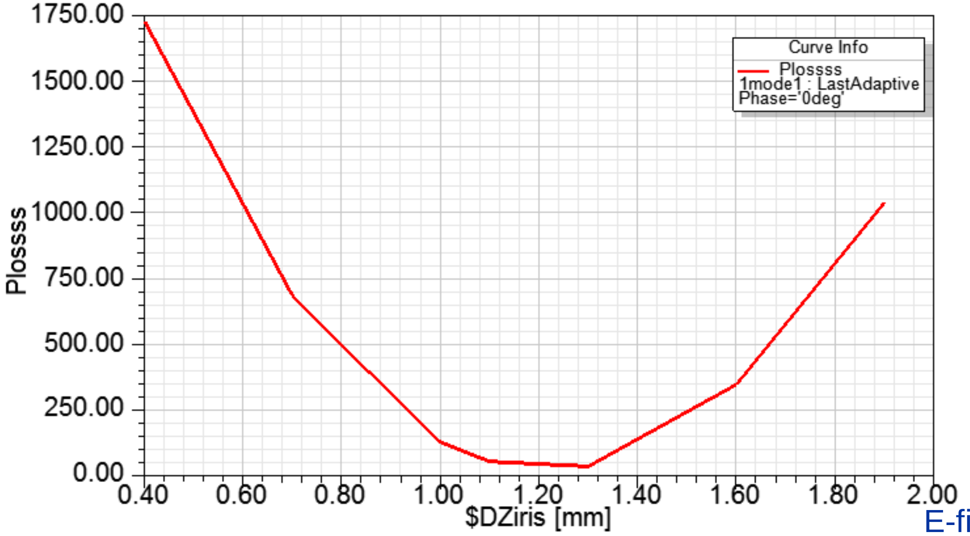
Coupling iris model



$\mathrm{Q}_{\mathrm{ext}}$



Power loss in stainless steel

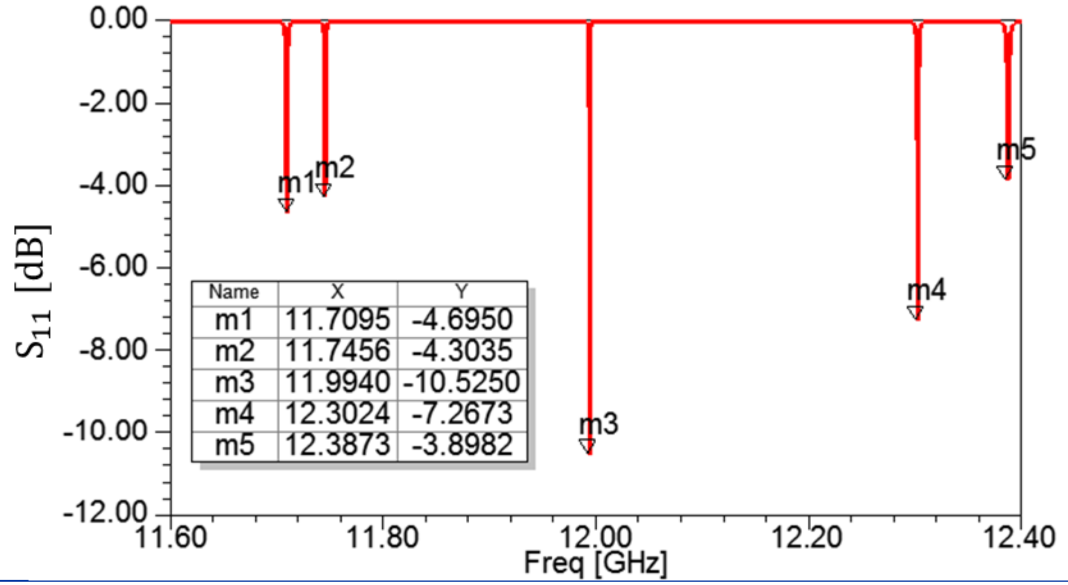


E-field in logarithmic scale

Correction cavity design

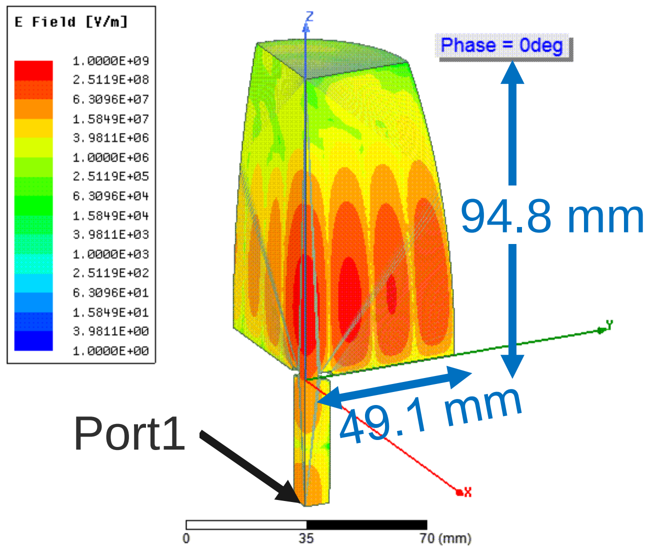
	Frequency [GHz]	Q_0
Working mode	11.9940	74659
Parasitic mode1	11.7456	16063
Parasitic mode2	12.3024	14700

S_{11} sweep of $\mathrm{TE}_{1,2,4}$

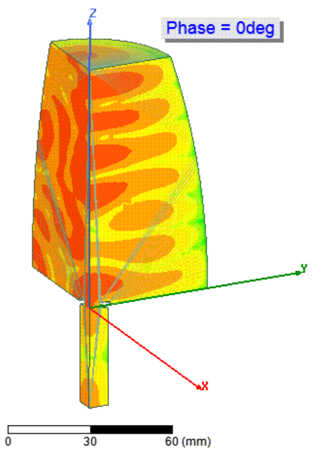


Name	X	Y
m1	11.7095	-4.6950
m2	11.7456	-4.3035
m3	11.9940	-10.5250
m4	12.3024	-7.2673
m5	12.3873	-3.8982

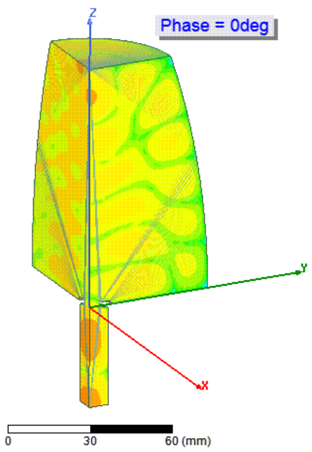
$\mathrm{TE}_{1,2,4}$ rotating mode



Parasitic mode1



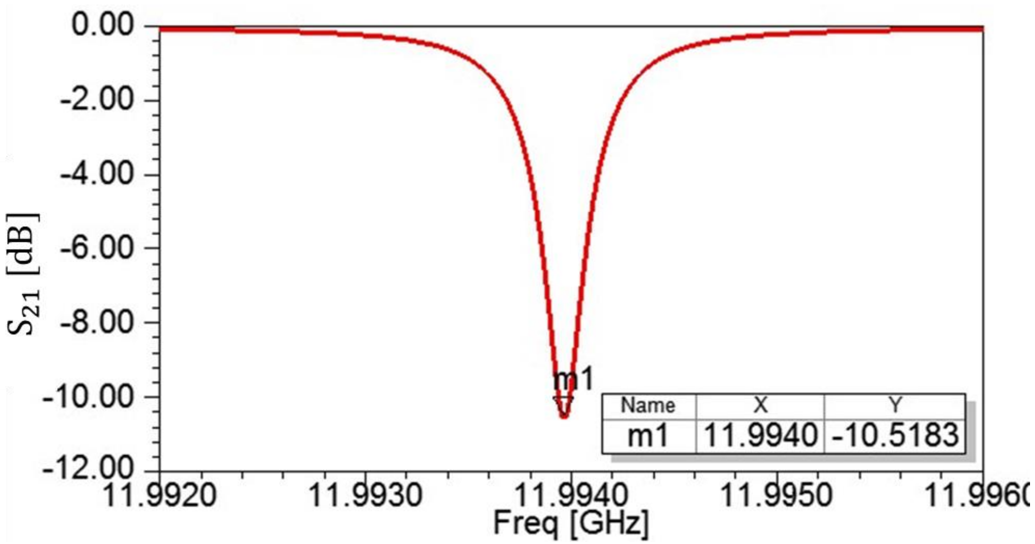
Parasitic mode2

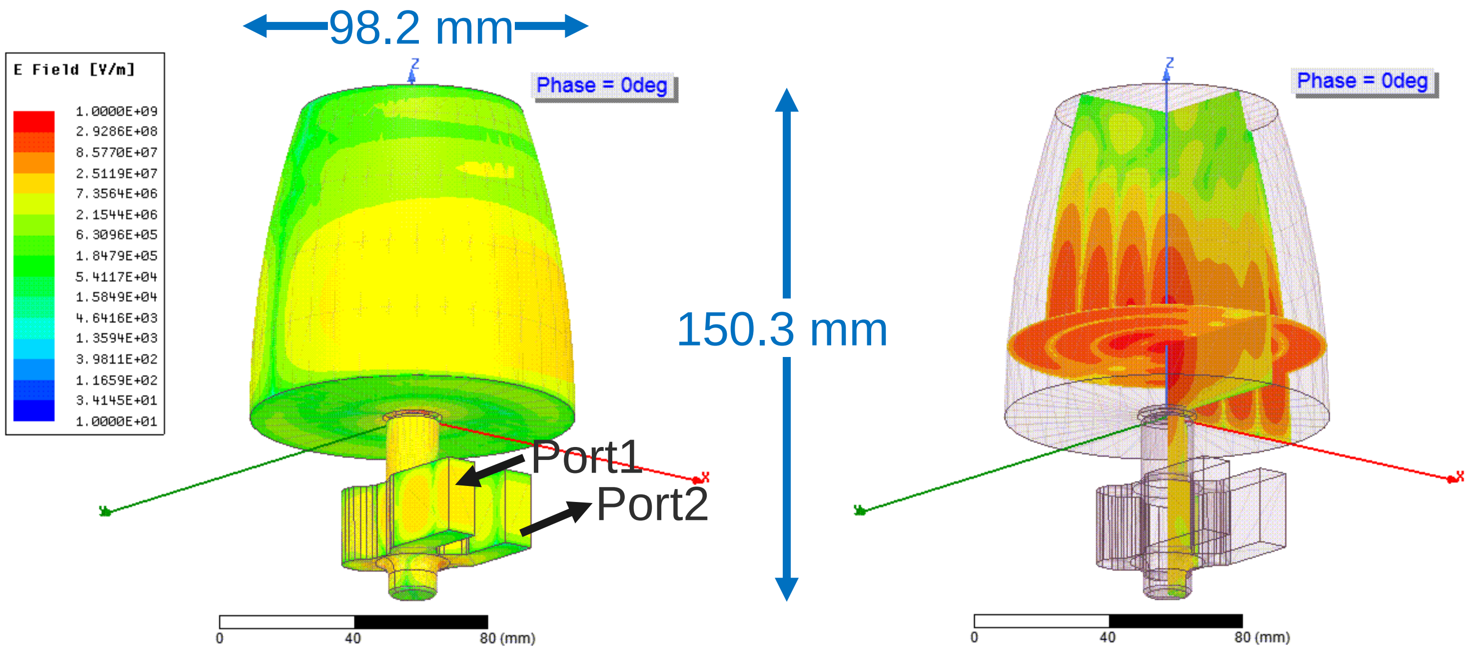


Correction cavity with E-rotator

E-rotator converts $\mathrm{TE}_{1,0}$ rectangular waveguide mode to $\mathrm{TE}_{1,1}$ circular waveguide mode and excites $\mathrm{TE}_{1,2,4}$ rotating mode in the open cavity

S_{21} sweep of the correction cavity





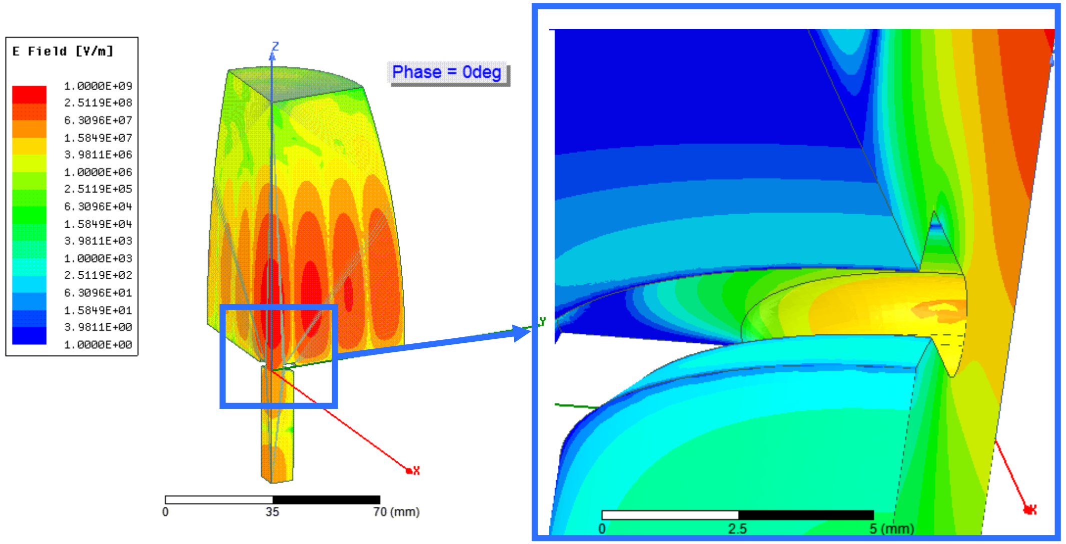
E-field in logarithmic scale

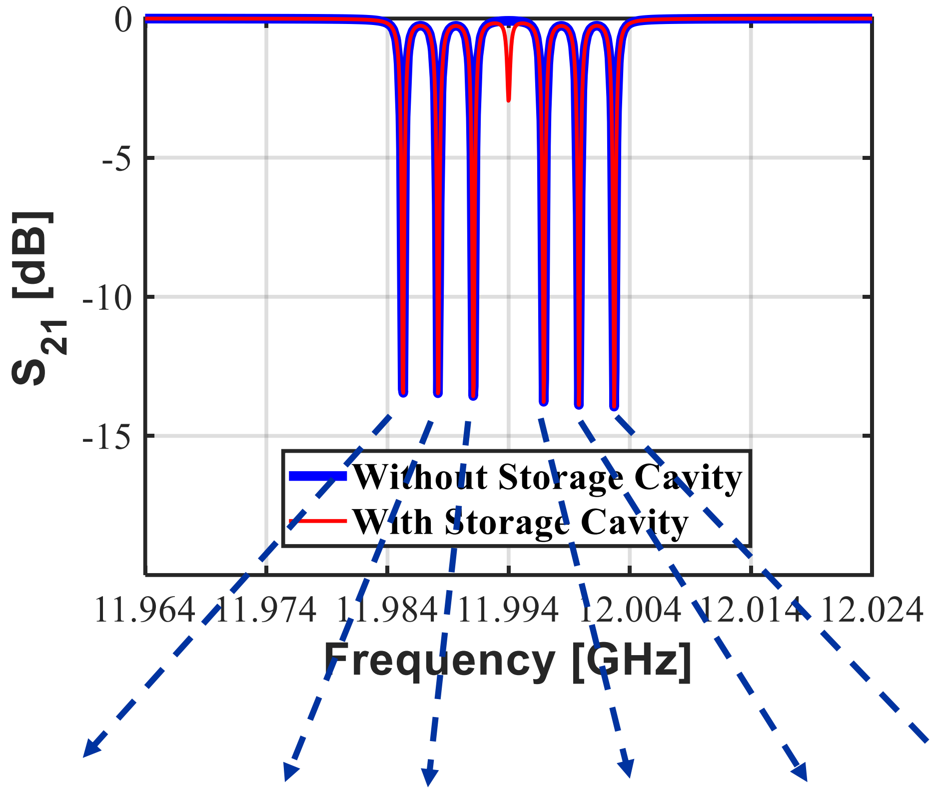
Limitation study

Coupling iris could be a critical area with high field

Check the rf parameters at 50 MW, 2.25 μs input power in steady-state

Results shows low field due to detuning





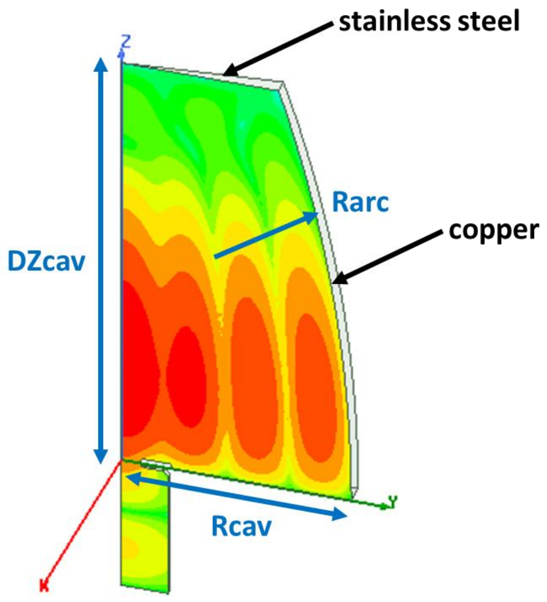
Frequency [GHz]	11.985	11.988	11.991	11.997	12.000	12.003
Max E [MV/m]	11.1	10.4	8.26	17.8	15.0	14.1
Max H [kA/m]	82.43	78.01	65.89	125.8	107.0	101.4
S_c [MW/mm^2]	0.041	0.037	0.027	0.095	0.069	0.062

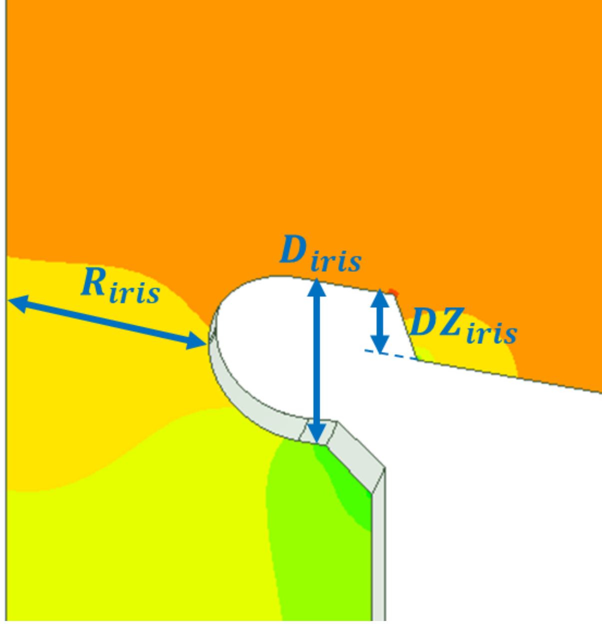
Tolerance study

Key dimensions are checked for tolerance study

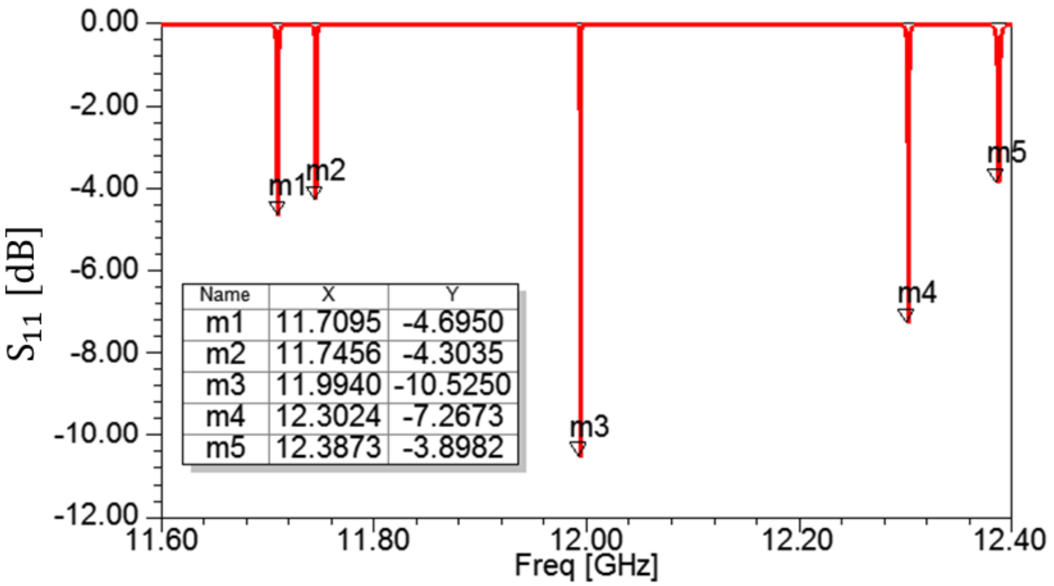
Frequency shifts of work mode and parasitic mode are relatively small (0.01 mm R_{cav} → 2.38 MHz)

Coupling factor and more dimension study will be carried out in future





S_{11} sweep of $\mathrm{TE}_{1,2,4}$



Dimension	$\Delta f/\Delta x$ [MHz/mm]		
	Work mode	Parasitic mode1	Parasitic mode2
R_{cav}	-238.45	-50.64	-119.48
DZ_{cav}	<±1.00	-96.90	-58.06
R_{arc}	-1.39	<±1.00	-3.43
R_{iris}	-3.38	-2.82	-3.50

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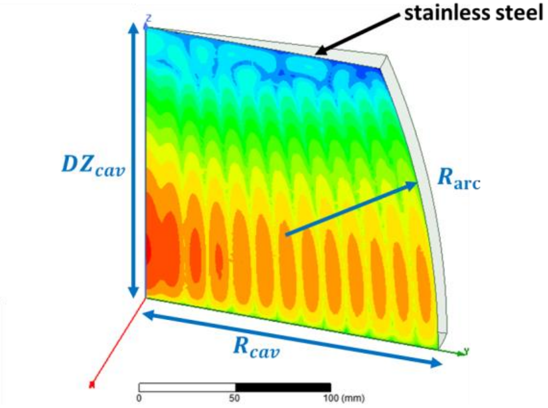
Mode spectrum of storage cavity

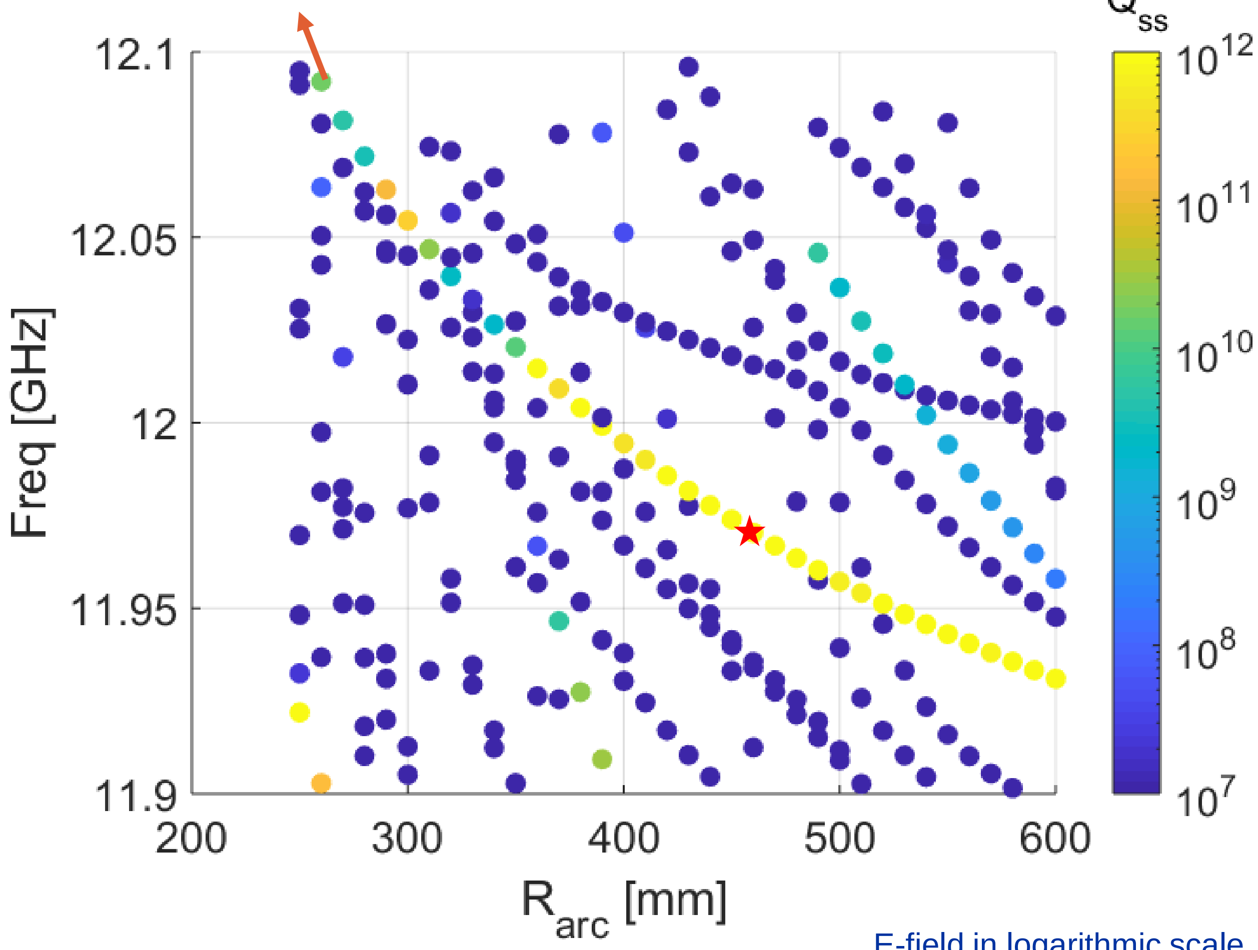
Work at $TE_{1,2,13}$ mode

Chose R_{arc}=460 mm

- denser spectrum than correction cavity
- relatively large frequency (~40 MHz) separation from parasitic modes
- high Q for working mode

Q_{ss} model



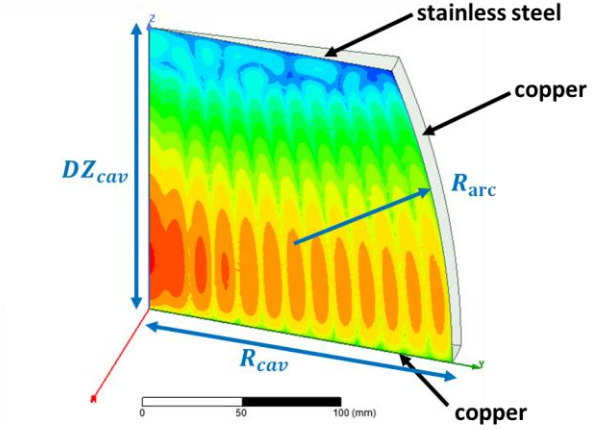


E-field in logarithmic scale

Storage cavity design

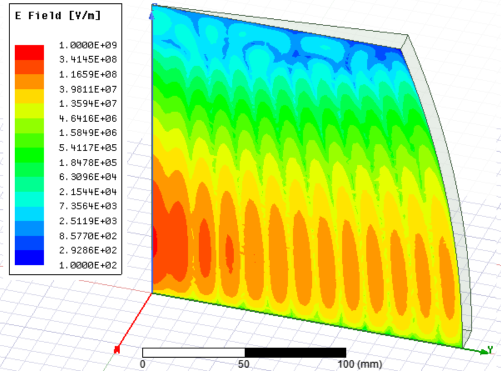
Work at $TE_{1,2,13}$ mode
DZ_{cav}=170 mm, R_{arc}=460 mm

Q_0 model

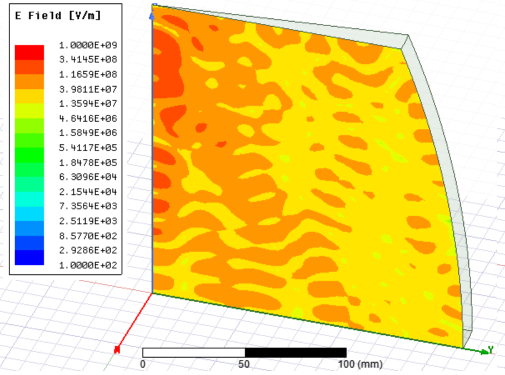


	Work mode	Parasitic Mode1	Parasitic Mode2	Parasitic Mode3	Parasitic Mode4
Frequency [GHz]	12.0000	11.9636	11.9651	12.0454	12.0556
Q_0	249658	30716.8	47116.8	62083.3	120104

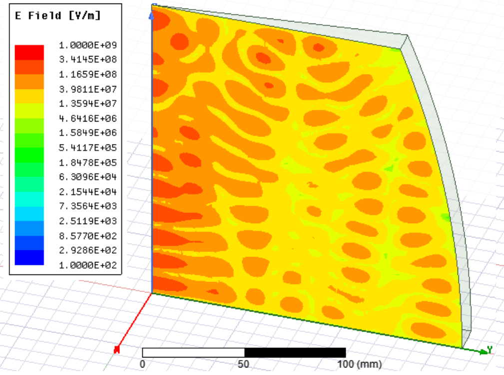
$TE_{1,2,13}$



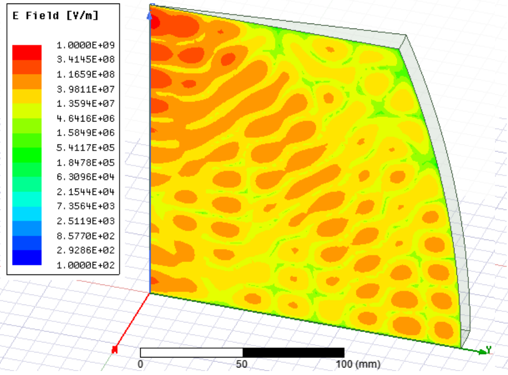
PM1



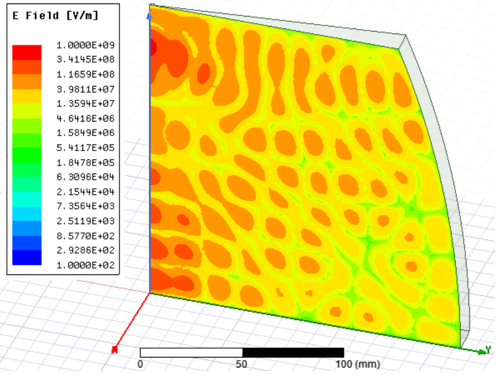
PM2



PM3



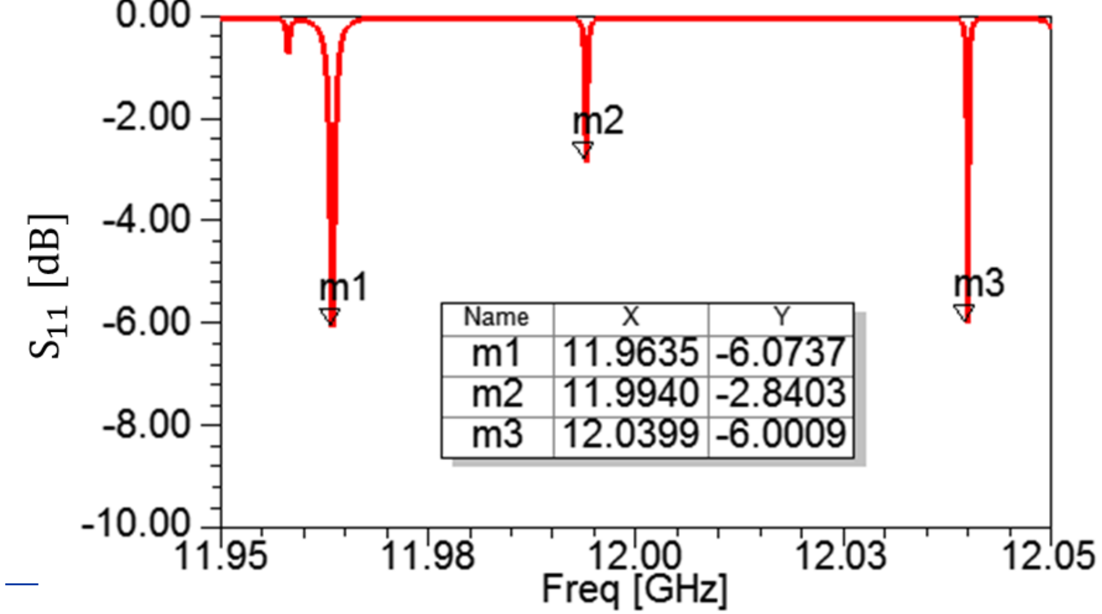
PM4



Storage cavity design

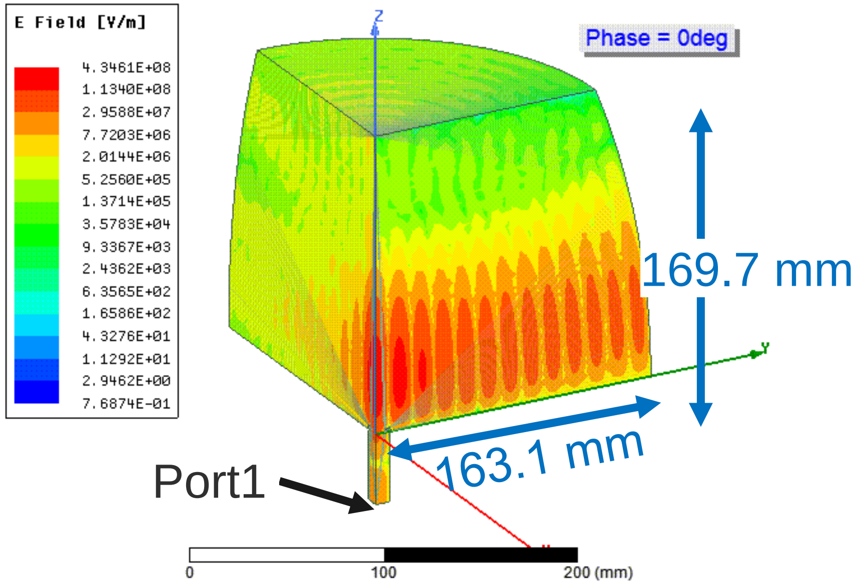
	Frequency [GHz]	Q_0
Working mode	11.9940	244542
Parasitic mode1	11.9635	51431
Parasitic mode2	12.0399	61012

S_{11} sweep of $\mathrm{TE}_{1,2,13}$

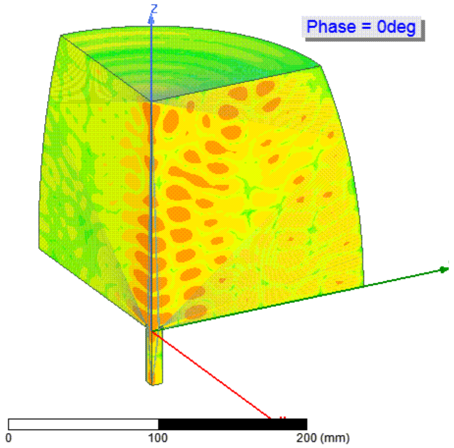


Name	X	Y
m1	11.9635	-6.0737
m2	11.9940	-2.8403
m3	12.0399	-6.0009

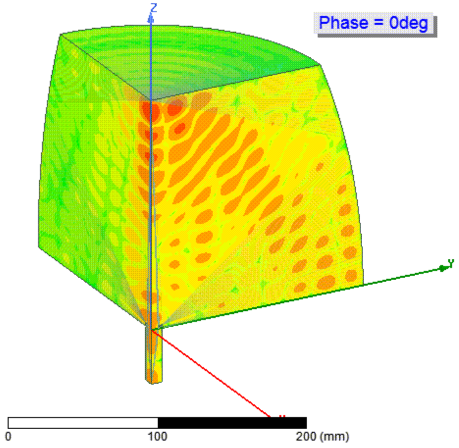
$\mathrm{TE}_{1,2,13}$ rotating mode



Parasitic mode1

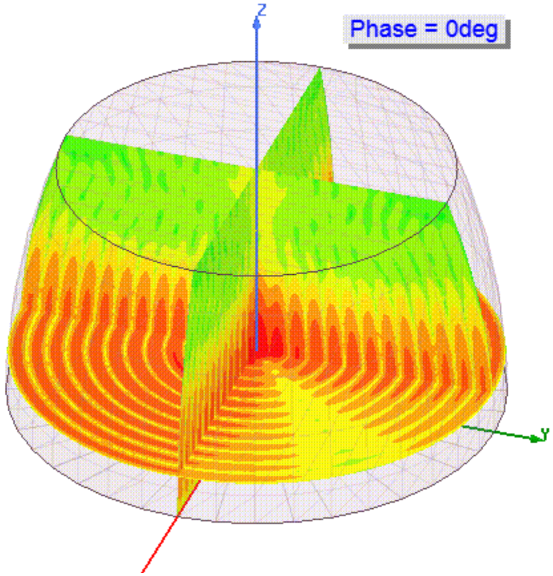


Parasitic mode2

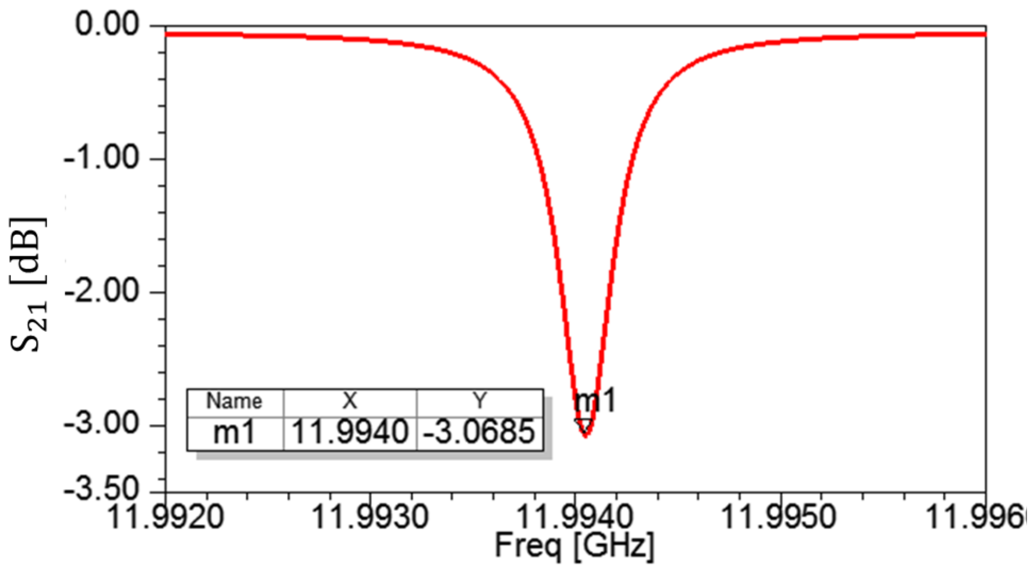


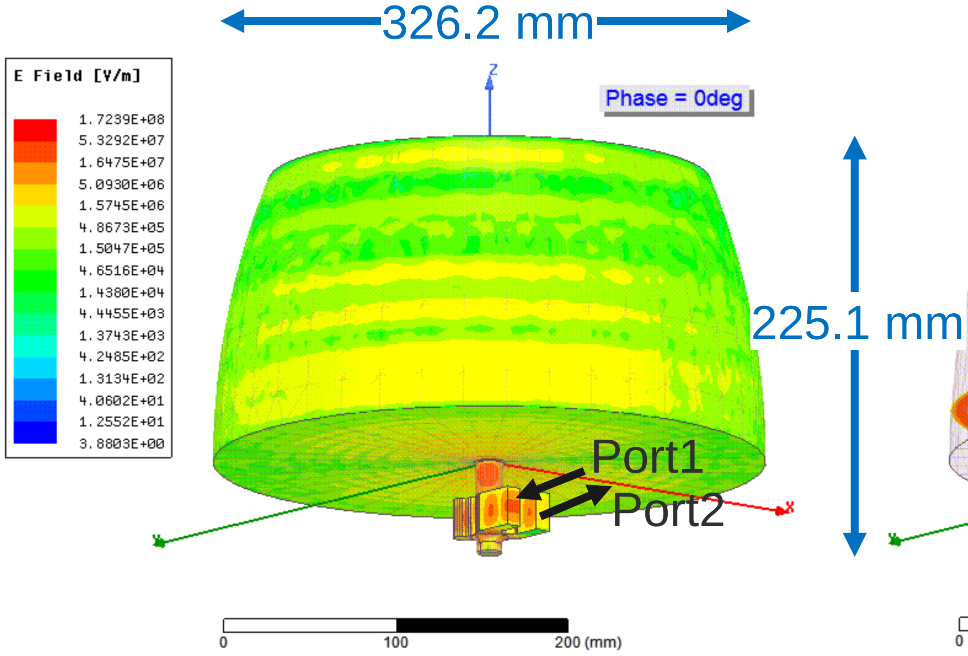
Storage cavity with E-rotator

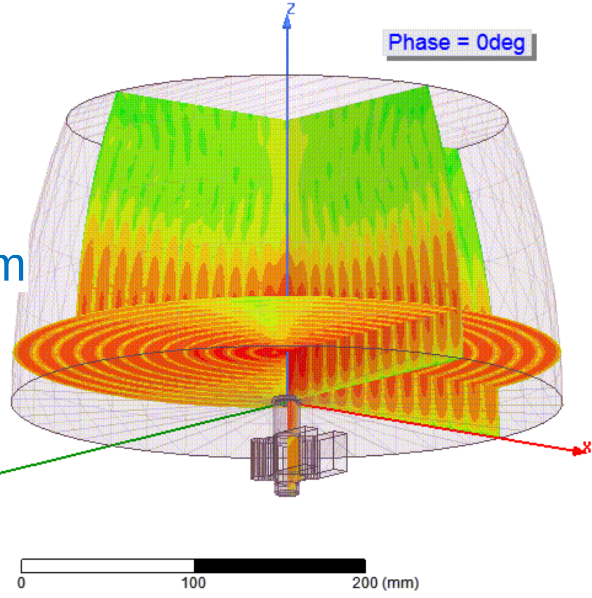
E-rotator converts $\mathrm{TE}_{1,0}$ rectangular waveguide mode to $\mathrm{TE}_{1,1}$ circular waveguide mode and excites $\mathrm{TE}_{1,2,13}$ rotating mode in the open cavity



S_{21} sweep of the storage cavity



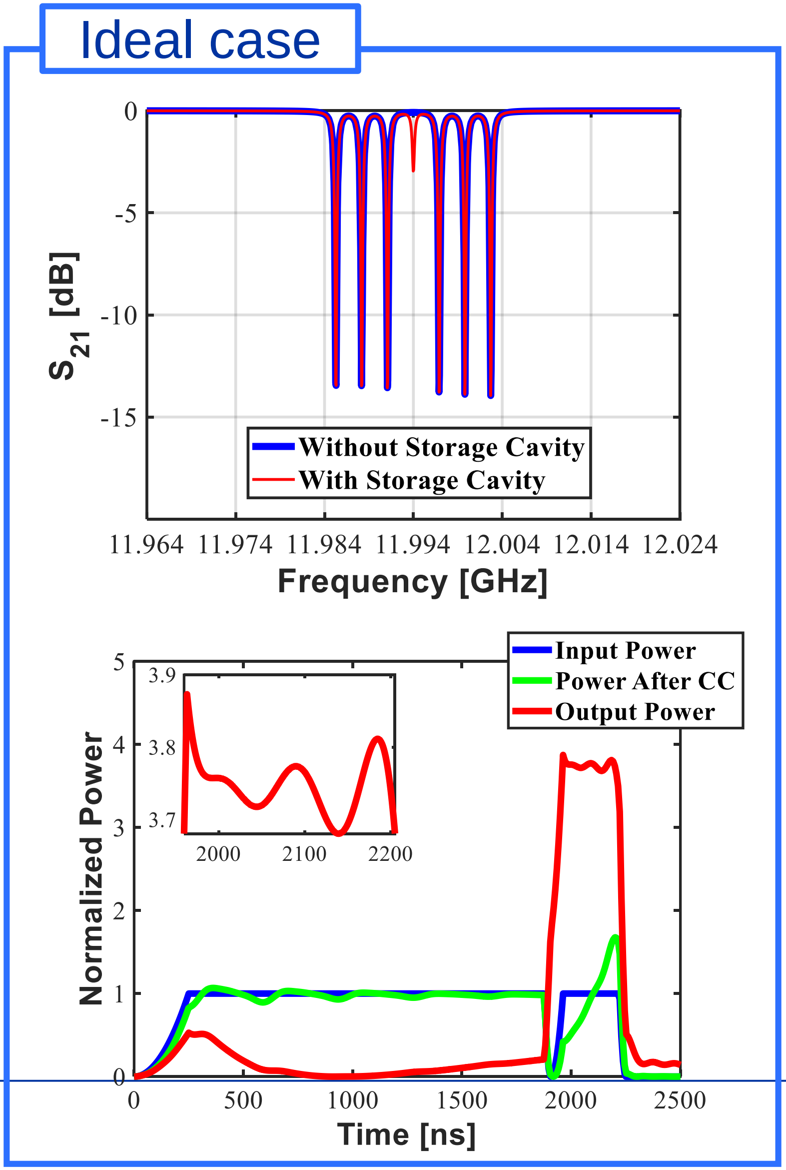


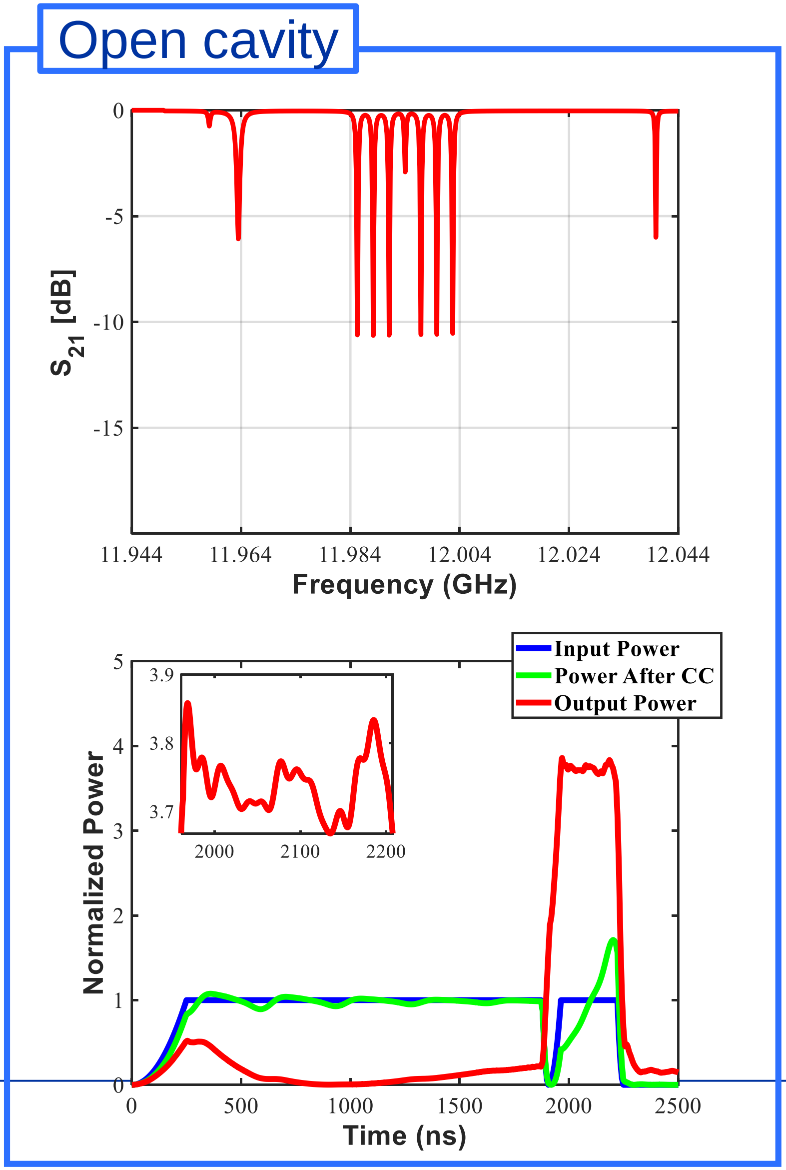


E-field in logarithmic scale

Pulse shape check

The influence to the pulse shape of the parasitic modes are checked





Limitation study

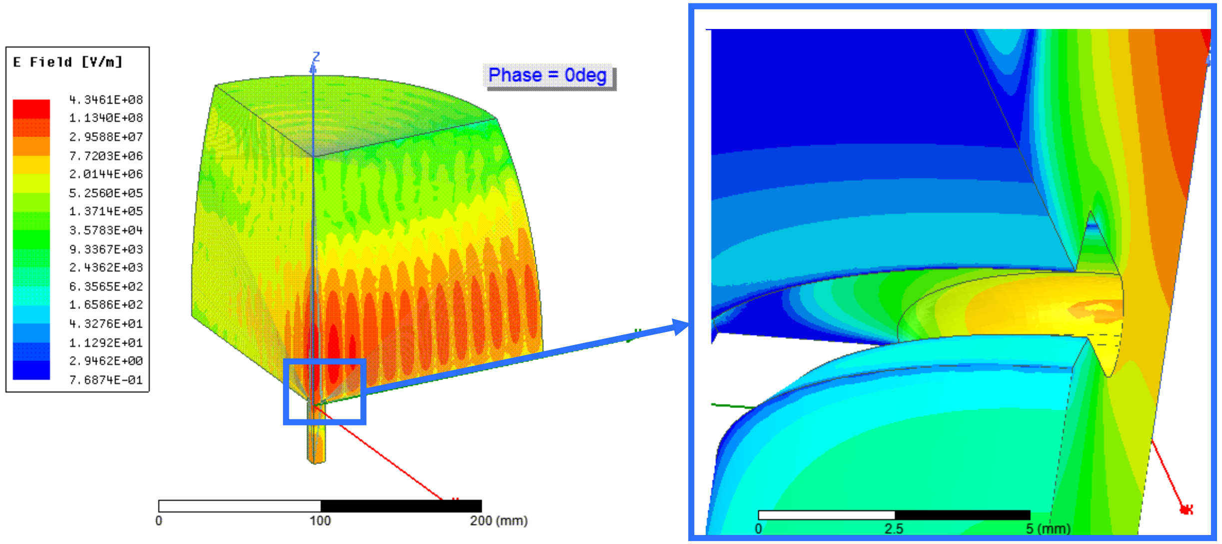
Check the rf parameters at 50 MW, 2.25 μs input power in steady-state

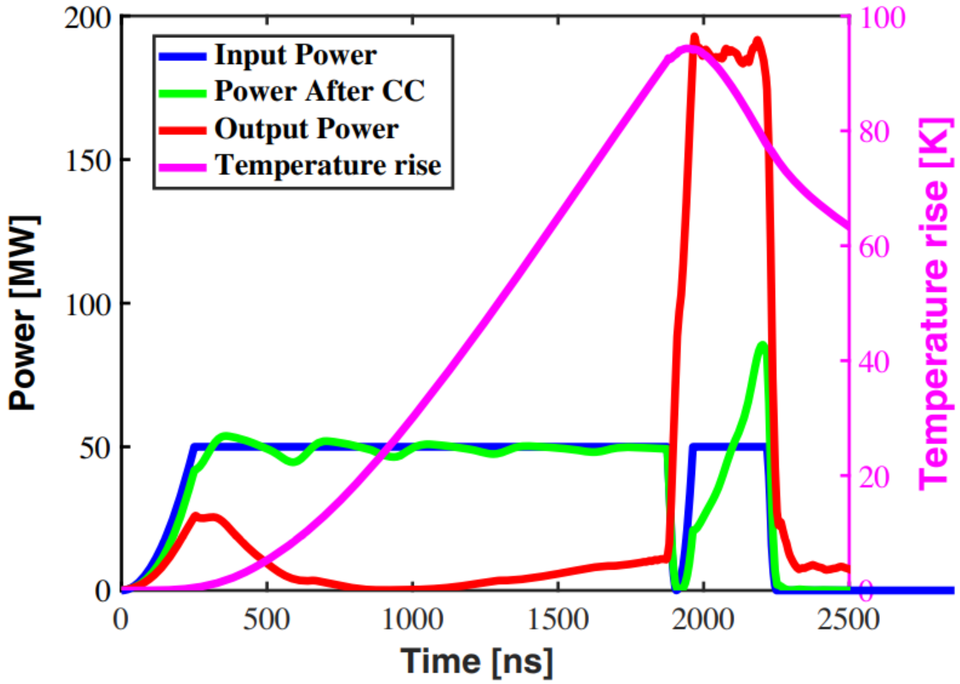
High magnetic field is seen at the coupling iris (Max T rise around 94 K)

[1] reports stable operation of similar coupling iris at T rise of 658 K

High power test is needed to verify the performance

Frequency [GHz]	11.994
Max E [MV/m]	97.79
Max H [kA/m]	577.0
S_c [MW/mm^2]	2.46





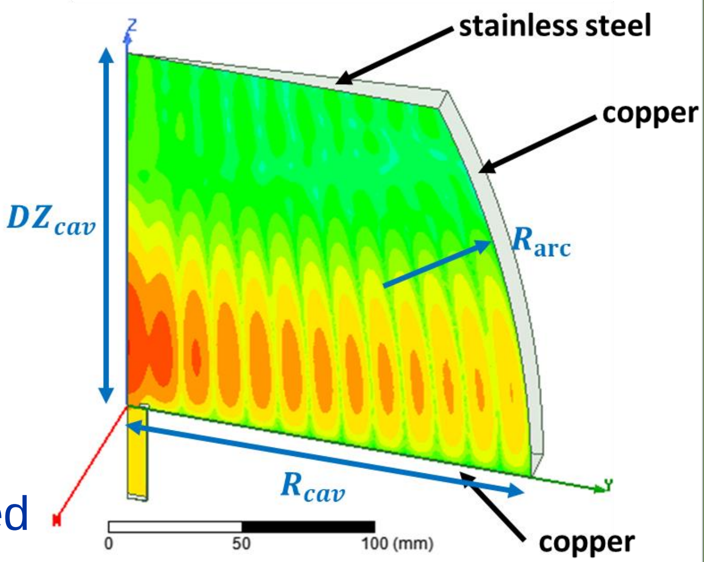
[1] Y. Jiang, H. Zha, J. Shi, M. Peng, X. Lin and H. Chen, "A Compact X-Band Microwave Pulse Compressor Using a Corrugated Cylindrical Cavity," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 69, no. 3, pp. 1586-1593, March 2021, doi: 10.1109/TMTT.2021.3053913.

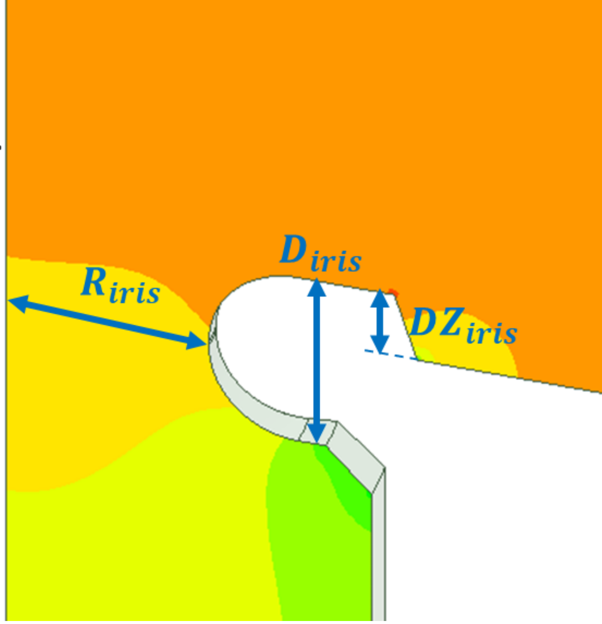
Tolerance study

Key dimensions are checked for tolerance study

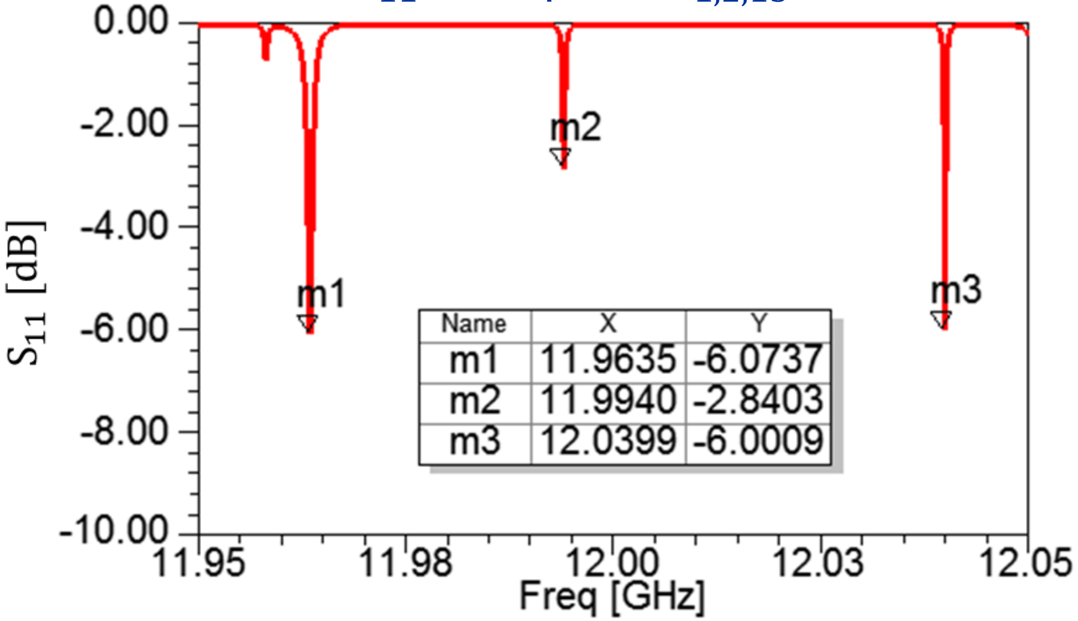
Frequency shifts of work mode and parasitic mode are very small (0.01 mm $\boldsymbol{R_{cav}}$→0.07 MHz)

Coupling factor and more dimension study will be carried out in future





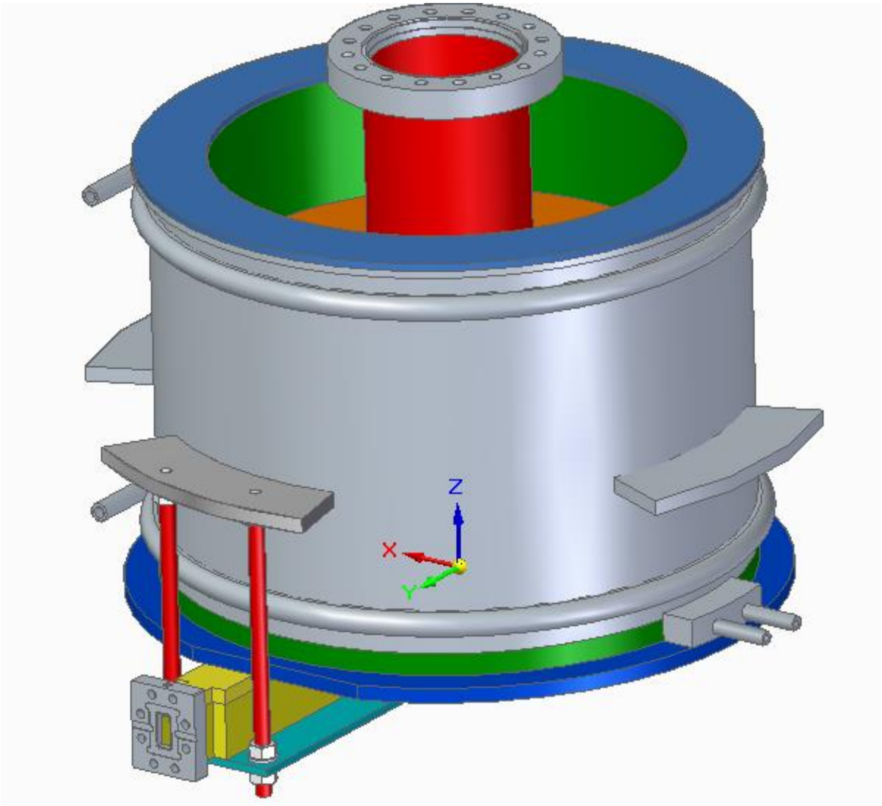
S_{11} sweep of $\mathrm{TE}_{1,2,13}$

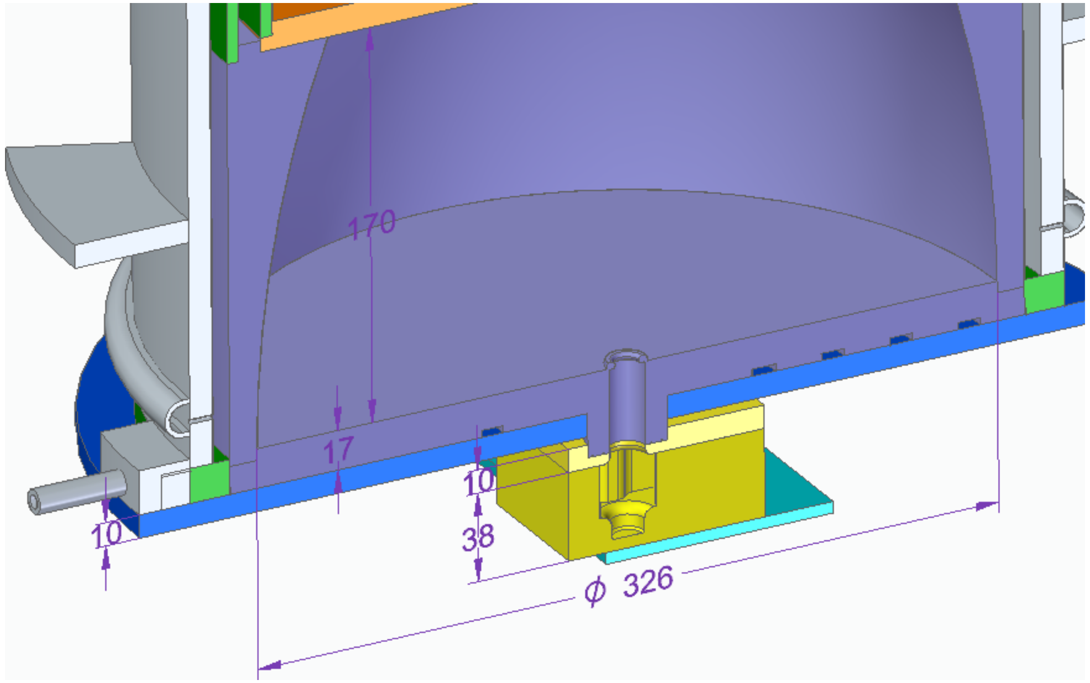


Dimension	$\Delta f/\Delta x$ $[MHz/mm]$		
	Work mode	Parasitic mode1	Parasitic mode2
R_{cav}	-72.66	-24.41	-34.07
DZ_{cav}	<±1.00	-45.50	-37.64
R_{arc}	<±1.00	<±1.00	<±1.00
R_{iris}	<±1.00	-2.44	<±1.00

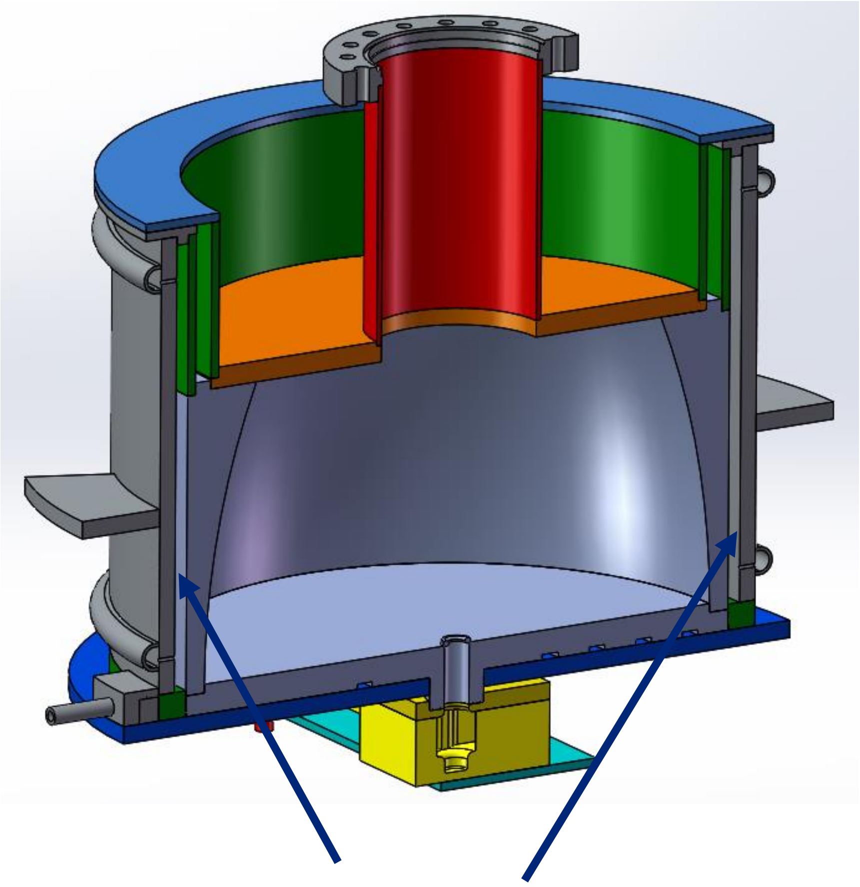
Preliminary mechanical design of the storage cavity

First design from the workshop

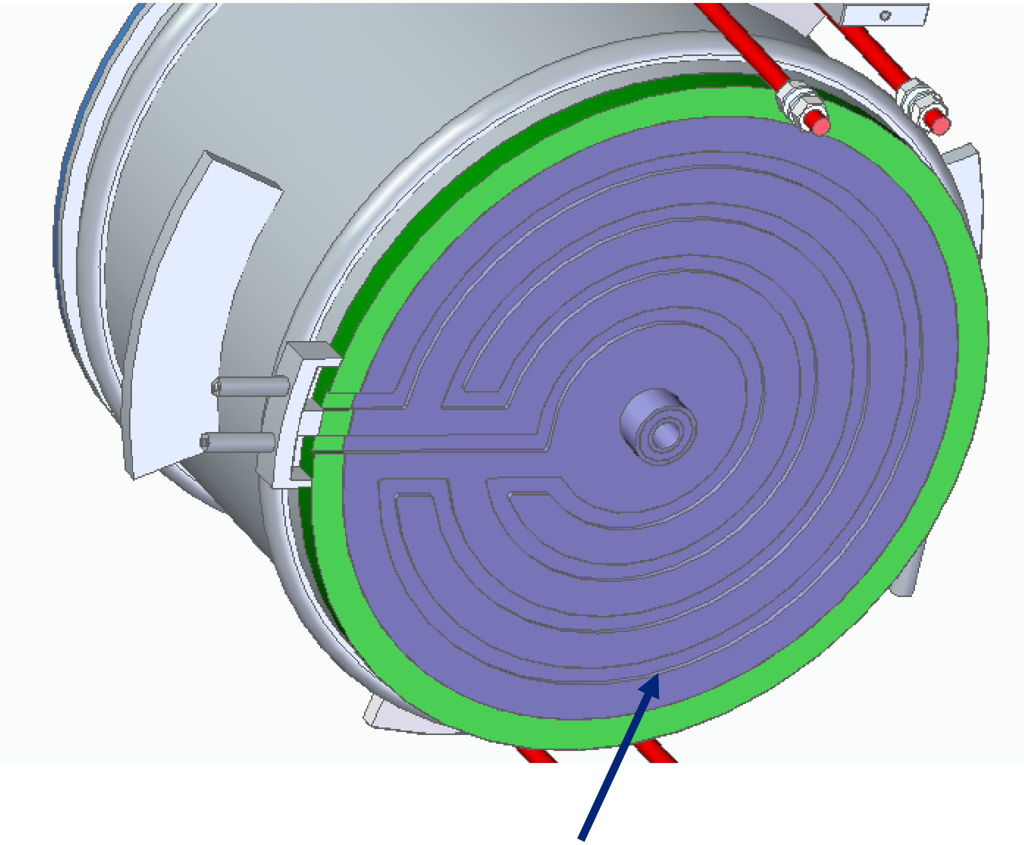




Cooling system



jacket cooling outside of the cavity



Spiral cooling at the bottom of the cavity

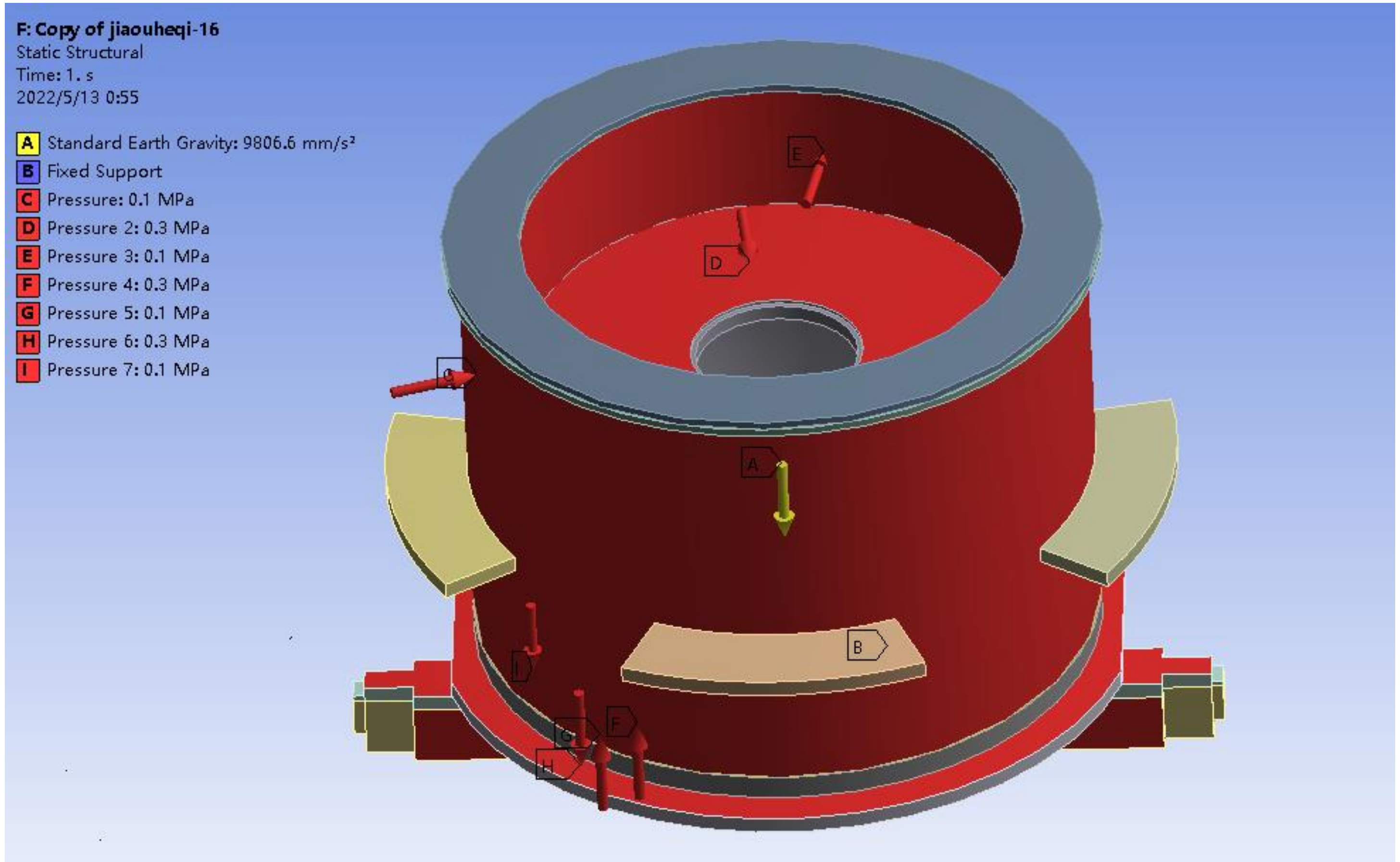
Static structure analysis

Apply 0.1 MPa from outside

- atmospheric pressure

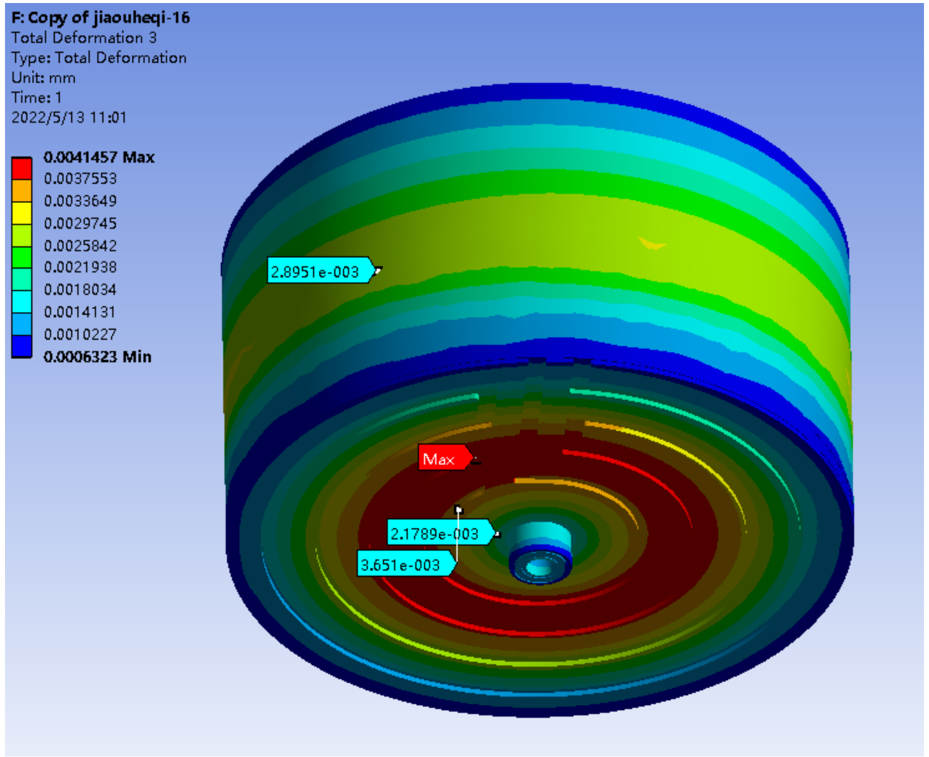
Apply 0.3 MPa water pressure

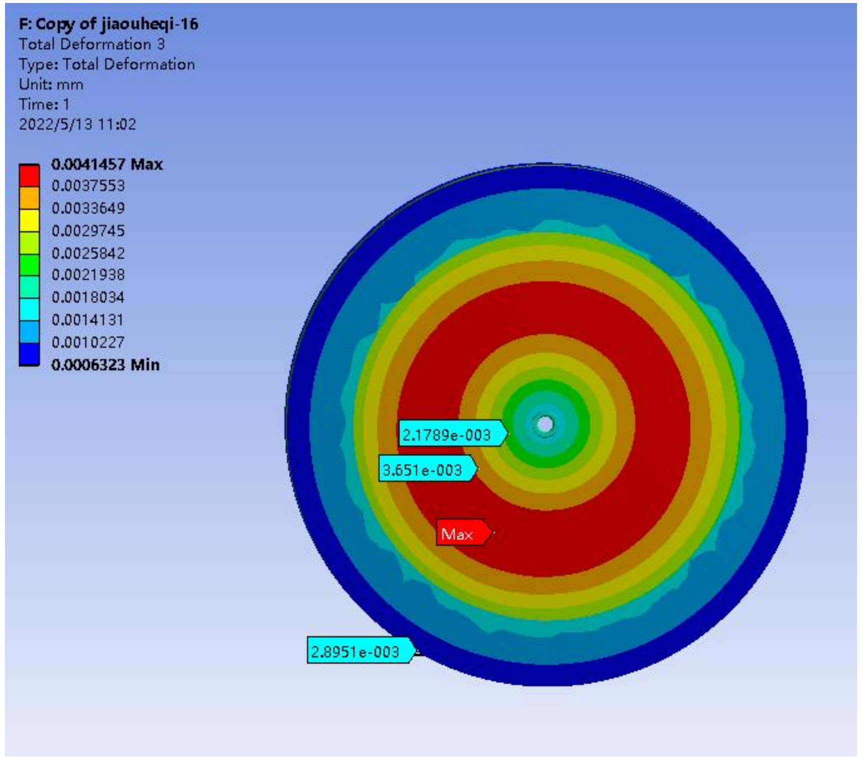
- between cavity and the cooling jacket
- between bottom and spiral cooling slot



Static structure analysis

Maximum deformation of 0.004 mm when bottom thickness is 17 mm



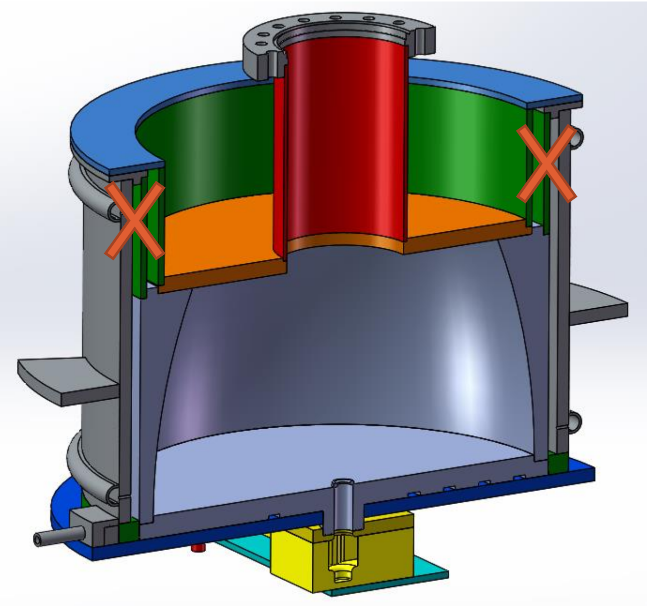


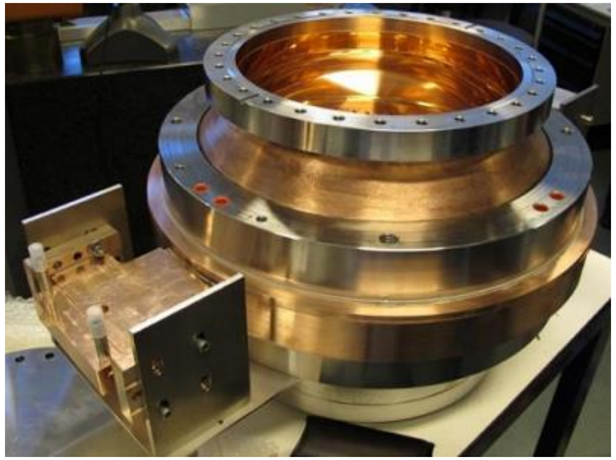
Further study on mechanical design is ongoing

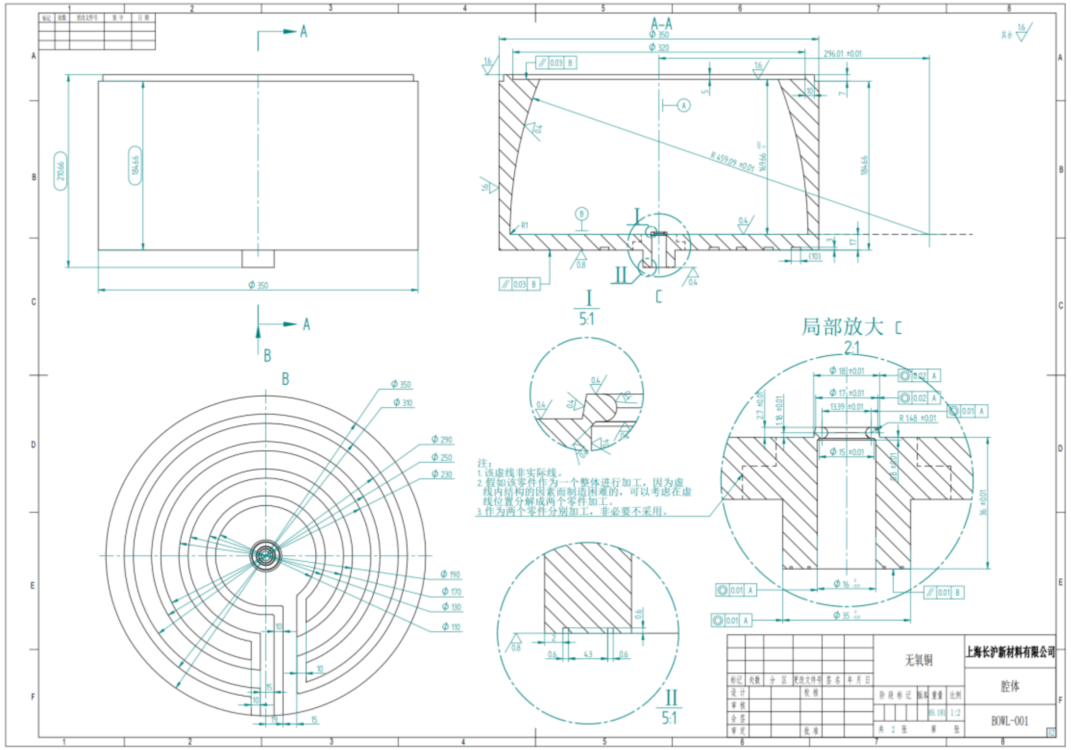
Working on adopting BOC mechanical design

Iris shape optimization

Copper thickness optimization



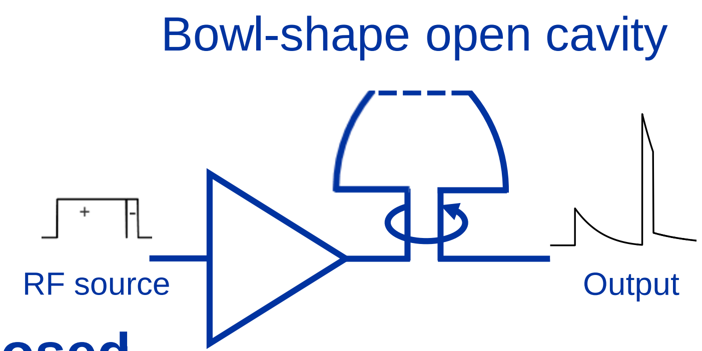




Outline

1. Overview of existing pulse compressors
2. Introduction to bowl-shape open cavity
3. Correction cavity design
4. Storage cavity design
5. Conclusion and future work

Conclusion



A bowl-shape open cavity working at $TE_{1,2,i}$ rotating mode is proposed

$TE_{1,2,4}$ mode with Q~74000 has been studied for CLIC correction cavity

$TE_{1,2,13}$ mode with Q~240000 has been studied for CLIC storage cavity

Tolerance study shows promising results for fabrication

Mechanical design has been started

More details…

PHYSICAL REVIEW ACCELERATORS AND BEAMS **24,** 112001 (2021)

Novel open cavity design for rotating mode rf pulse compressors

Xiaowei Wu* and Alexej Grudiev
European Organization for Nuclear Research (CERN), 1211 Geneva 23, Switzerland

(Received 14 July 2021; accepted 14 October 2021; published 9 November 2021)

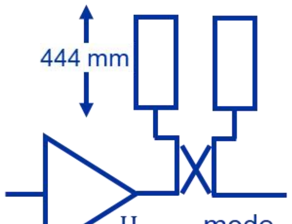
A new *X*-band high-power rotating mode SLAC energy doubler (SLED)-type rf pulse compressor is proposed. It is based on a novel cavity type, a single open bowl-shaped energy storage cavity with high-quality factor and compact size, which is coupled to the waveguide using a compact rotating mode launcher. The novel cavity type is applied to the rf pulse compression system of the main linac rf module of the klystron-based option of the Compact Linear Collider. Quasispherical rotating modes of $TE_{1,2,4}$ and $TE_{1,2,13}$ are proposed for the correction cavity and storage cavity of the rf pulse compression system, respectively. The storage cavity working at $TE_{1,2,13}$ has a quality factor above 240 000 and a diameter less than 33 cm. The design of the pulse compressor and in particular of the high-Q cavity will be presented in detail.

DOI: 10.1103/PhysRevAccelBeams.24.112001

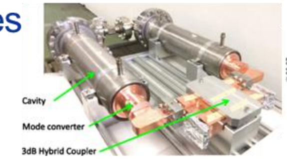
https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.24.112001

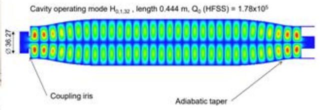
SLED-type pulse compressors in my eyes

Cylinder cavities



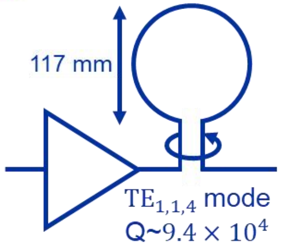
$H_{0,1,32}$ mode
Q~1.8×10^5



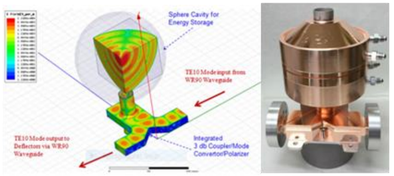


- ✓ Easy fabrication
- ✗ Not compact
  Dipole mode "breakdown"

Spherical cavity

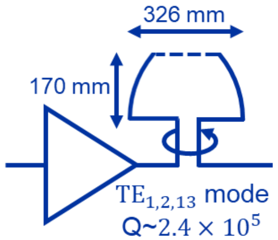


$TE_{1,1,4}$ mode
Q~9.4×10^4

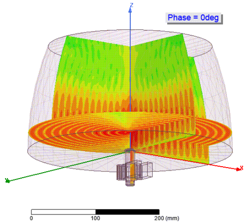


- ✓ Very compact
  Relatively easy fabrication
- ✗ Relatively low Q
  Dense mode spectrum

Bowl-shape open cavity

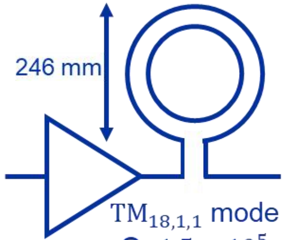


$TE_{1,2,13}$ mode
Q~2.4×10^5

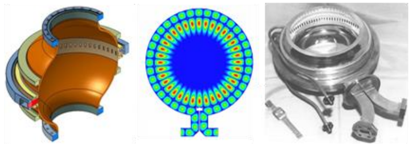


- ✓ Very high Q with compact size
  Easy fabrication with low cost
- ✗ High magnetic field at coupling iris

Barrel open cavity

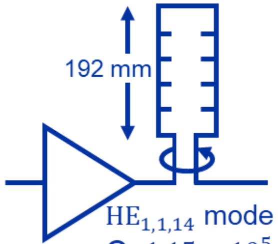


$TM_{18,1,1}$ mode
Q~1.5×10^5

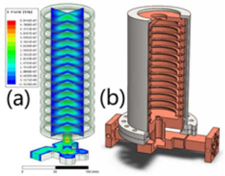


- ✓ Very stable performance
- ✗ Difficult fabrication
  Relatively not compact
  Additional loss in waveguides

Corrugated cavity

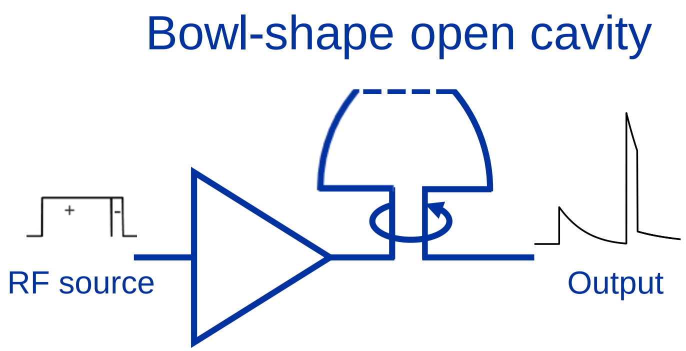


$HE_{1,1,14}$ mode
Q~1.15×10^5



- ✓ Compact
- ✗ High magnetic field at coupling iris
  Many pieces for assembling

Future work



X-band bowl-shape open cavity design

- Parasitic modes suppression for storage cavity (absorption material?)
- Coupling iris optimization to reduce surface field/pulse heating/…

X-band bowl-shape open cavity development for CLIC

- Finalize the mechanical design and fabrication
- Lower-power rf measurement and high-power test of the bowl-shape open cavity

C-band bowl-shape open cavity design is undergoing

Future work

X-band bowl-shape open cavity design

- Parasitic modes suppression for storage cavity (
- Coupling iris optimization to

Looking forward to fruitful results from the bowl!

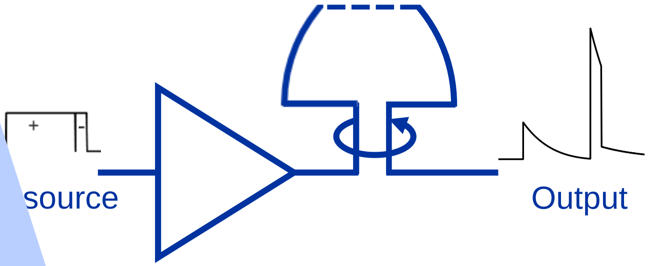
X-band l ... LIC

abrication

measurement and high-power test of the bowl-shape
vity

C-band bowl-shape open cavity design is undergoing

Bowl-shape open cavity



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Thanks for your attention!

Reference

[1] Z. D. Farkas, H. A. Hogg, G. A. Loew, and P. B. Wilson, in *Proceedings of 9th International Conference on High Energy Accelerators*, (SLAC, 1974), p. 576.

[2] P. B. Wilson, Z. Farkas, and R. D. Ruth, *SLED II: A new method of RF pulse compression*, Stanford Linear Accelerator Center Technical Report, 1990.

[3] B. Woolley, I. Syratchev, and A. Dexter, *Control and performance improvements of a pulse compressor in use for testing accelerating structures at high power*, Phys. Rev. Accel. Beams **20**, 101001 (2017).

[4] I. Syrachev, V. Vogel, H. Mizuno, J. Odagiri, Y. Otake, and S. Tokumoto et al., in Proceedings of the 17th International Linear Accelerator Conference (LINAC-1994), Tsukuba, Japan, 1994, (KEK, Tsukuba, Japan, 1994), pp. 475–477.

[5] J. W. Wang, S. G. Tantawi, C. Xu, M. Franzi, P. Krejcik, G. Bowden, S. Condamoor, Y. Ding, V. Dolgashev, J. Eichner, A. Haase, J. R. Lewandowski, and L. Xiao, *Development for a supercompact* x*-band pulse compression system and its application at slac*, Phys. Rev. Accel. Beams **20**, 110401 (2017).

[6] P. Wang, H. Zha, I. Syratchev, J. Shi, and H. Chen, *rf design of a pulse compressor with correction cavity chain for klystron-based compact linear collider*, Phys. Rev. Accel. Beams **20**, 112001 (2017).

[7] Y. Jiang, H. Zha, P. Wang, J. Shi, H. Chen, W. L. Millar, and I. Syratchev, *Demonstration of a cavity-based pulse compression system for pulse shape correction*, Phys. Rev. Accel. Beams **22**, 082001 (2019).

[8] A. Grudiev, CERN CLIC - Note No. 1067, 2016.

[9] M. Franzi, J. Wang, V. Dolgashev, and S. Tantawi, *Compact rf polarizer and its application to pulse compression systems*, Phys. Rev. Accel. Beams **19**, 062002 (2016).

[10] Y. Jiang, H. Zha, J. Shi, M. Peng, X. Lin and H. Chen, "A Compact X-Band Microwave Pulse Compressor Using a Corrugated Cylindrical Cavity," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 69, no. 3, pp. 1586-1593, March 2021, doi: 10.1109/TMTT.2021.3053913.

[11] C. Jin, I. Syrachev, CERN CLIC - Note No. 1166, 2020.