My recent research activities at IHEP

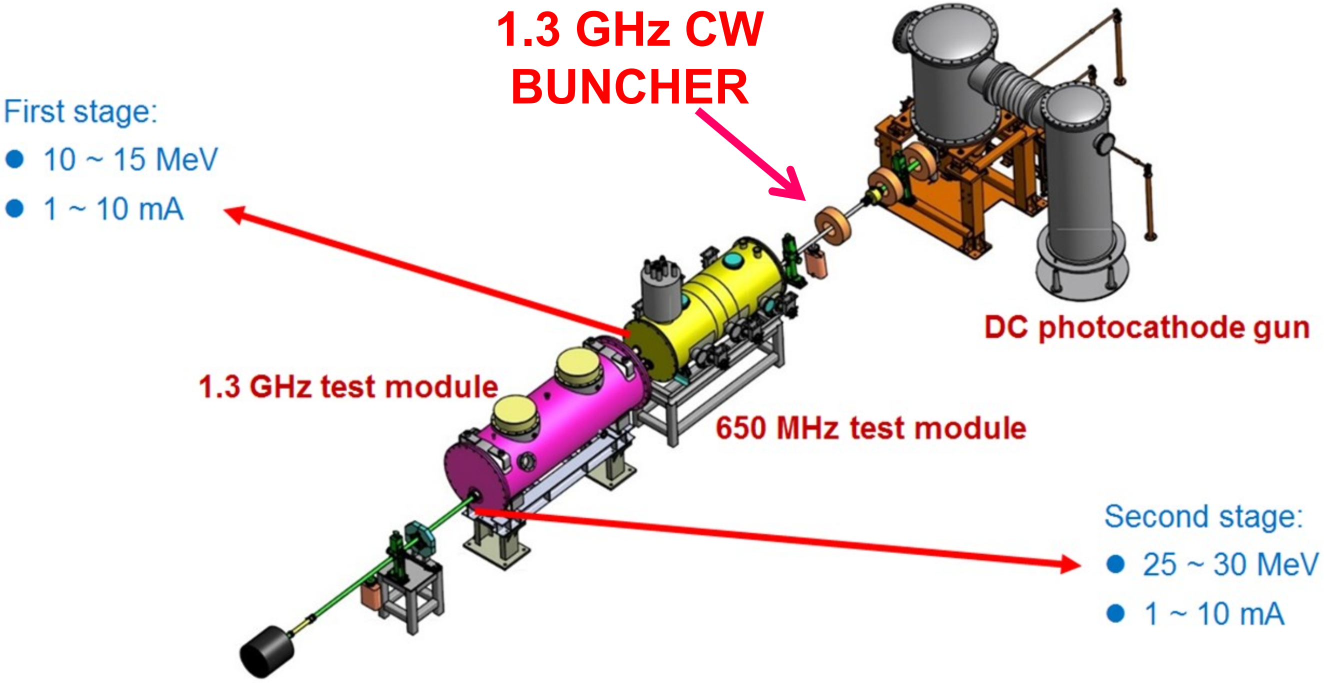
- L band 1.3 GHz normal-conducting CW buncher system
- S band 2.998 GHz 6 MeV side-coupled accelerating tube
- C band 5.712 GHz SLED & BOC pulse compressor
- R&D of high power RF components
- Summary

Guan Shu

PITZ physics Seminar
Zeuthen, 03.05.2018

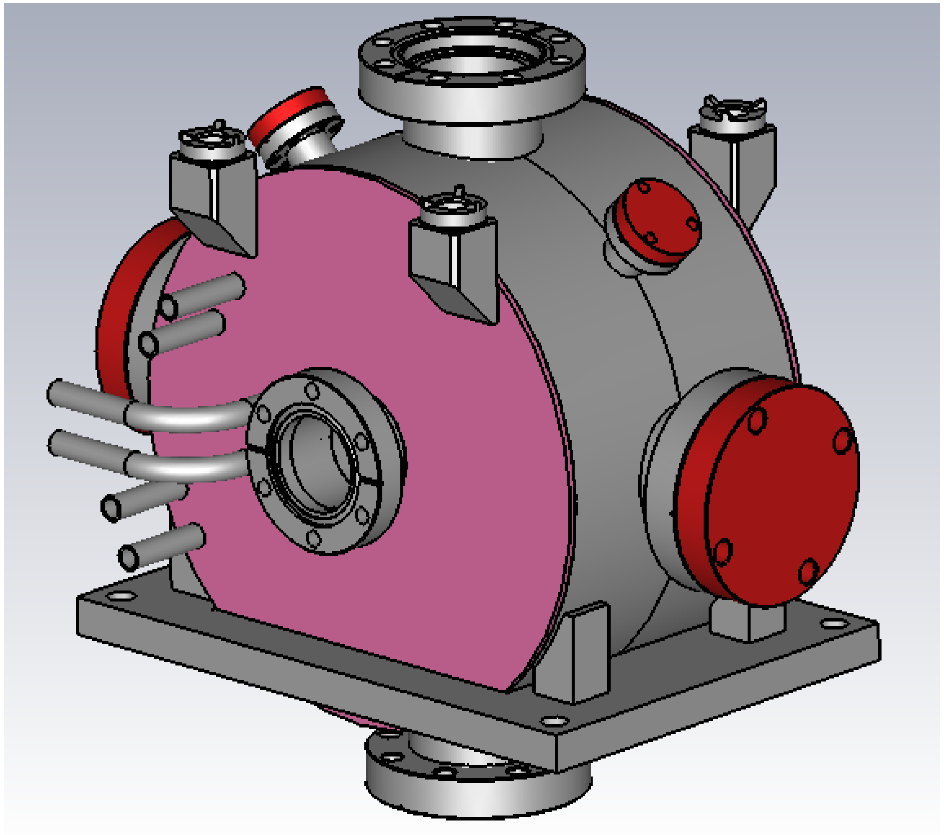
1.3 GHz normal-conducting CW buncher system

- Project status:
  - Design for PAPS project, Condense 500 keV/20 ps beam to ~2ps
  - RF and mechanical design has finished (03.2018), fabrication is undergoing, test will be carried out this Autumn.

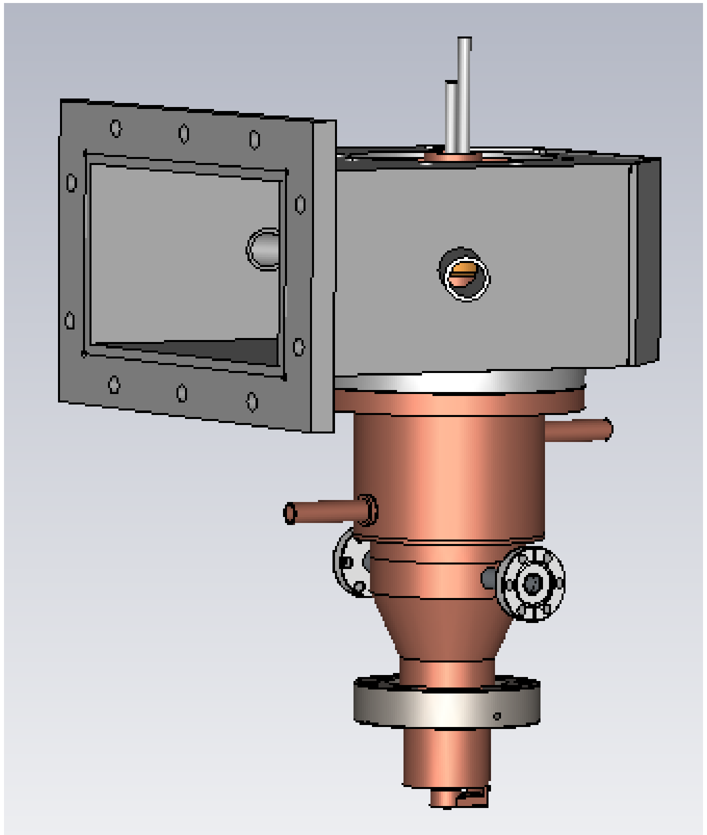


Layout of PAPS

1.3 GHz normal-conducting CW buncher system

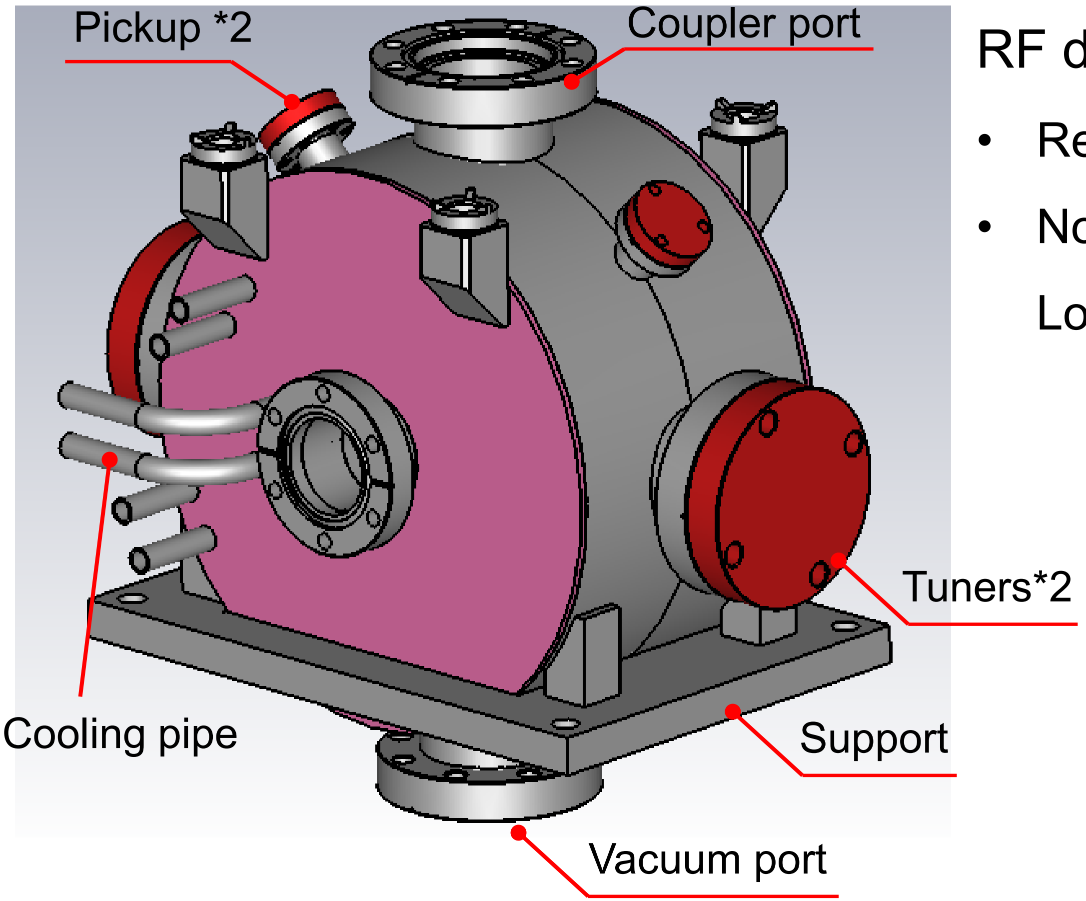


cavity



coupler

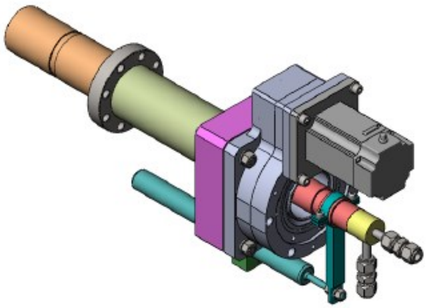
1.3 GHz CW buncher cavity



RF design target:

- Resonant frequency 1.3 GHz, CW
- Nominal voltage ~120 kV

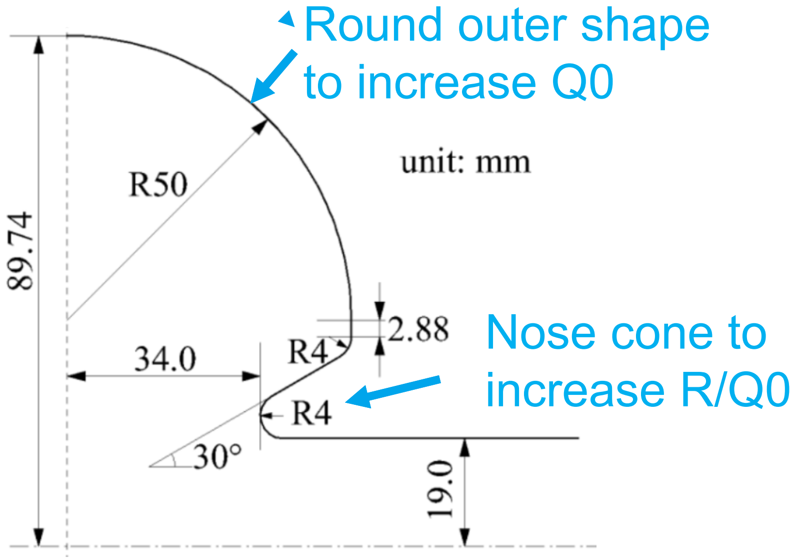
Longitudinal size 180 mm



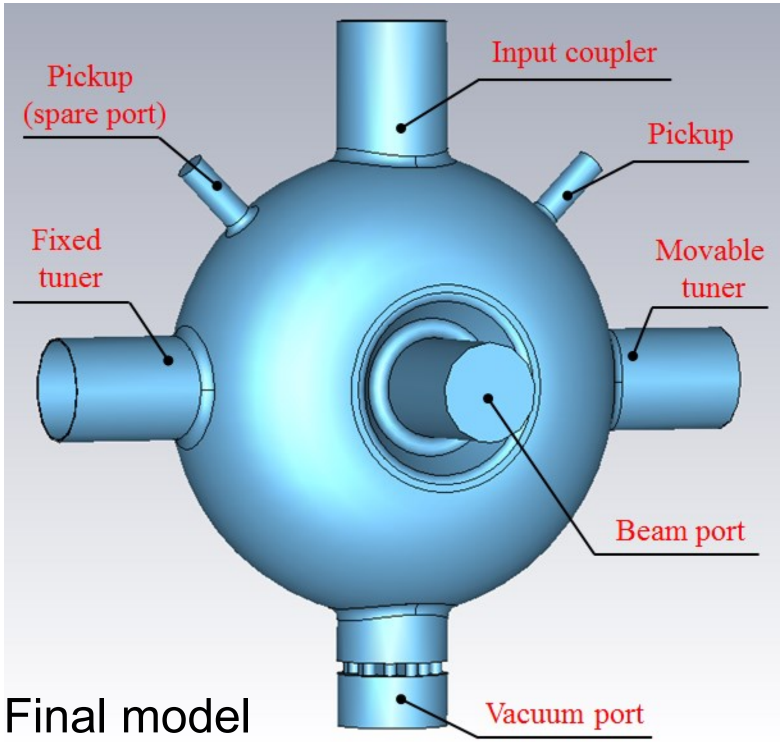
Automatic tunner

RF design

- Cavity design based upon the basic size of KEK cERL buncher [1]
  - Vacuum geometry consists of input coupler, vacuum pump port, 2 slug tuners (manual + auto) and 2 pickups.
  - Symmetrically place to suppress the field distortion .
  - 3D EM code: CST MWS, checked with HFSS.



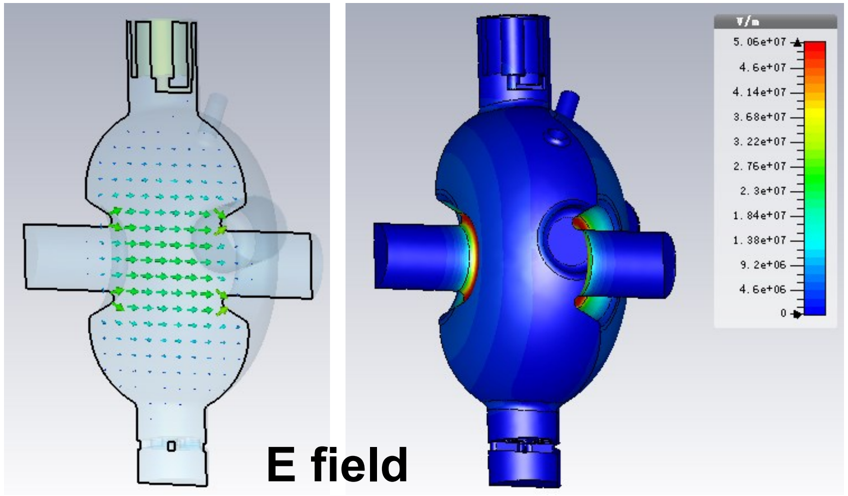
KEK cavity basic sizes
Scaled from a 500 MHz cavity



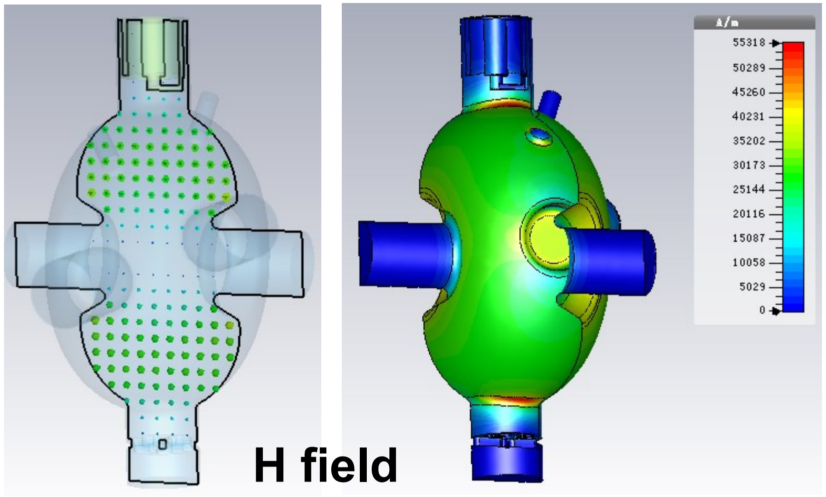
Final model

Main parameters of the cavity

Parameters	Values	Units
Frequency	1.3	GHz
Eff. cavity voltage	120	kV
Unload Q0	23000	
Shunt impedance Rs* (β=v/c=1)	5.35	MΩ
Rs/Q0 (β=v/c=1)	232	Ω
Transit time factor	0.777	
Max. dissipated power in cavity @Vc=120 kV	2.64	kW
Max. power density on the inner surface @Vc=120 kV	5.5	W/cm^2
E peak on the surface @Vc=120 kV	4.6	MV/m
Kilpatric factor (For 1.3 GHz critical surface field is 32.14 MV/m)	0.14	
Max. tuning range	10.3	MHz
Coupling factor (adjustable)	~1.0	Critical coupling



E field



H field

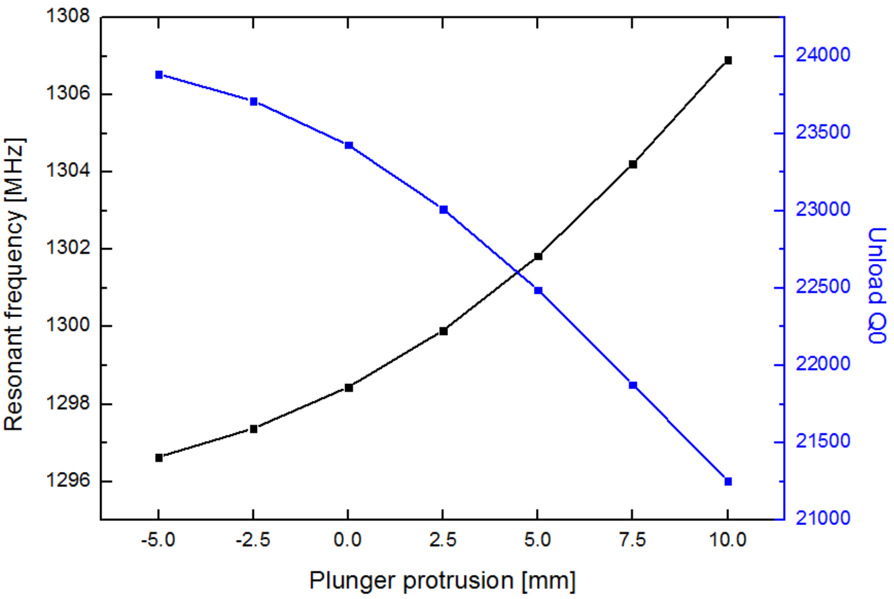
Tuner

Role of RF tuner [2]:

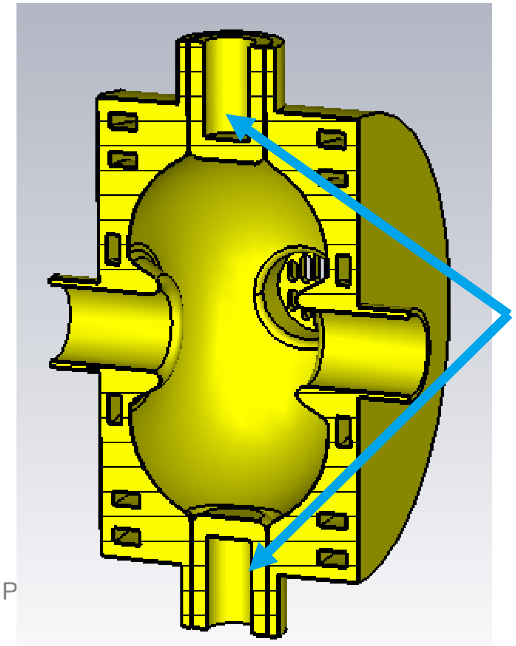
- Correct the resonant frequency due to the machining error and temperature change
- Detuning the resonant frequency to compensate the beam loading effect

In this case:

- 15 mm movement range of the plungers corresponding to ~10.3MHz tuning range
- Cooling water in the plunger
- Using bellows to move the plungers while isolating cavity vacuum
- Using RF spring to shield the bellows from RF field
- Gap between tuner and cavity should be selected carefully to avoid multipacting

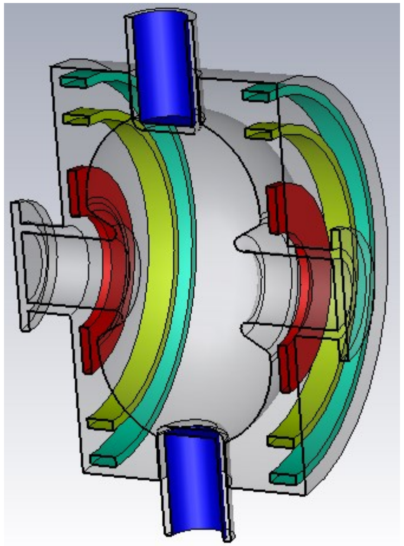


Frequency shift by two tuners

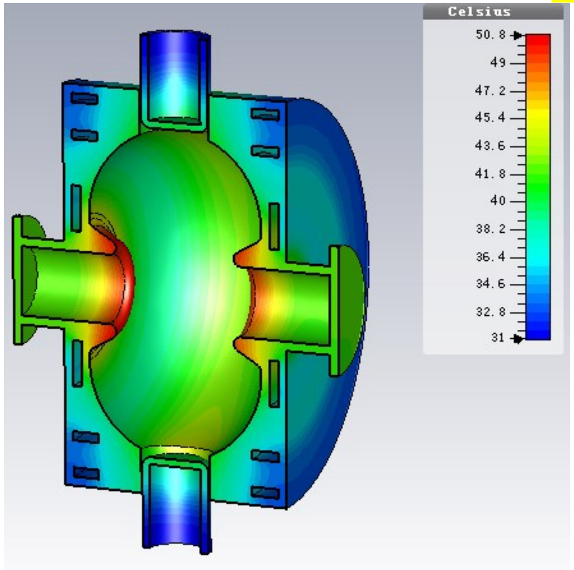


Cooling design

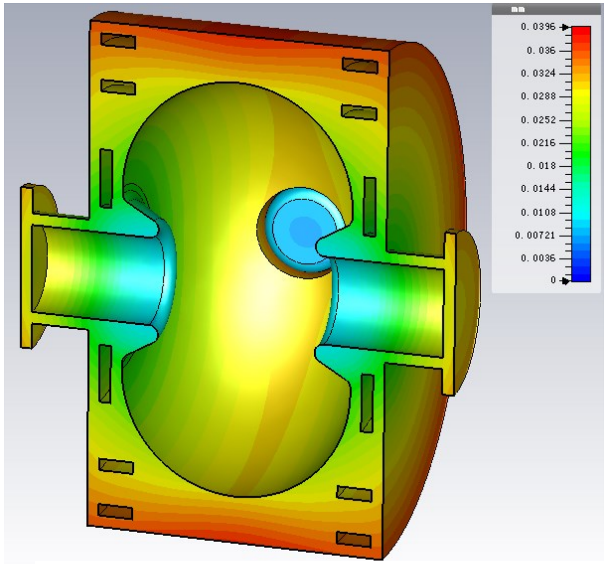
- Cavity is made by OFHC (C10100)
- RF-thermal-structure coupled analysis is calculated by CST MPHYSICS STUDIO and checked with ANSYS
  - Max. heat load ~ 7kW
  - 8 cooling channels, 6 for cavity, 2 for tuners
  - Cooling water temperature 20℃, water speed ~2m/s
  - Heat transfer coefficient 6707W/(m·K),



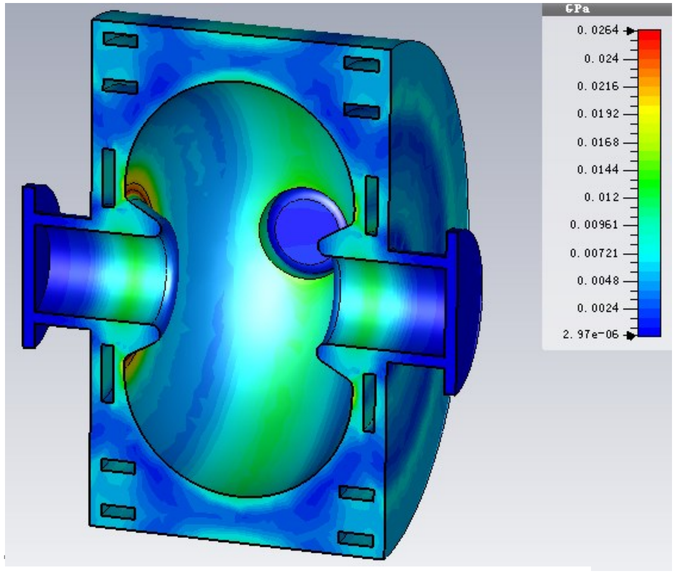
Structure analysis consider both vacuum load and thermal load



Max. temperature = 50.8℃



Max. deformation = 39.6um



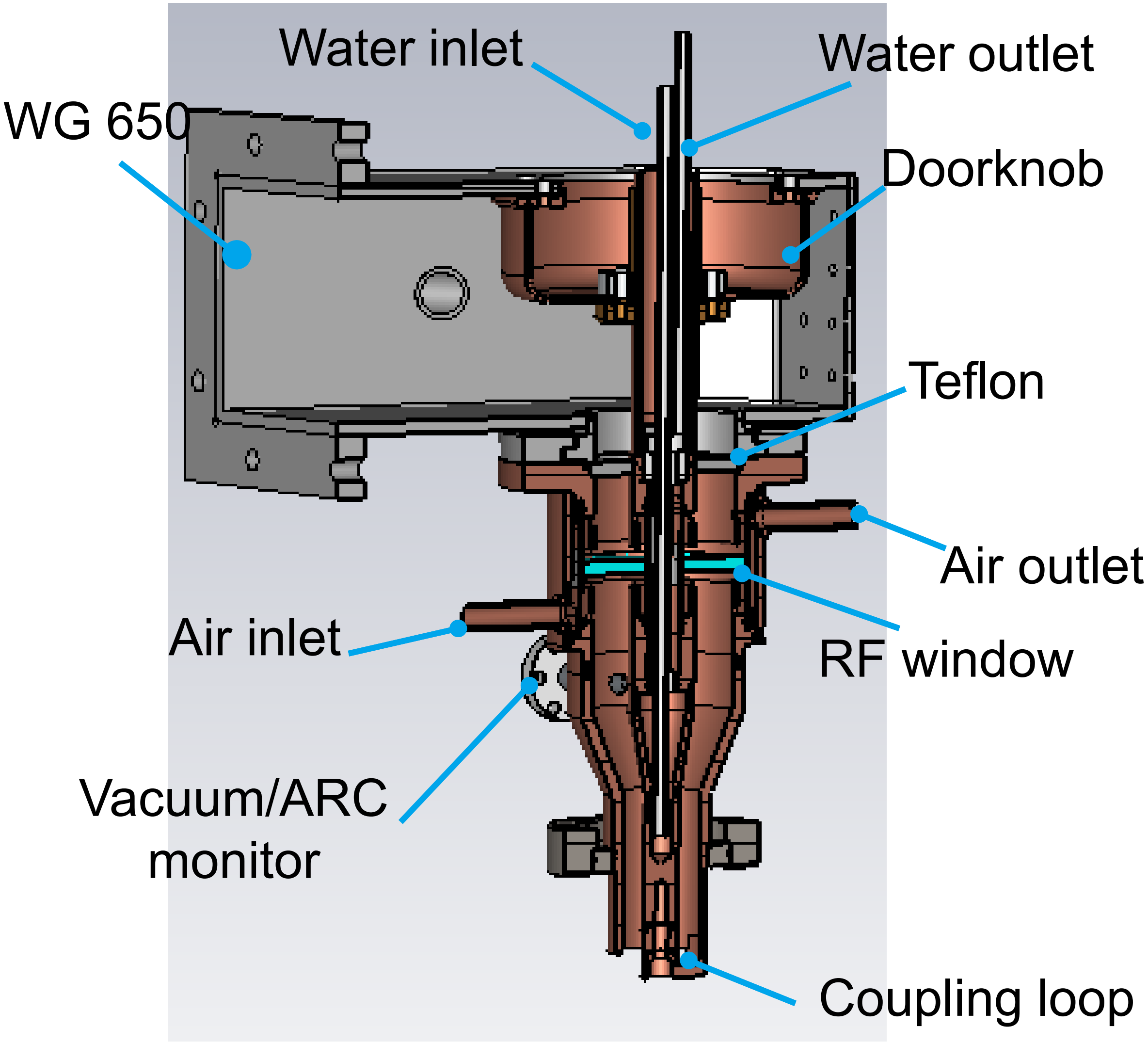
Max. von Mises = 26.4MPa

1.3 GHz CW Coupler

Role of RF power coupler [3]:

- Impedance matching between incoming RF and cavity
- Couplers the incoming RF line’s EM mode to cavity mode
- Provide vacuum barrier between cavity and RF line

1.3 GHz CW Coupler



Cutview of coupler

- Waveguide-coaxial line transformer
- Planar/disk type RF window
- Coaxial transmission line
- Coupling loop, coupling factor adjustable(loop area, position, angle)

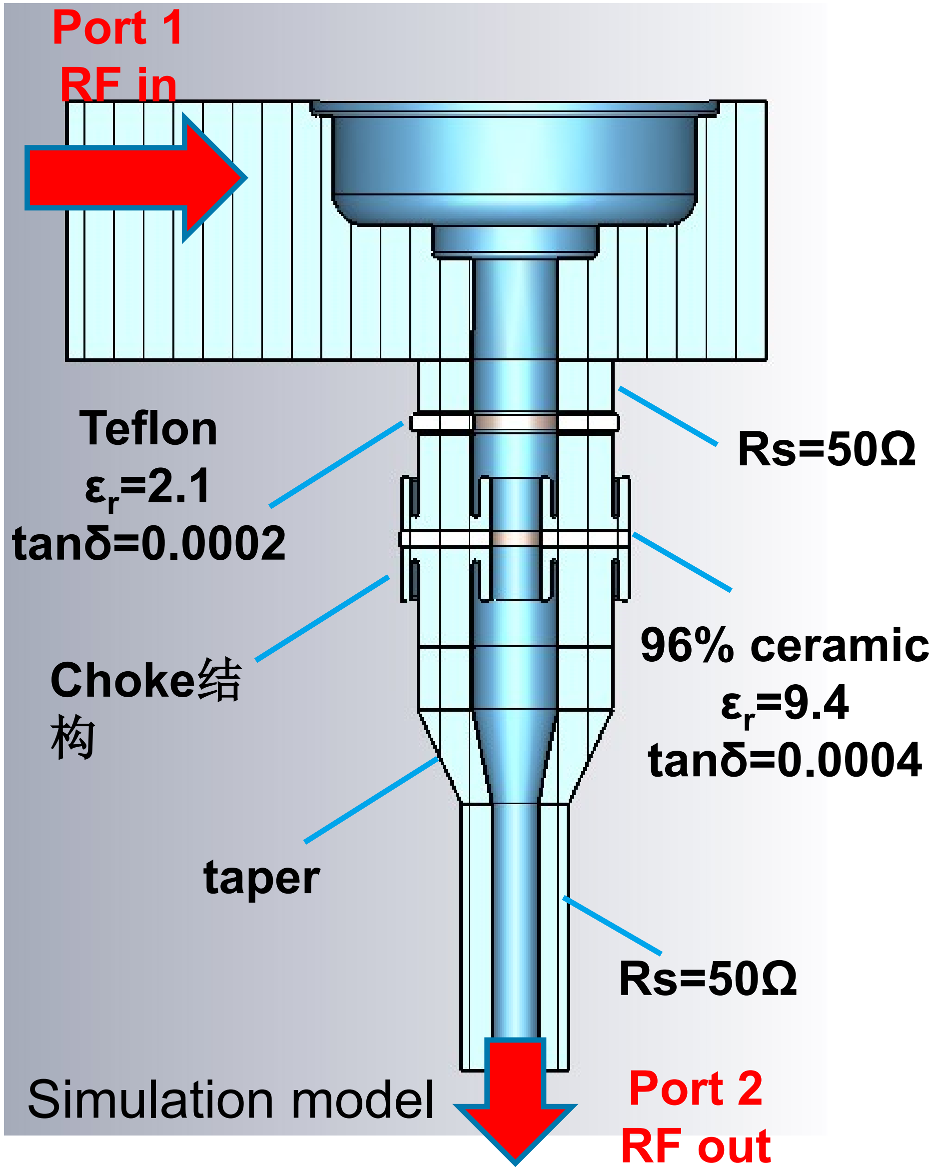
Material:

- Waveguide: Aluminum
- Coaxial coupler parts: OFHC
- Teflon: ε_r=2.1, tanδ=0.0002
- Ceramic: coating by TiN

  96%, ε_r=9.4

  tanδ=0.0004
- Coaxial flange: SS 316L

Transmission analysis



Port 1

RF in

Teflon

ε_r=2.1

tanδ=0.0002

Choke结构

taper

Rs=50Ω

96% ceramic

ε_r=9.4

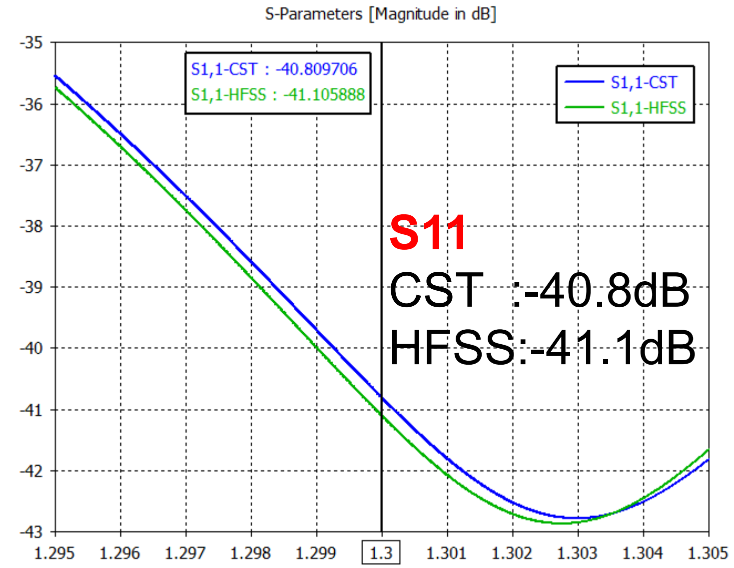
tanδ=0.0004

Rs=50Ω

Simulation model

Port 2

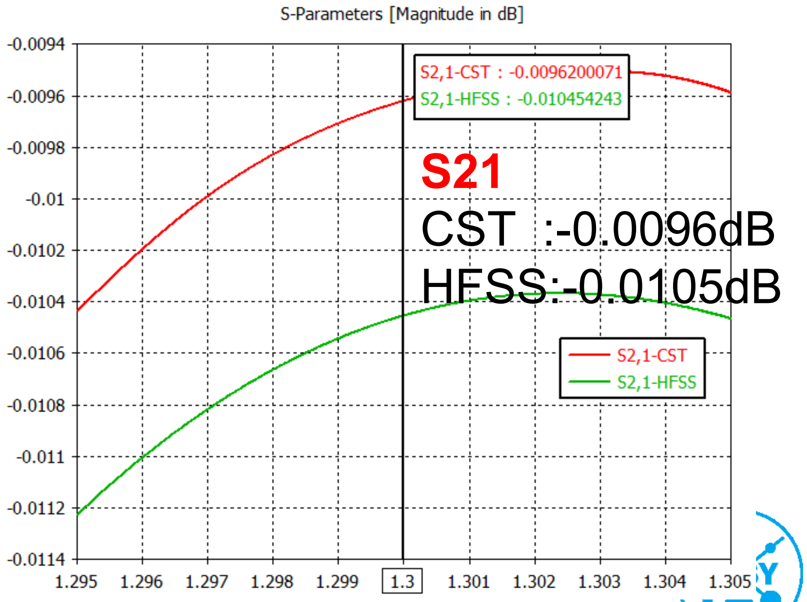
RF out



S11

CST :-40.8dB

HFSS:-41.1dB



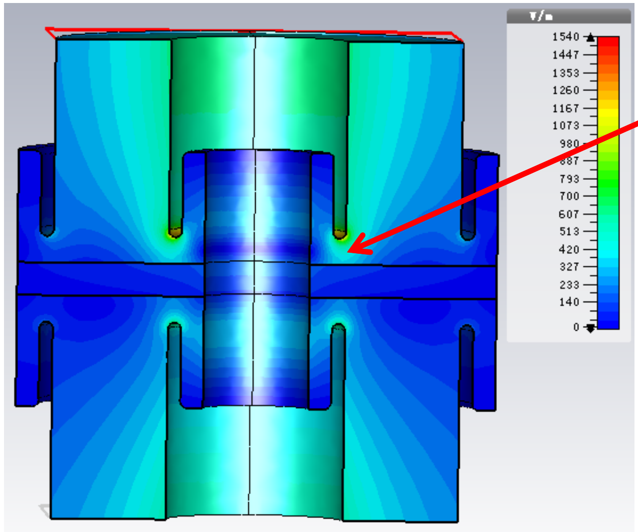
S21

CST :-0.0096dB

HFSS:-0.0105dB

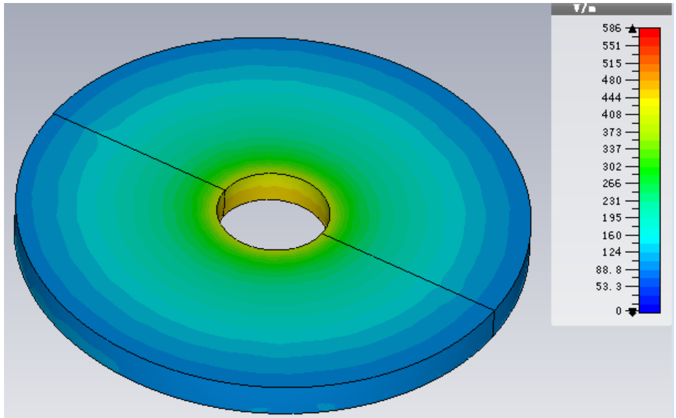
RF breakdown analysis

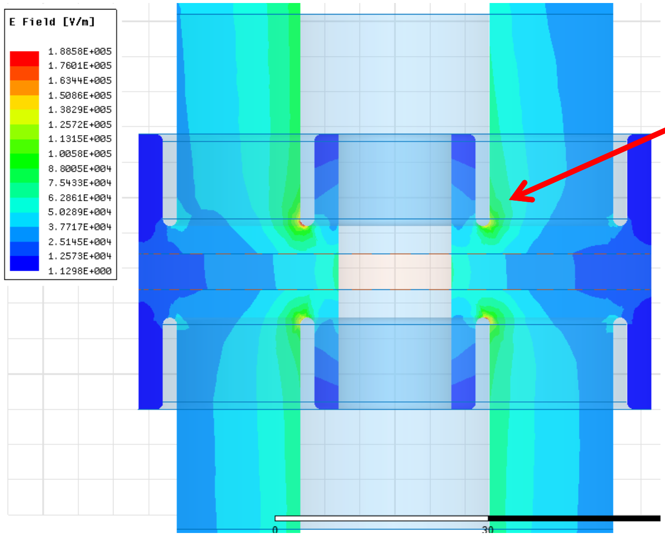
Input 7kW RF power, the max. E field of the air side is ~0.18MV/m, which is much lower than the breakdown limit of air (3MV/m).



CST

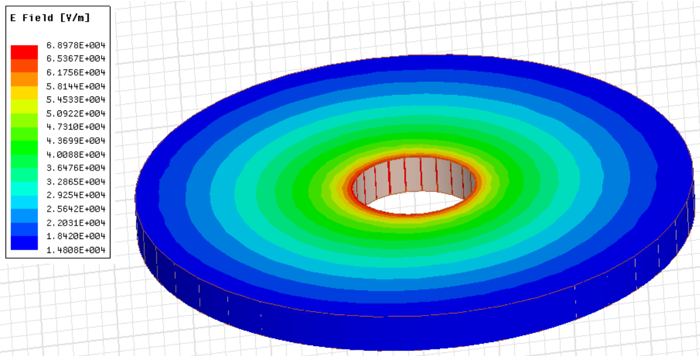
Emax=0.182MV/m



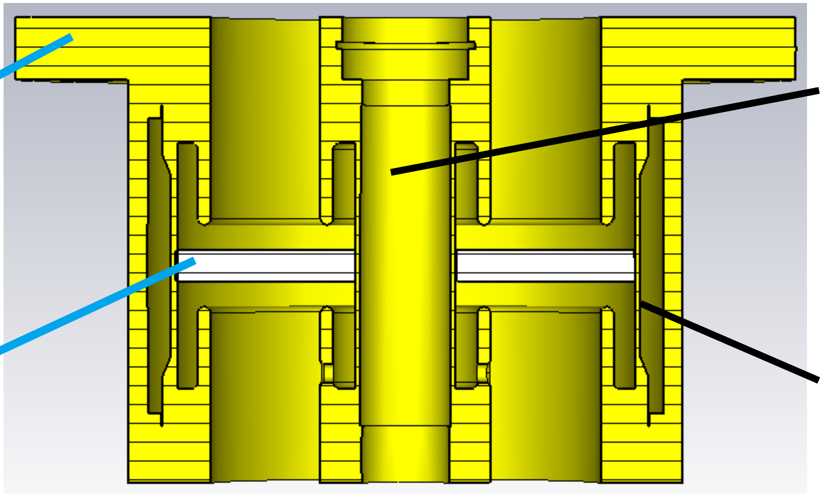


HFSS

Emax=0.188MV/m



Window analysis



Surface ohm loss=3.8W

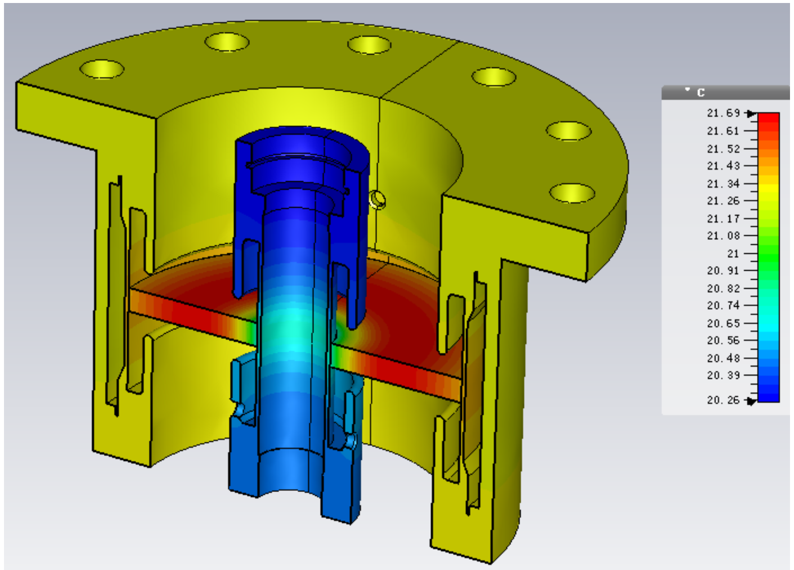
$$\overline{P_J} = \frac{1}{2} R_s \oiint |H|^2\, ds$$

Dielectric loss = 2.2W

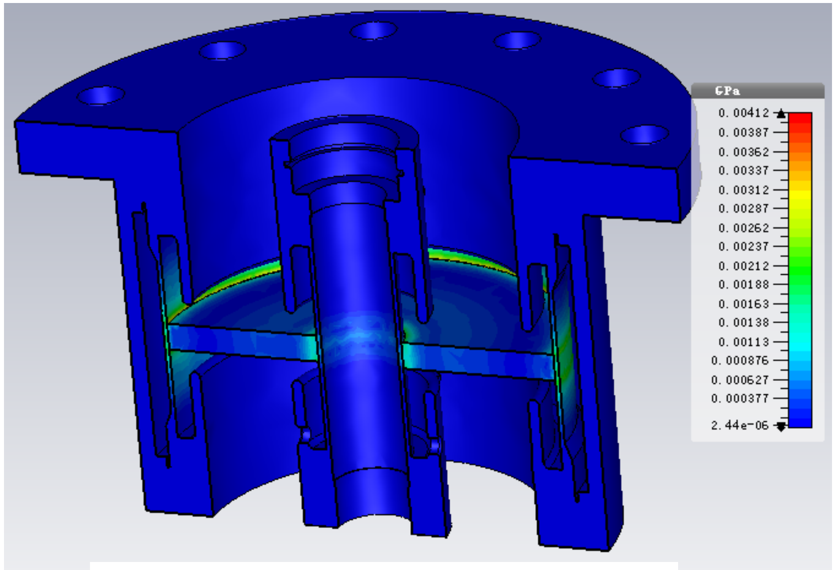
$$\overline{P_E} = \frac{1}{2} \omega \varepsilon_r \varepsilon_0 \tan\delta \oiiint |E|^2\, dv$$

water cooling, 20℃, heat transfer coefficient 2700W/(m·K)

air cooling,20 ℃,heat transfer coefficient 50W/(m·K)



Max. temperature = 21.7℃

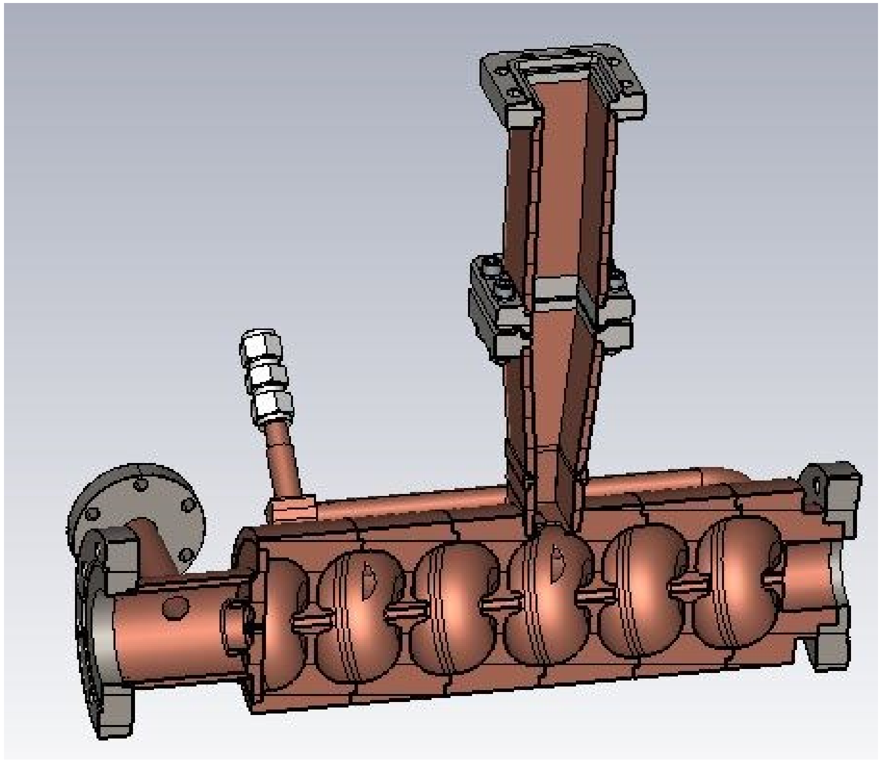


Max. von-Mises = 4.1 MPa

Yield strength of ceramic ~ 200MPa

S band 6 MeV side coupled accelerator structure [4]

- Project status:
  - Design for medical application for Pakistan
  - Design and fabrication have been finished, cold test and tuning is undergoing



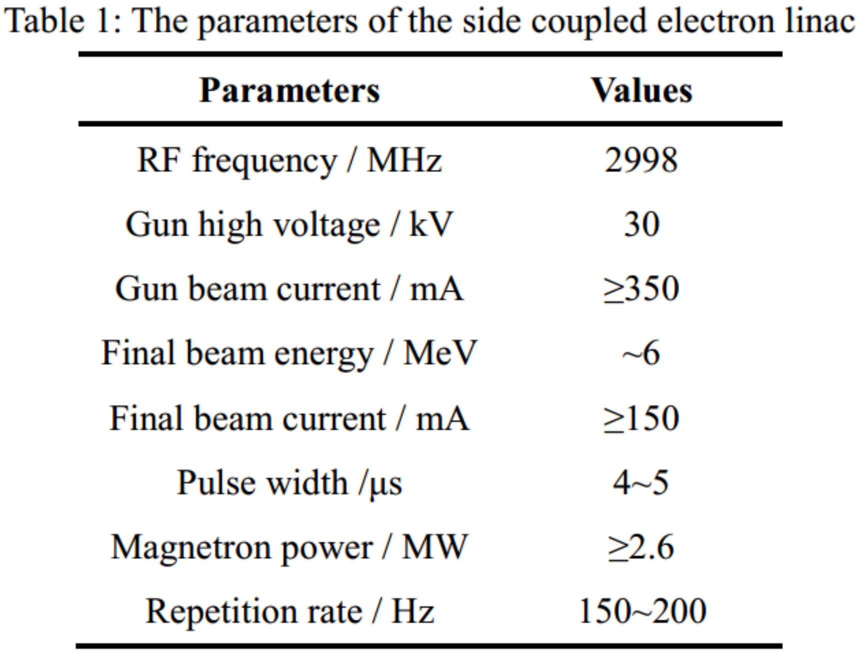


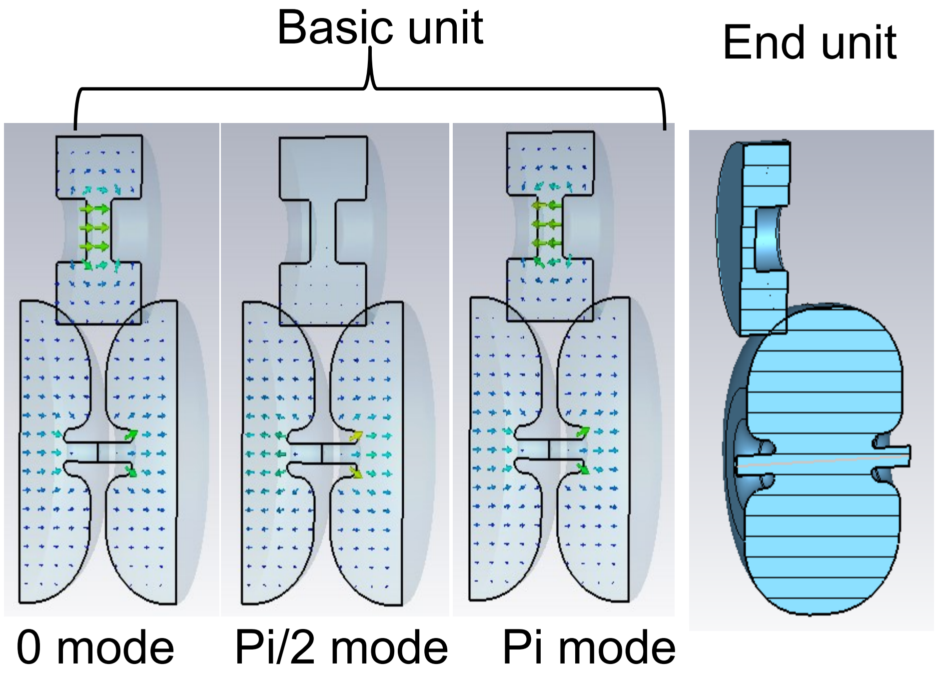
Table 1: The parameters of the side coupled electron linac

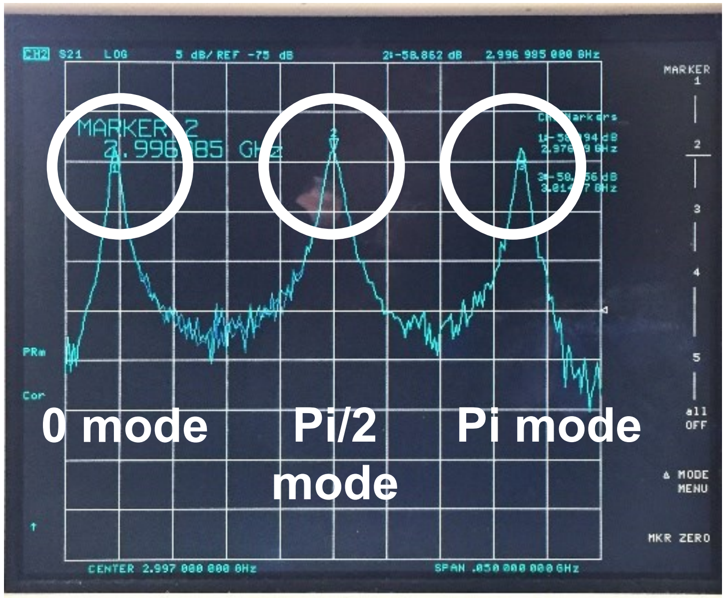
Parameters	Values
RF frequency / MHz	2998
Gun high voltage / kV	30
Gun beam current / mA	≥350
Final beam energy / MeV	~6
Final beam current / mA	≥150
Pulse width /μs	4~5
Magnetron power / MW	≥2.6
Repetition rate / Hz	150~200

RF design by CST MWS
Beam dynamic design by Parmela

RF design

Parameters	Values	Units
Frequency	2998	MHz
Mode	π/2	
Unload Q0	17000	
Shunt impedance Rs	160	MΩ/m
Transient time factor	0.84	
Coupling factor between WG and accelerator	~2	

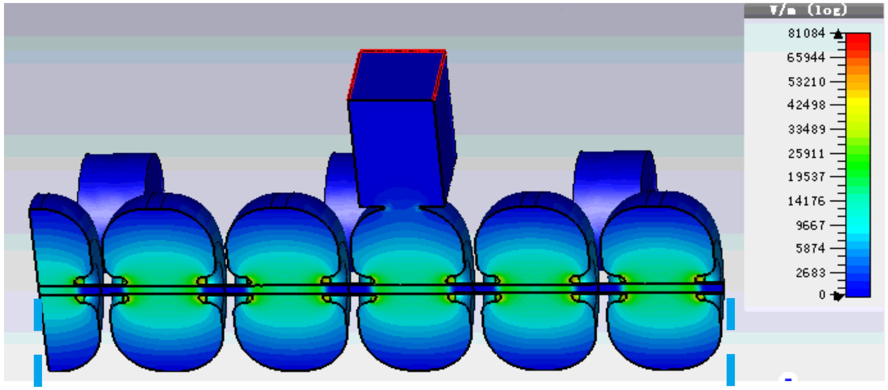




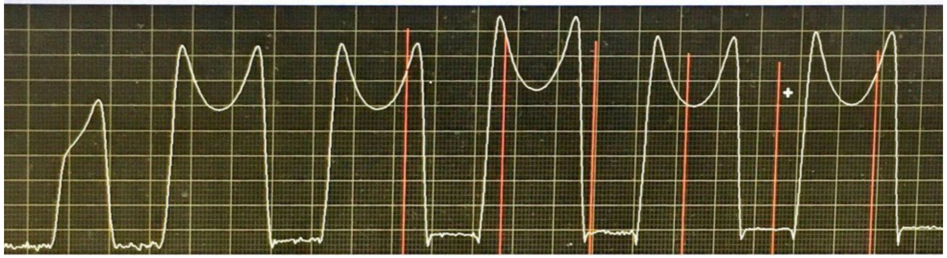
	0 mode [MHz]	Pi/2 mode [MHz]	Pi mode [MHz]
Design	2977.83	2998.43	3015.95
Test	2976.59	2996.99	3014.57

Tuning

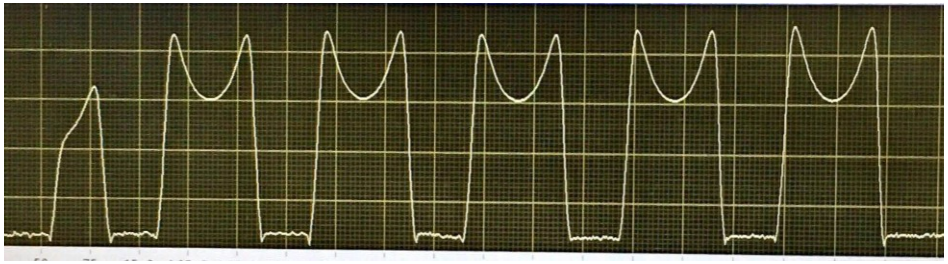
- Optimize the coupling slit size to achieve target coupling factor (~2).
- Coupling slit introduces a perturbation to the coupling cell, frequency tuning of the coupling cell is critical.
- Using the bead-pull measurement method for cell tuning.

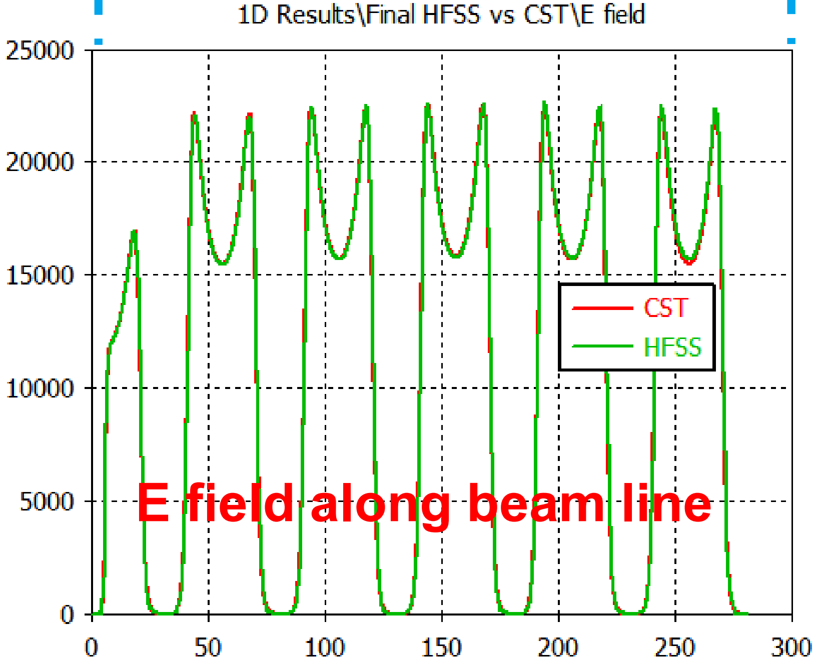


Before tuning



After tuning

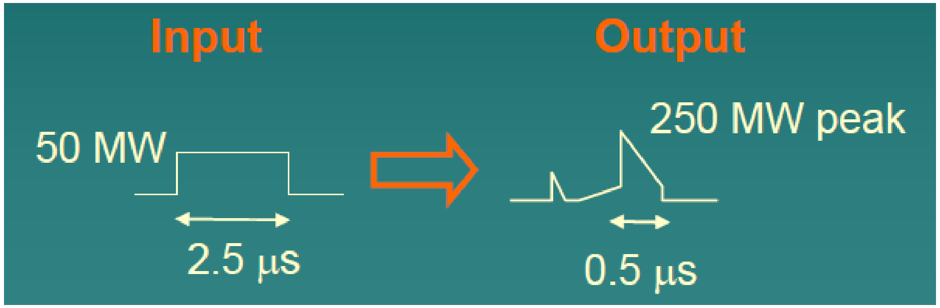




E field along beam line

C band pulse compressor

- Topic of my Ph.D thesis
- SELD design for INFN SPARK energy upgrade project
- BOC is designed for the interest of novel structure



Schematic of Pulse compress

Widely used in:

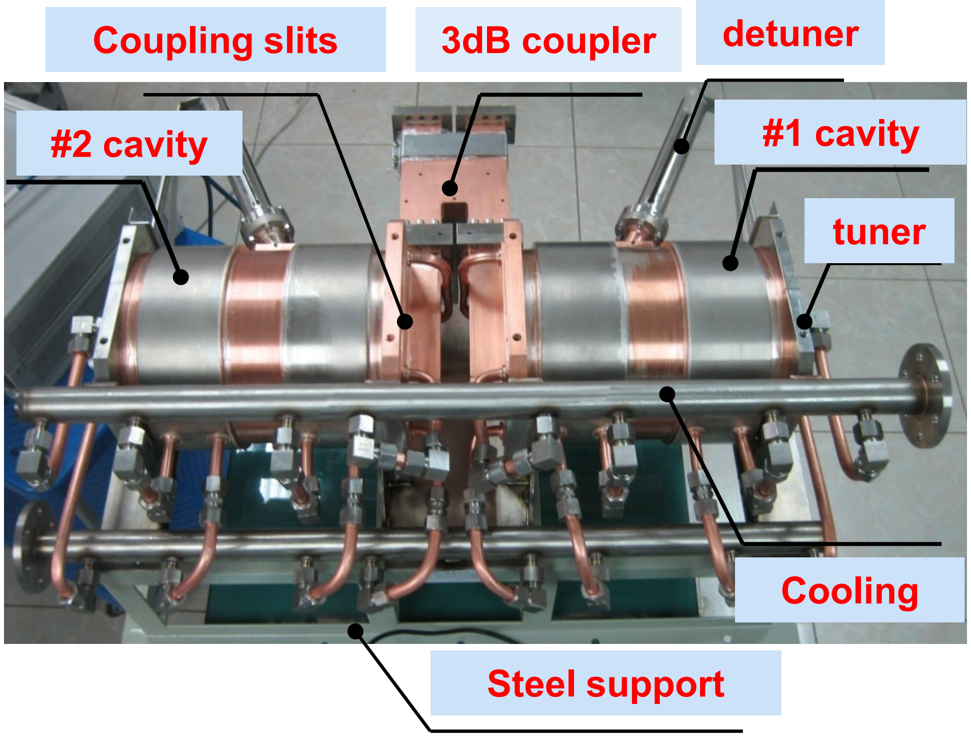
SACLA (SLED)

SWISSFEL(BOC)

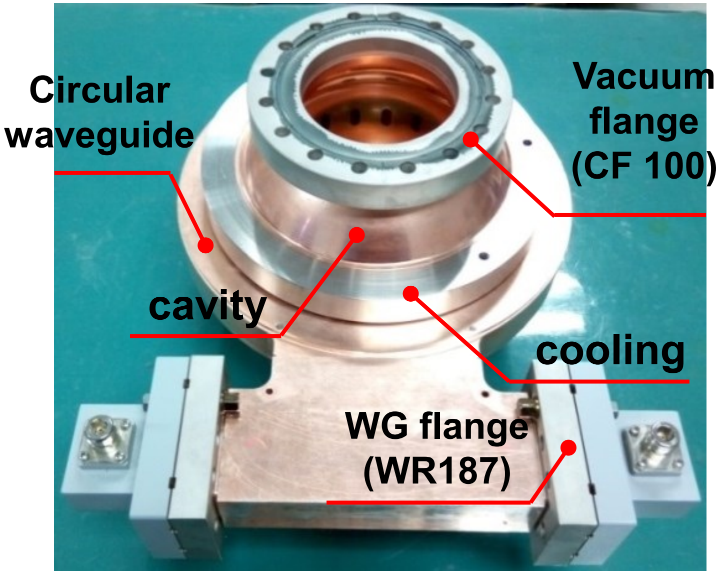
SPARK (SLED)

PAL-XFEL (SLED)

SXFEL (SLED)



Traditional SLED [5]

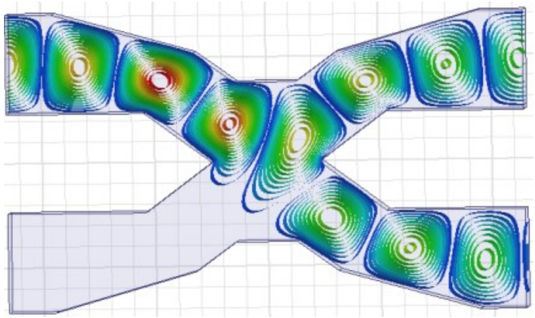


BOC [6]

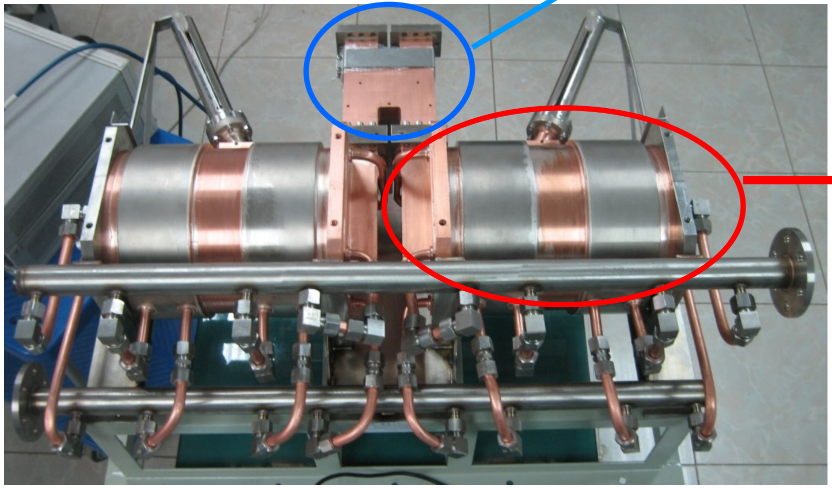
RF design of SLED

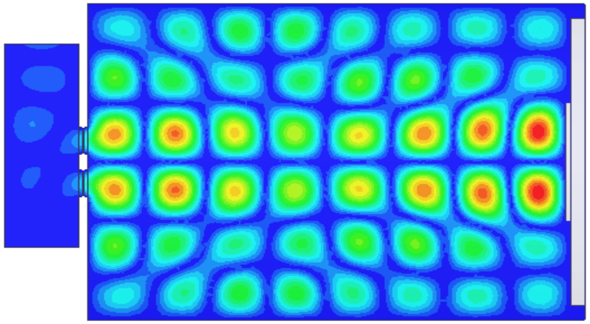
Key points in designing SLED

- Frequency 5.712 GHz
- Mode $TE_{0,3,8}$ with wide mode separation
- Unloaded Q ~150,000, compromise between the cavity size and SLED energy gain
- Coupling factor, determined by the coupling slots dimensions
- Tuning and detuning
- Cooling scheme



3dB coupler



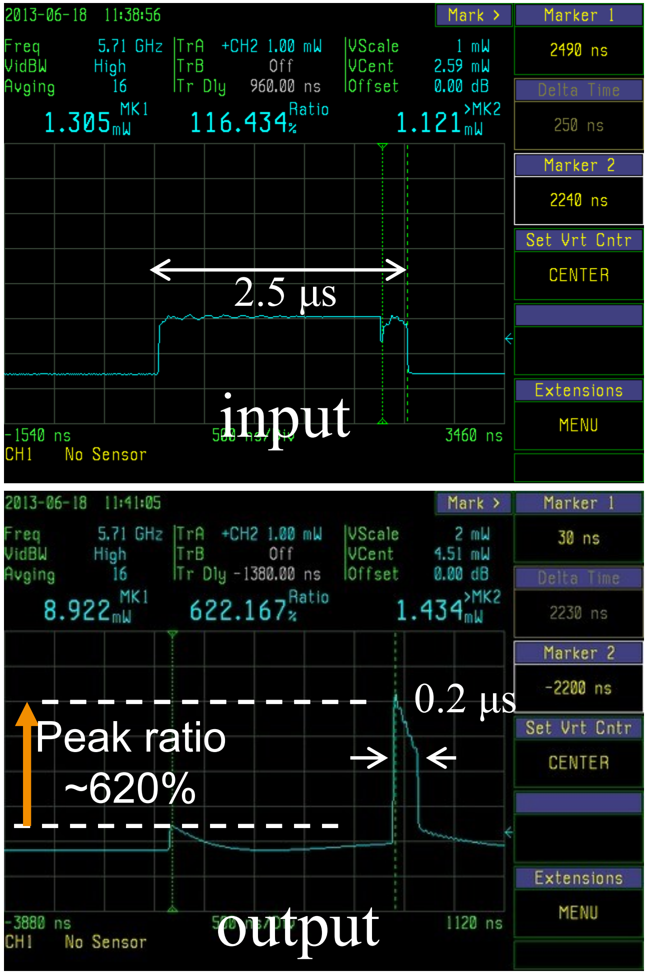


Cavity

Low power test at IHEP

Precisely tuning (±10 kHz) the two cylindrical cavities is the key point in the cold test.

- Maximum the SLED energy gain
- Minimize the reflect power to the power source



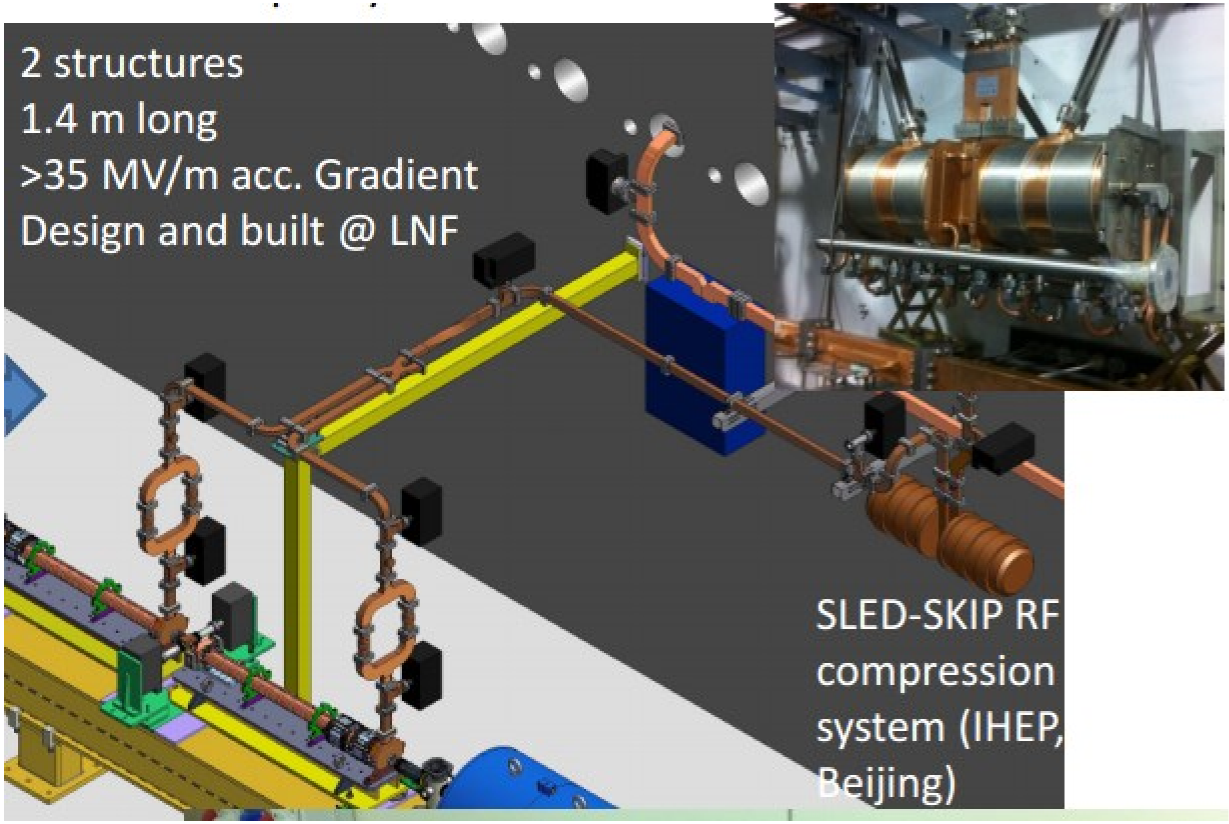
```
2013-06-18  11:38:56                                          Mark >   Marker 1
Freq      5.71 GHz |TrA  +CH2 1.00 mW |VScale      1 mW        2490 ns
VidBW     High     |TrB       Off     |VCent    2.59 mW       Delta Time
Avging    16       |Tr Dly  960.00 ns |Offset   0.00 dB        250 ns
  1.305 mW MK1       116.434% Ratio        1.121 mW >MK2       Marker 2
                                                               2240 ns
-1540 ns                                   3460 ns
CH1   No Sensor
```

```
2013-06-18  11:41:05                                          Mark >   Marker 1
Freq      5.71 GHz |TrA  +CH2 1.00 mW |VScale      2 mW        30 ns
VidBW     High     |TrB       Off     |VCent    4.51 mW       Delta Time
Avging    16       |Tr Dly -1380.00 ns|Offset   0.00 dB        2230 ns
  8.922 mW MK1       622.167% Ratio        1.434 mW >MK2       Marker 2
                                                               -2200 ns
-3880 ns                                   1120 ns
CH1   No Sensor
```

	Design	Test
Frequency / GHz	5.712	5.712
Mode	$TE_{0,3,8}$	$TE_{0,3,8}$
Unloaded Q	150000	130000
Coupling factor	7.0	6.5
Tuning range / MHz	>2 MHz	> 2MHz
Peak power gain	>600%	620%

Current status

This SLED was delivered to INFN in 2015, installed at the SPARK tunnel for the energy upgrade program.



2 structures
1.4 m long
>35 MV/m acc. Gradient
Design and built @ LNF

SLED-SKIP RF compression system (IHEP, Beijing)

Design of BOC

- RF design

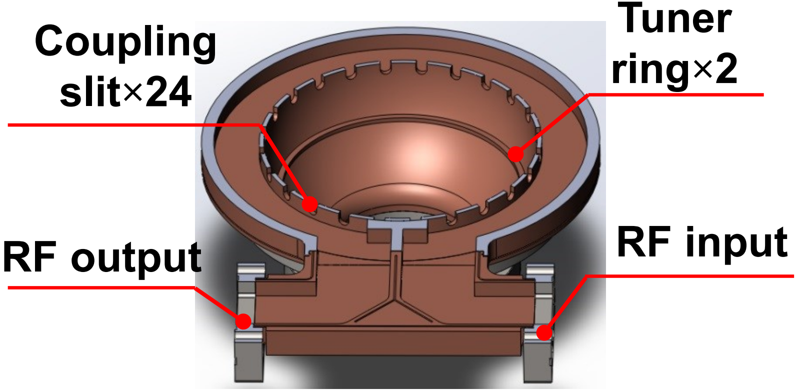
  Key points in designing BOC

  - Frequency 5.712 GHz
  - Mode $TE_{6,1,1}$
  - Unloaded Q ~100,000
  - Coupling factor ~ 4.0
  - Travelling wave resonator
  - TW in the waveguide and cavity should be synchronous to avoid reflect power

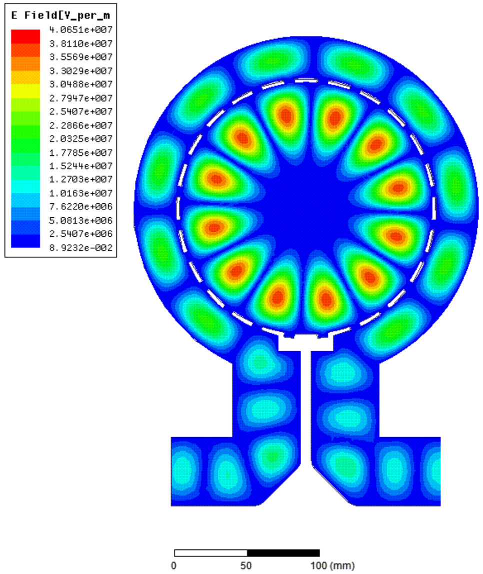
- Mechanical design

  - Machining error, surface roughness,

    braze process, cooling scheme…

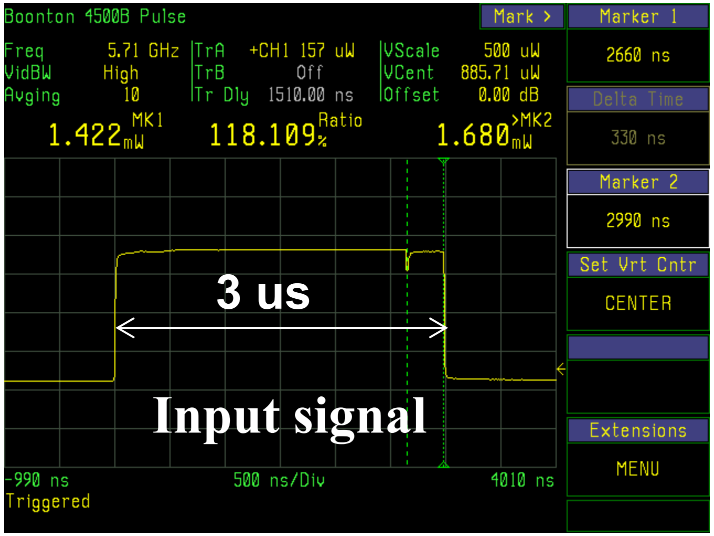


BOC cutview

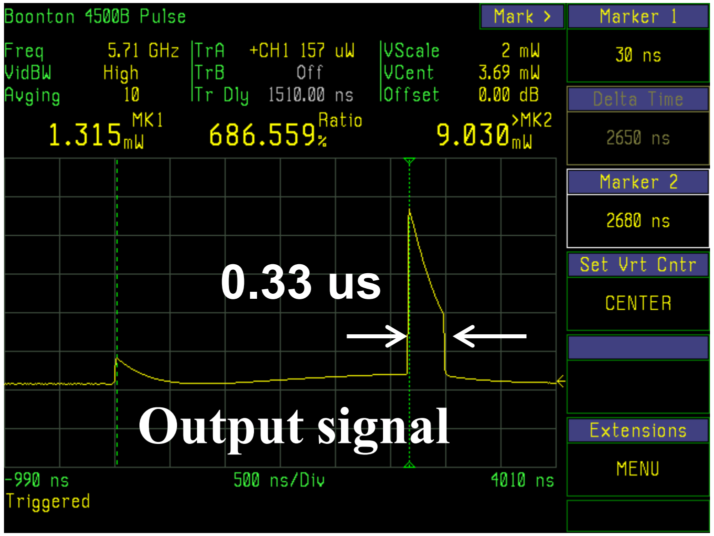


Synchronous waves in the outer waveguide and inner cavity

Cold test



```
Boonton 4500B Pulse
Freq      5.71 GHz  TrA    +CH1 157 uW  VScale   500 uW
VidBW     High      TrB         Off     VCent    885.71 uW
Avging    10        Tr Dly  1510.00 ns  Offset   0.00 dB
1.422 mW MK1        118.109 % Ratio     1.680 mW >MK2
-990 ns             500 ns/Div          4010 ns
Triggered
Marker 1  2660 ns
Delta Time  330 ns
Marker 2  2990 ns
```



```
Boonton 4500B Pulse
Freq      5.71 GHz  TrA    +CH1 157 uW  VScale   2 mW
VidBW     High      TrB         Off     VCent    3.69 mW
Avging    10        Tr Dly  1510.00 ns  Offset   0.00 dB
1.315 mW MK1        686.559 % Ratio     9.030 mW >MK2
-990 ns             500 ns/Div          4010 ns
Triggered
Marker 1  30 ns
Delta Time  2650 ns
Marker 2  2680 ns
```

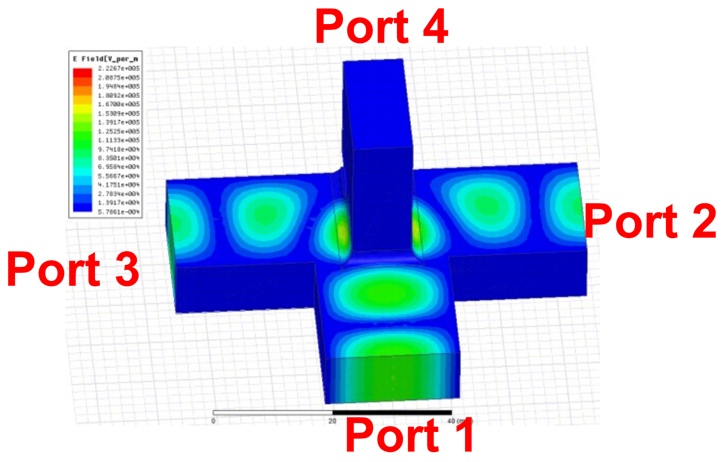
BOC specifications

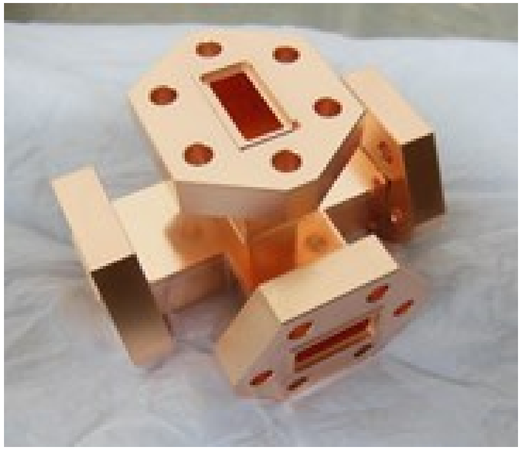
	Design	Test
Frequency/ GHz	5.712	5.7146
Resonant mode	TM_{611}	TM_{611}
Unload Q-factor	**95000**	**87700**
Coupling factor	4	4.7
Insert loss at detuned condition /dB	-0.1	-0.46
Peak power gain	**600%**	**560%**
Average power gain	4.21	3.50

The cold test shows the expected results, the high power conditioning has not been done because of the lack of C band klystron system.

R&D high power RF components

- X band (11.424GHz) magic tees for KEK (2013.09)





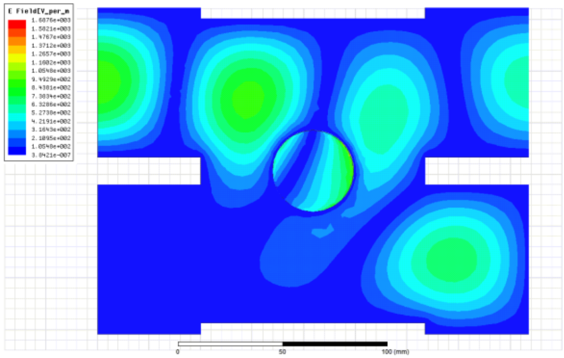
Cold test:

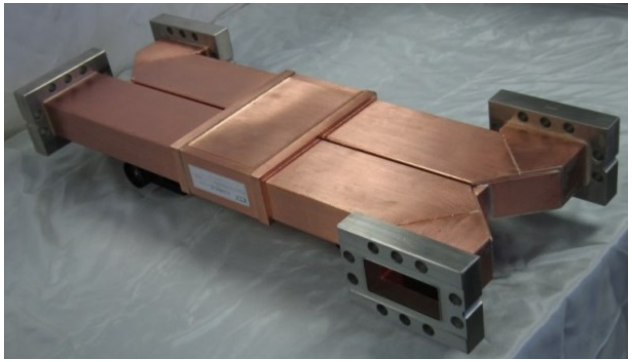
VSWR 1:1.05

S21= -3.0dB; S31=-2.9dB

Isolation 46.7 dB

- S band (2.856GHz) 2.5 dB directional coupler for PAL (2014.10)





Cold test:

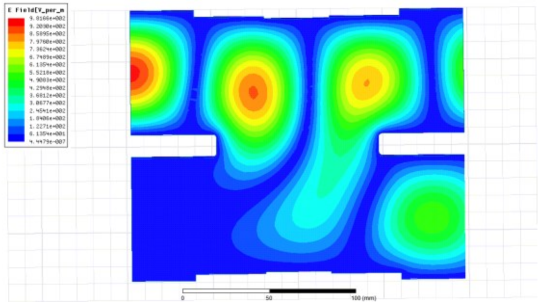
VSWR 1:1.04

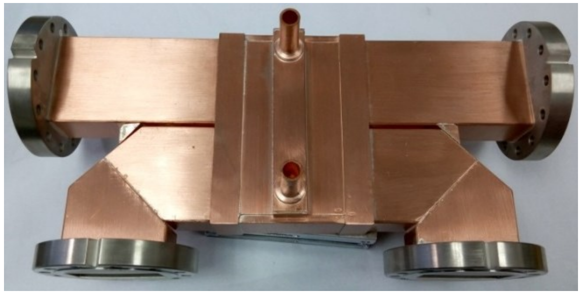
Coupling -2.55 dB

Isolation 45.7 dB

S band directional coupler

- S band (2.856GHz) 5 dB directional coupler



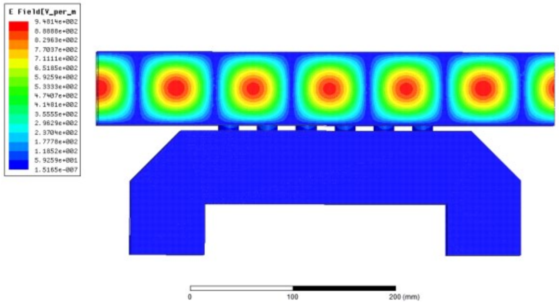


VSWR 1:1.06

Coupling -5.10 dB

Isolation 42.3 dB

- S band (2.856GHz) 25 dB directional coupler

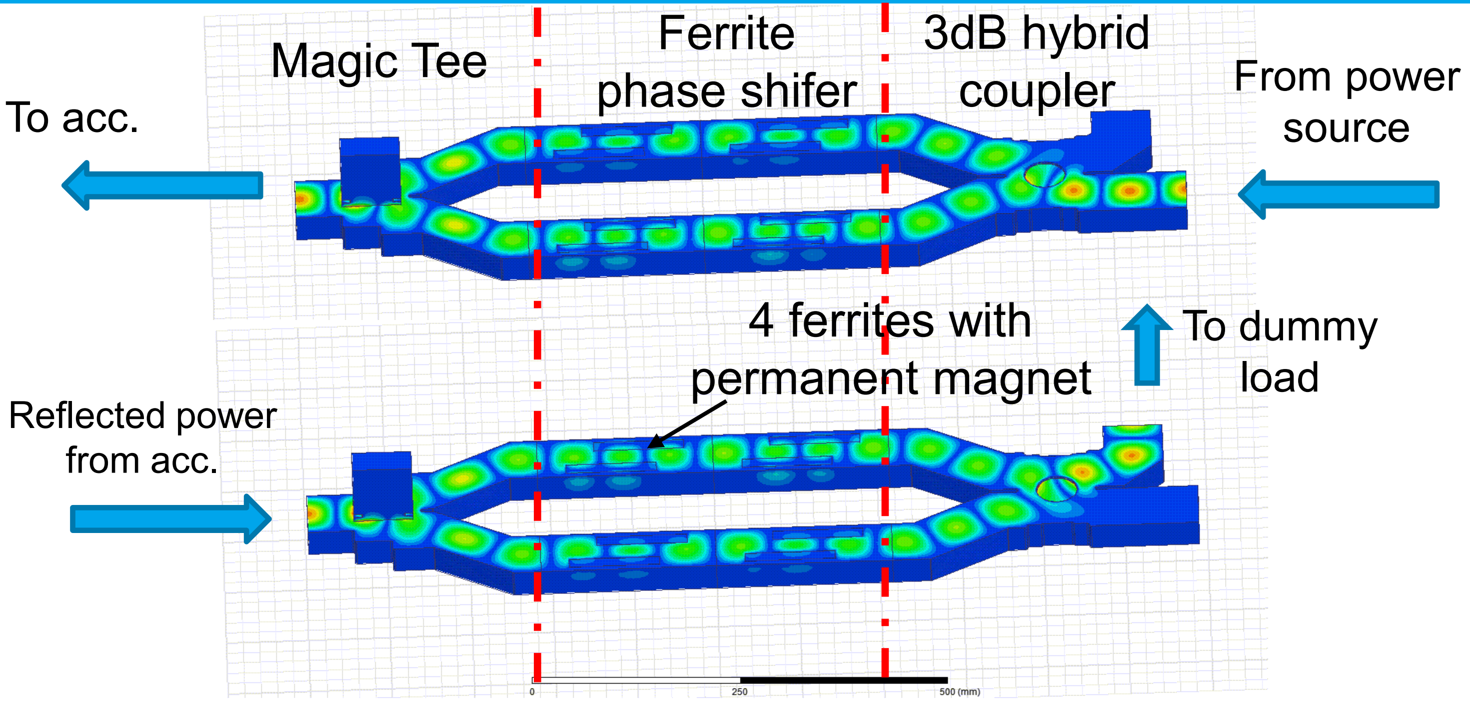


VSWR 1:1.06

Coupling -25.2 dB

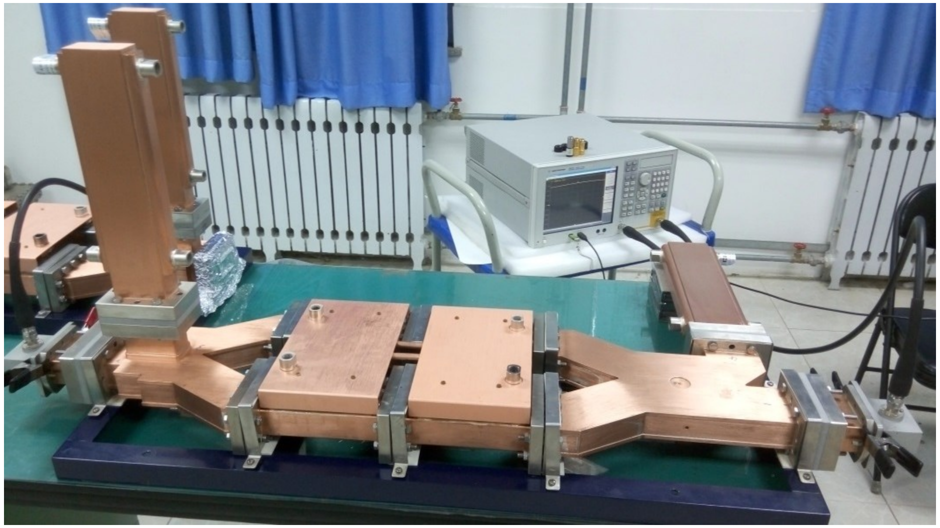
Isolation 39 dB

S band (2.998 GHz) high vacuum circulator

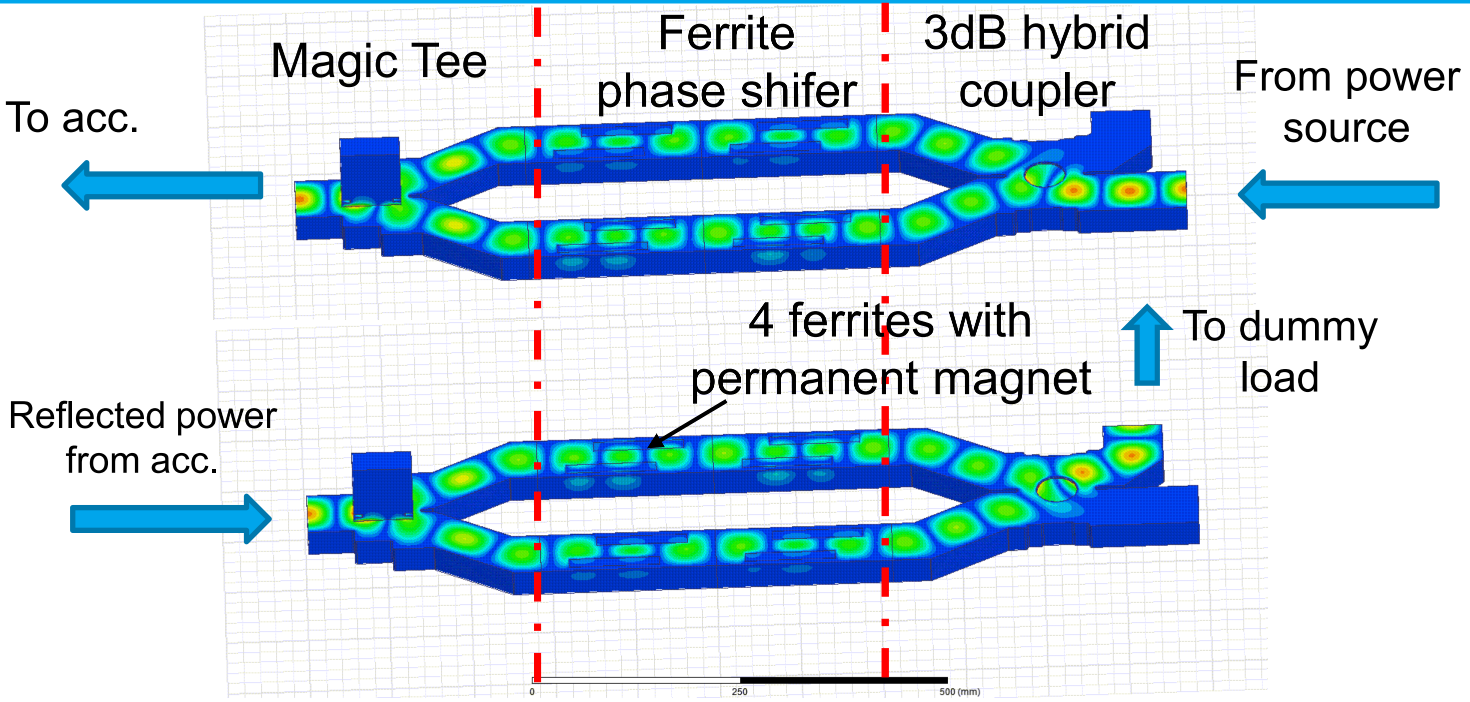


Cold test results

Parameters	Value
VSWR	1.02
Insert loss [dB]	0.36
Isolation [dB]	33.3
Vacuum leak rate	<10^{-10} Torr·l/sec



S band (2.998 GHz) high vacuum circulator



Magic Tee

Ferrite phase shifer

3dB hybrid coupler

To acc.

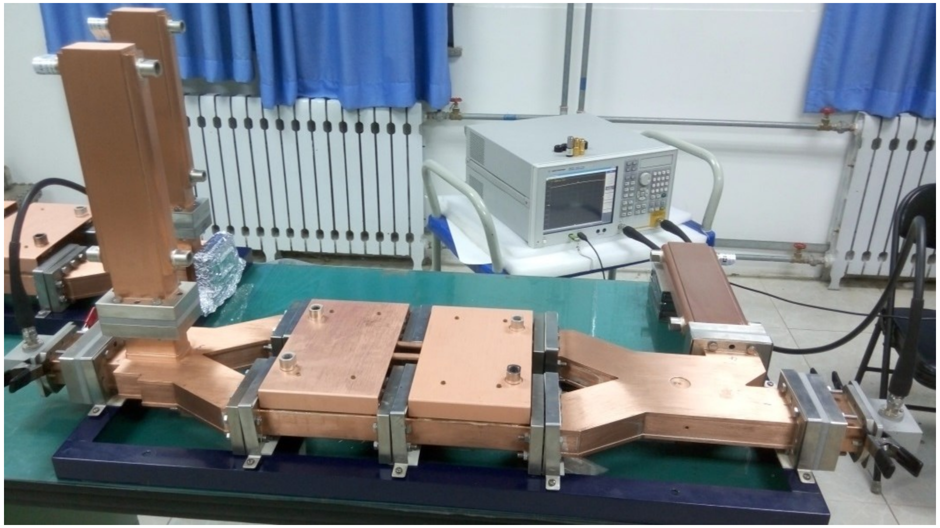
From power source

4 ferrites with permanent magnet

To dummy load

Reflected power from acc.

High power test will take place in May, 2018 at IHEP.



Summary

- During several years training, a series of accelerator RF components were designed and tested. The experience of CW buncher cavity and coupler may be helpful for the design of CW RF gun of DESY.
- The design of CW RF gun of DESY has already started. Some preliminary results have been obtained. Another talk?

Reference

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Thank you for your time!