Development of HOM coupler with C-shaped waveguide for ERL operation

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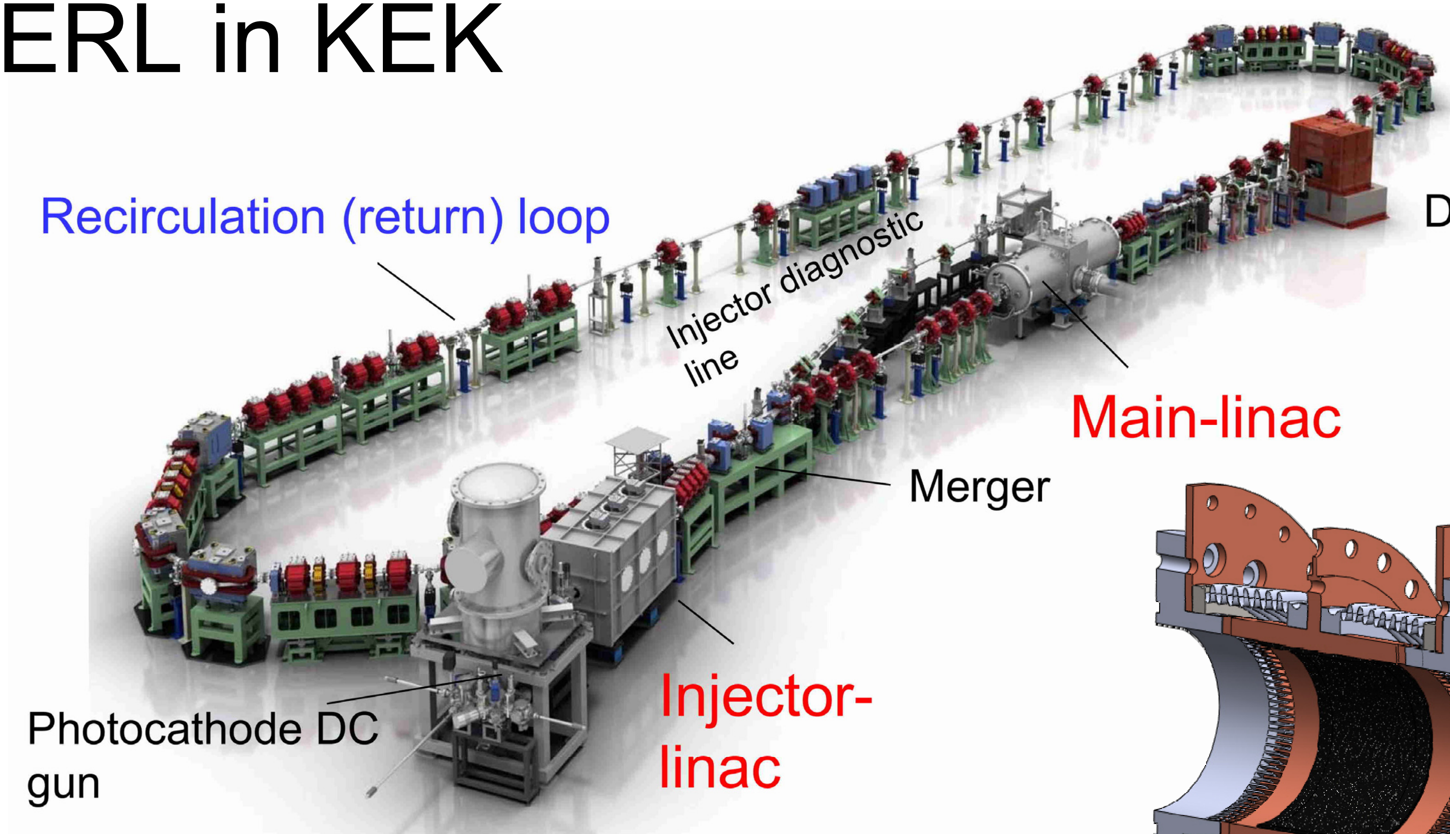
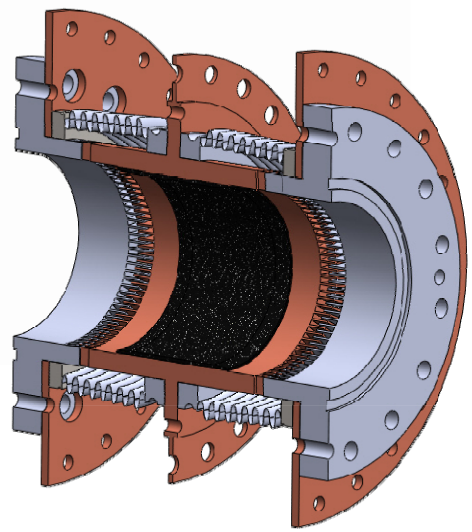
Workshop on Energy Recovery Linacs (ERL2019)

cERL in KEK



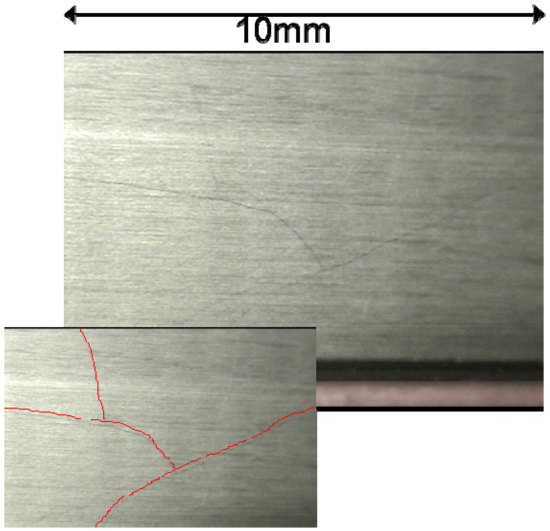
- Completed in 2013, and being operated
- Developed Main-linac
  - Development items
    - Cavity
    - Input coupler
    - Beamline HOM absorber
    - Tuner, etc.

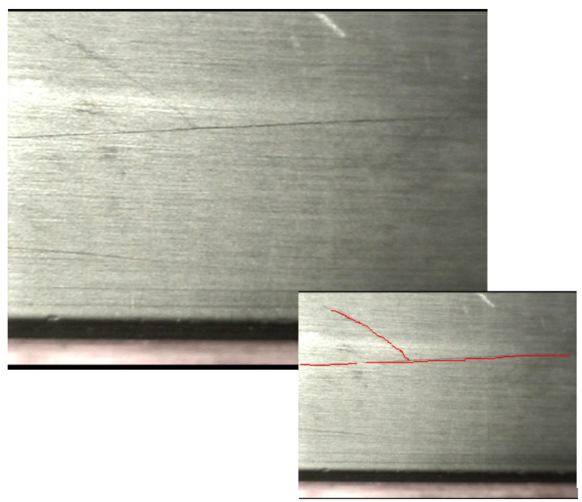


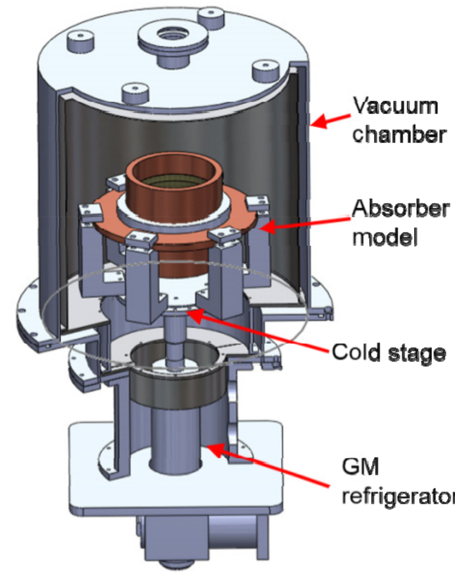
- Design
  - HIP ferrite of new-type IB004
  - Comb-type RF bridge
  - Two kinds of thermal anchor at 80K and 4K

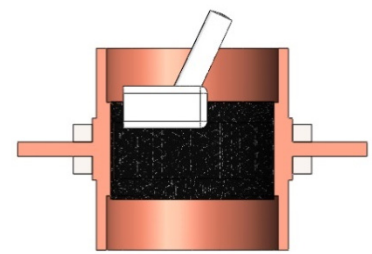
Cooling Cycle Test

- Controlled temperature pattern
  - RT → 80K (3 days) → keep (1 day) →RT (3days)
- Results of surface inspection
  - Cracks occurred especially near taper









- Other matters of concern
  - Total length (cavity + beamline + absorber) is long
    - low effective accelerating field
  - Source of gas and dust

Desirable HOM attenuator properties

- ability to install near the cavity not to decrease the effective accelerating field
- effective cooling to avoid temperature rise for high power of HOMs
- separation of RF absorbers (ceramics and ferrites) from the cavity vacuum to avoid sources of outgas and dust
- compactness to reduce the cryomodule size

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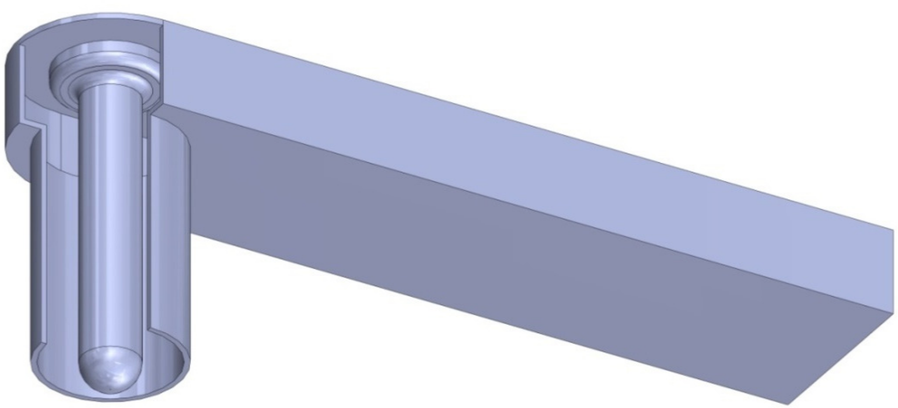
How about Coaxial-Waveguide converter?



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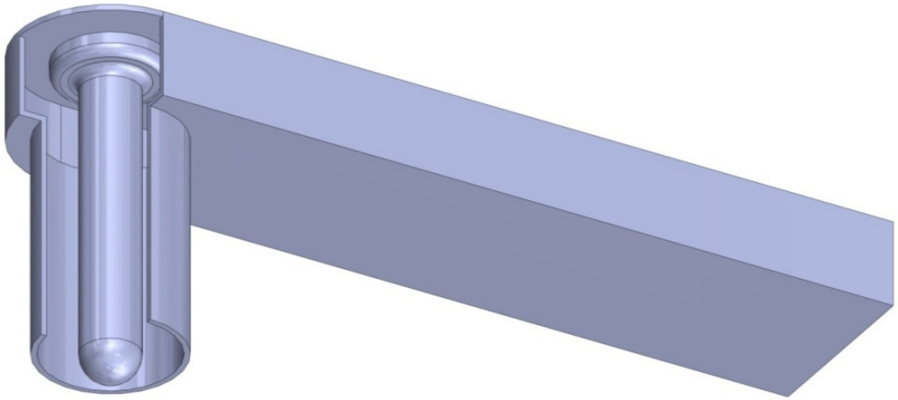
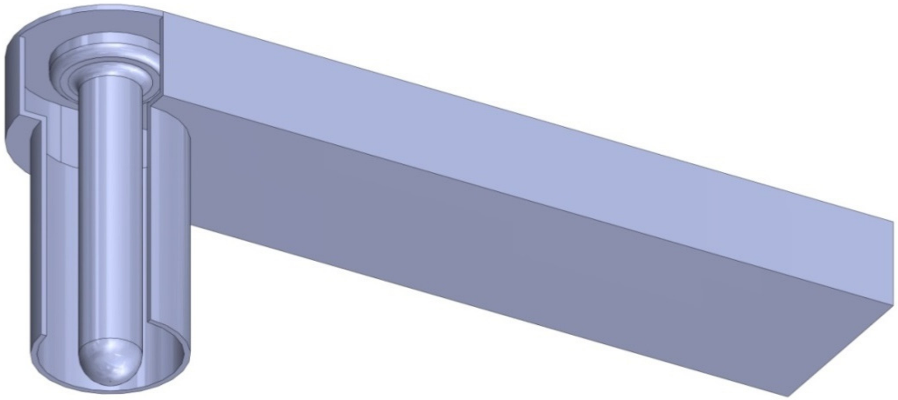


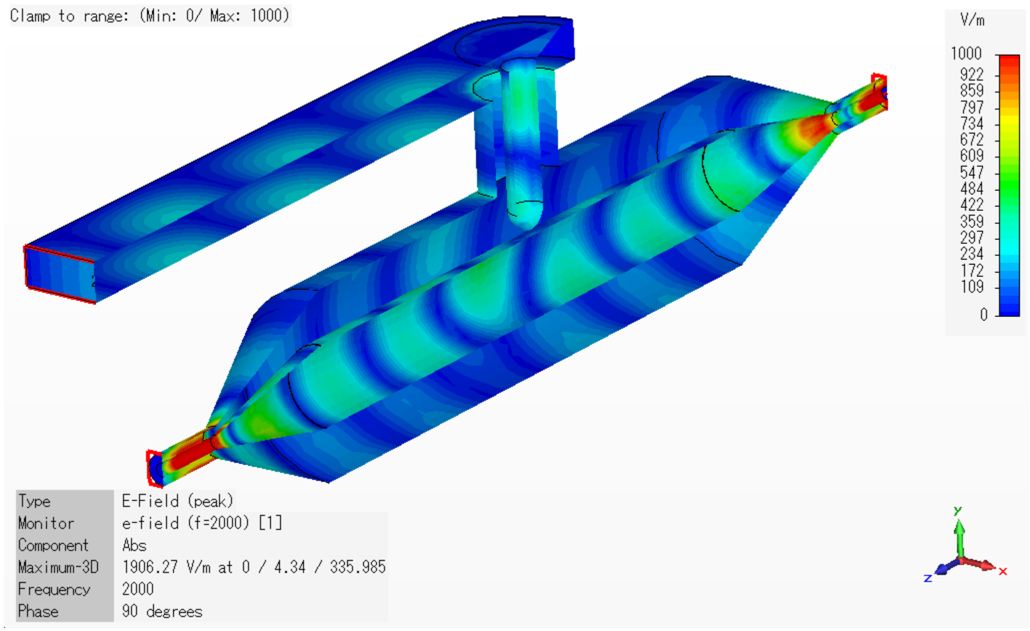
Desirable HOM attenuator properties

- ability to install near the cavity not to decrease the effective accelerating field
  - High-pass filter in principle
- effective cooling to avoid temperature rise for high power of HOMs
  - connected to WG
- separation of RF absorbers (ceramics and ferrites) from the cavity vacuum to avoid sources of outgas and dust
  - Possible
- compactness to reduce the cryomodule size

How about Coaxial-Waveguide converter?

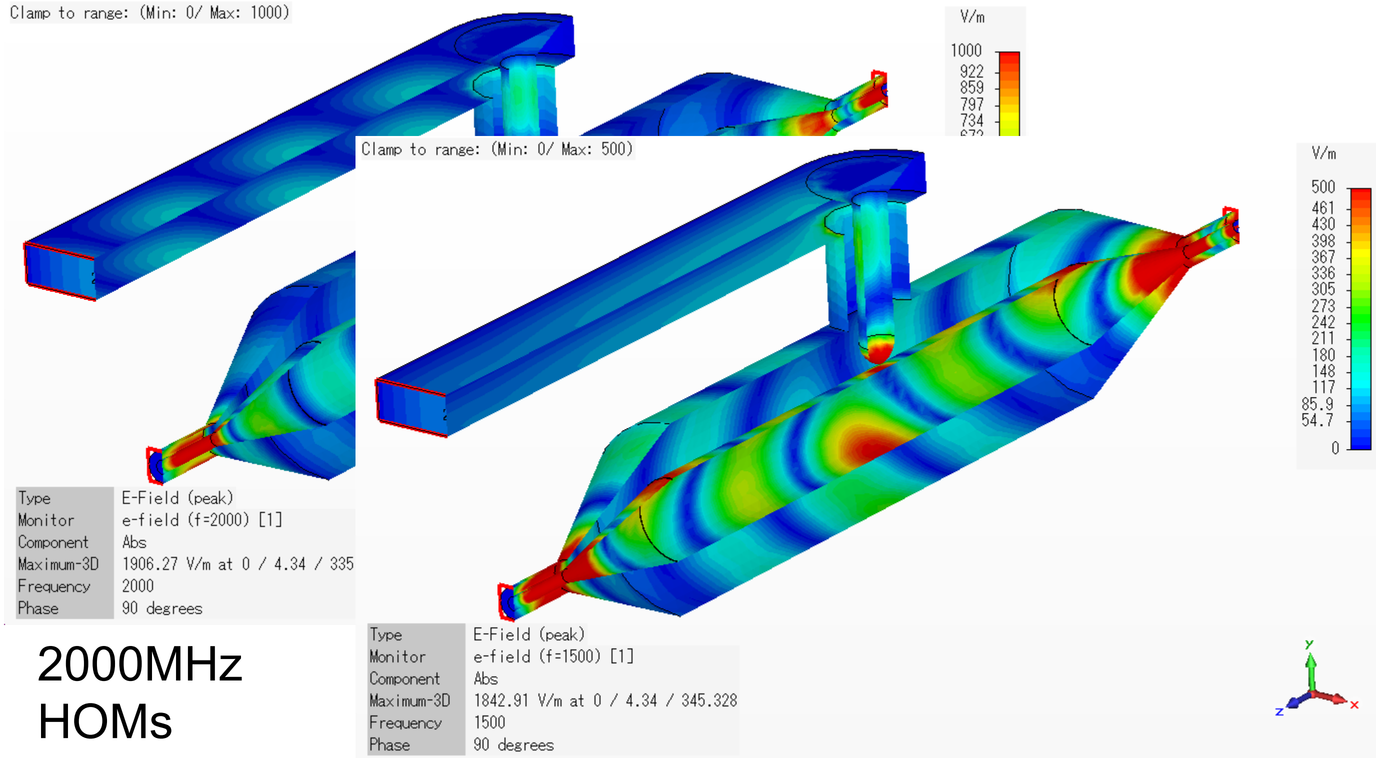


Coaxial-waveguide converter type



2000MHz
HOMs

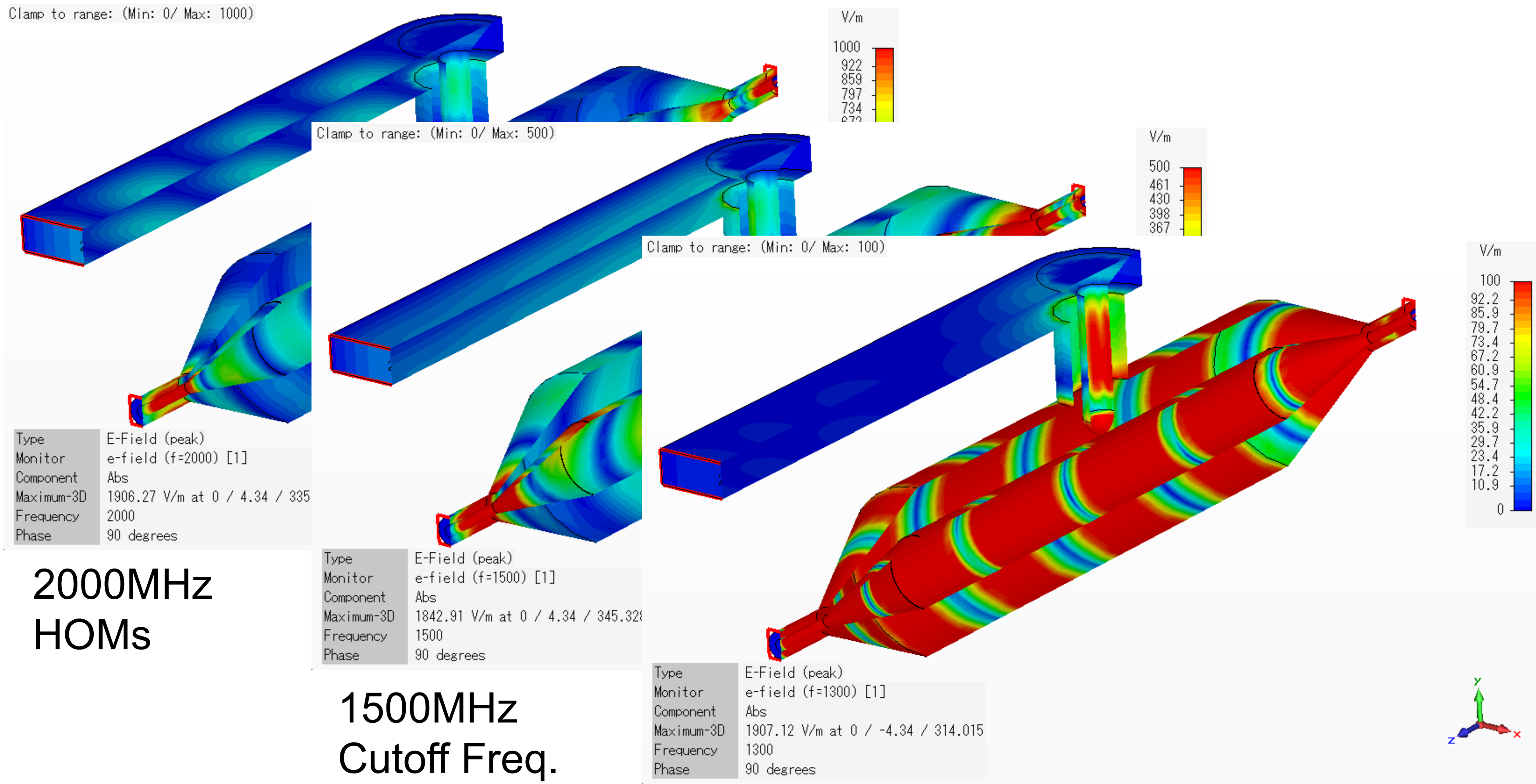
Coaxial-waveguide converter type



2000MHz
HOMs

1500MHz
Cutoff Freq.

Coaxial-waveguide converter type

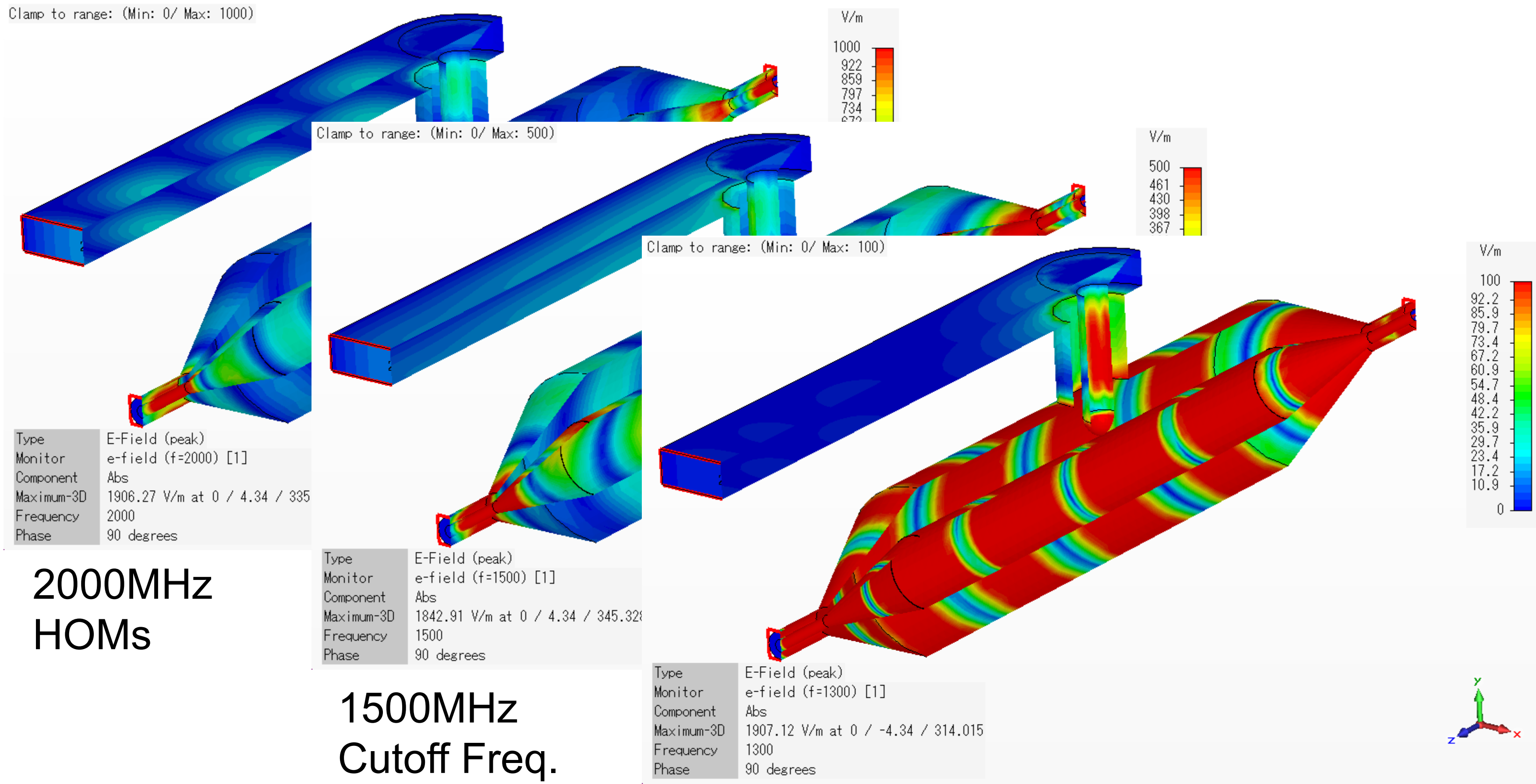


2000MHz
HOMs

1500MHz
Cutoff Freq.

1300MHz
Acc. mode

Coaxial-waveguide converter type

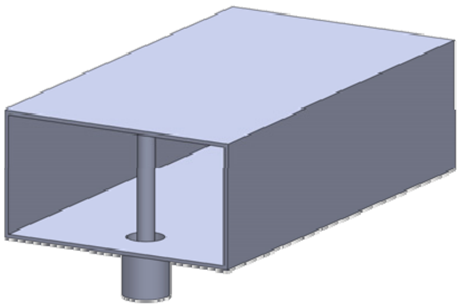


2000MHz
HOMs

1500MHz
Cutoff Freq.

1300MHz
Acc. mode

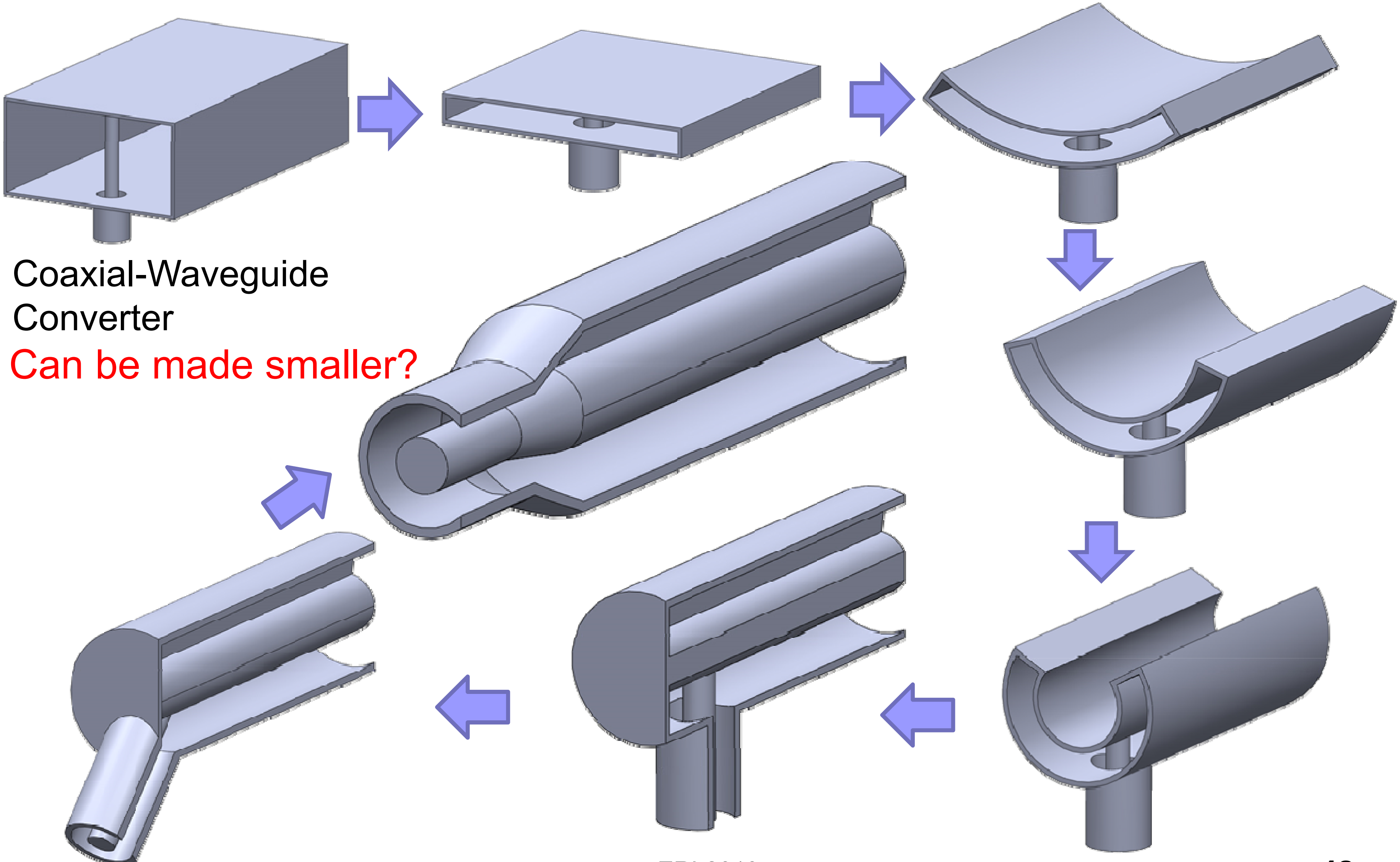
- Acc. mode cannot transmit through waveguide ⇨ But, Large



Coaxial-Waveguide Converter

Can be made smaller?

C-Shaped Wave Guide (CSWG)

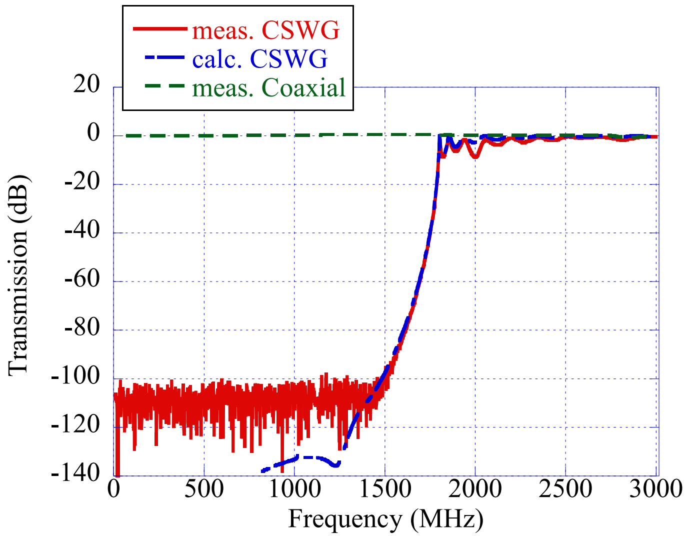


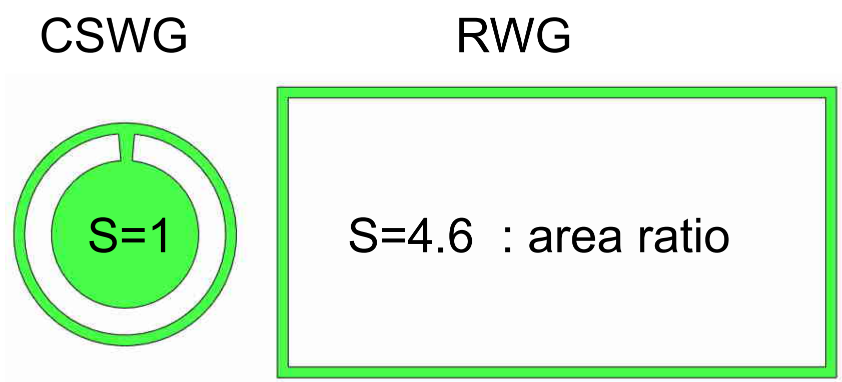
Coaxial-Waveguide Converter

Can be made smaller?

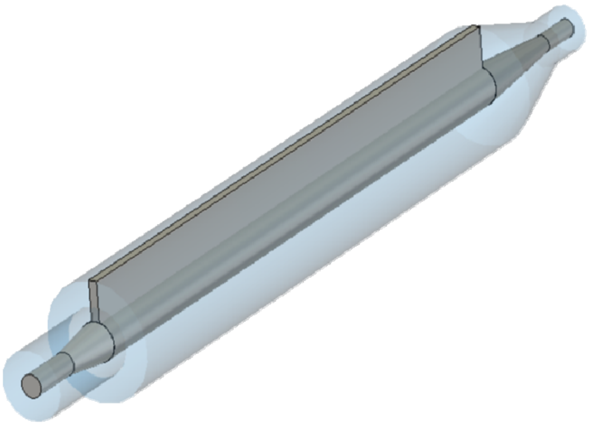
Characteristics of CSWG

- High-pass filter in principle and Adjustment-free
- Easy cooling of inner conductor through connection plate
- Easy convert to coaxial-line
- Compactness





Same cutoff frequency



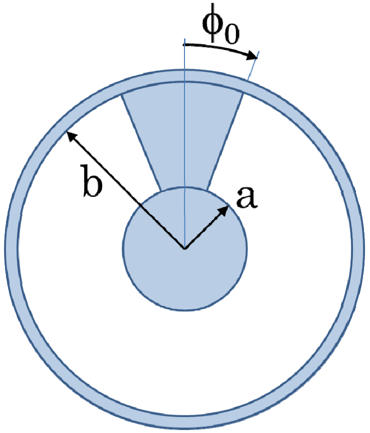
Cutoff Frequency

- general solution of TE mode in circular cylindrical coordinates

$$E_r = C\frac{j\omega\mu\nu}{k_c^2}\frac{1}{r}\left[A_1 J_\nu(k_c r) + A_2 Y_\nu(k_c r)\right]\sin(\nu\phi - \phi_c)$$

$$E_\phi = C\frac{j\omega\mu}{k_c}\left[A_1 J_\nu^{'}(k_c r) + A_2 Y_\nu^{'}(k_c r)\right]\cos(\nu\phi - \phi_c)$$

$$\nu = \frac{\pi}{2(\pi - \phi_0)}$$



- Boundary Conditions

$$\phi = \pm\phi_0 \Rightarrow E_r = 0 \quad and \quad r = a, b \Rightarrow E_\phi = 0$$

- Eigenvalue

$$J_\nu^{'}(k_c a)Y_\nu^{'}(k_c b) - J_\nu^{'}(k_c b)Y_\nu^{'}(k_c a) = 0$$

approximate solution

$$k_c \approx \frac{2\nu}{a+b}$$

- Cutoff wavelength

$$\lambda_c = \frac{2\pi}{k_c} \approx 2\times\frac{\pi - \phi_0}{\pi}\times\pi(a+b)$$

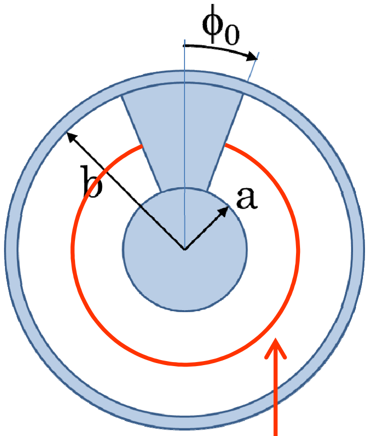
Cutoff Frequency

- general solution of TE mode in circular cylindrical coordinates

$$E_r = C\frac{j\omega\mu\nu}{k_c^2}\frac{1}{r}\left[A_1 J_\nu(k_c r) + A_2 Y_\nu(k_c r)\right]\sin(\nu\phi - \phi_c)$$

$$E_\phi = C\frac{j\omega\mu}{k_c}\left[A_1 J_\nu'(k_c r) + A_2 Y_\nu'(k_c r)\right]\cos(\nu\phi - \phi_c)$$

$$\nu = \frac{\pi}{2(\pi - \phi_0)}$$



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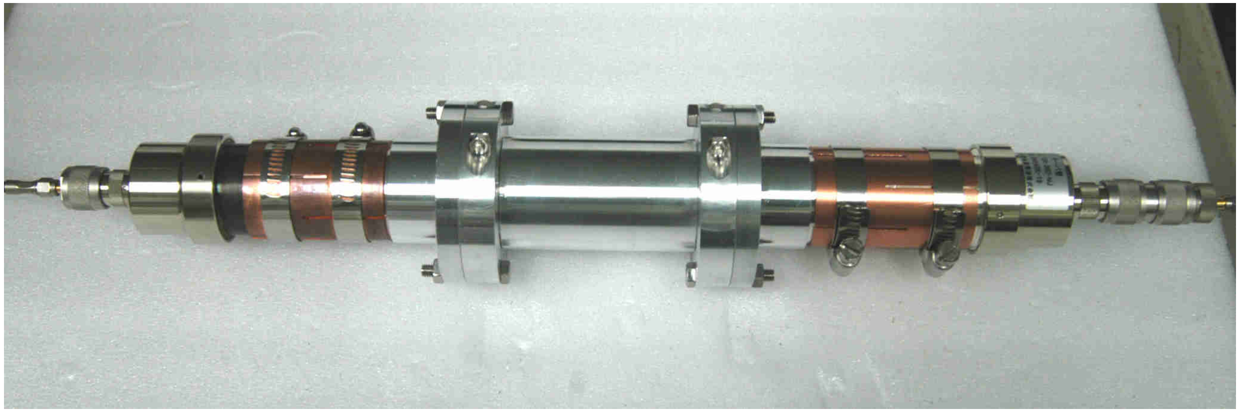
Average circumference

CSWG model



Parallel Radial

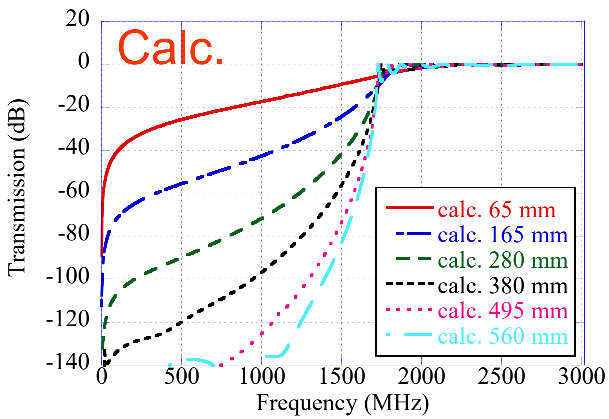
- CSWG model parameters

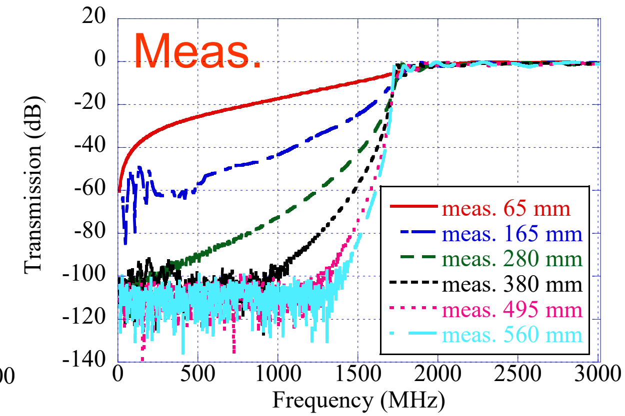
	1	2	3	4	5	6	7	8
Outer diameter	42mm							
Inner diameter	9mm	12mm	15mm	18mm				
Connection plate	Parallel				Radial			
	4mm				15deg	30deg	45deg	60deg
Cutoff frequency (MHz)	2115	1996	1822	1732	1783	1959	2180	2444
Length	65mm, 115mm, 165mm, 215mm （65~560mm)							

- Measure S_{21}

Calculation vs. Measurement

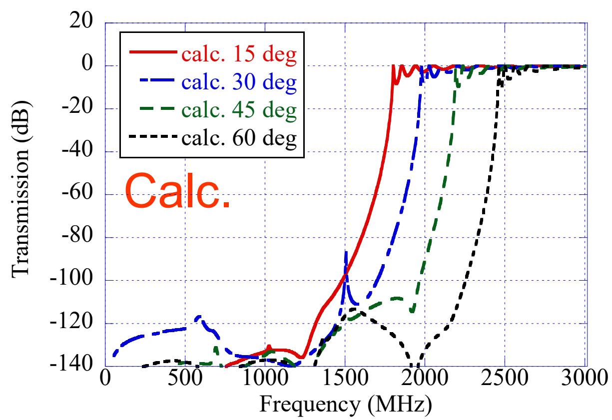
- Different CSWG Length

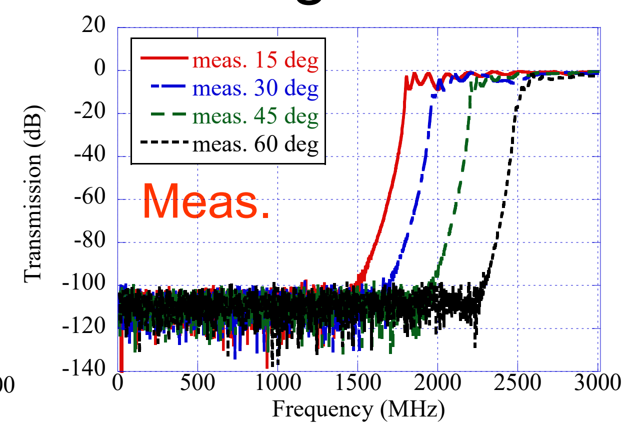




O.D. 42mm
I.D. 18mm
Connection plate: Parallel
Cutoff freq. 1732MHz

- Different Connection Plate Angle

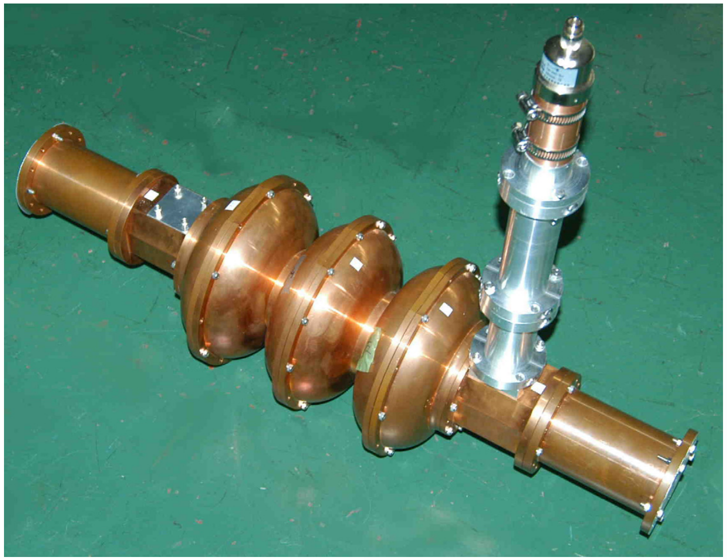


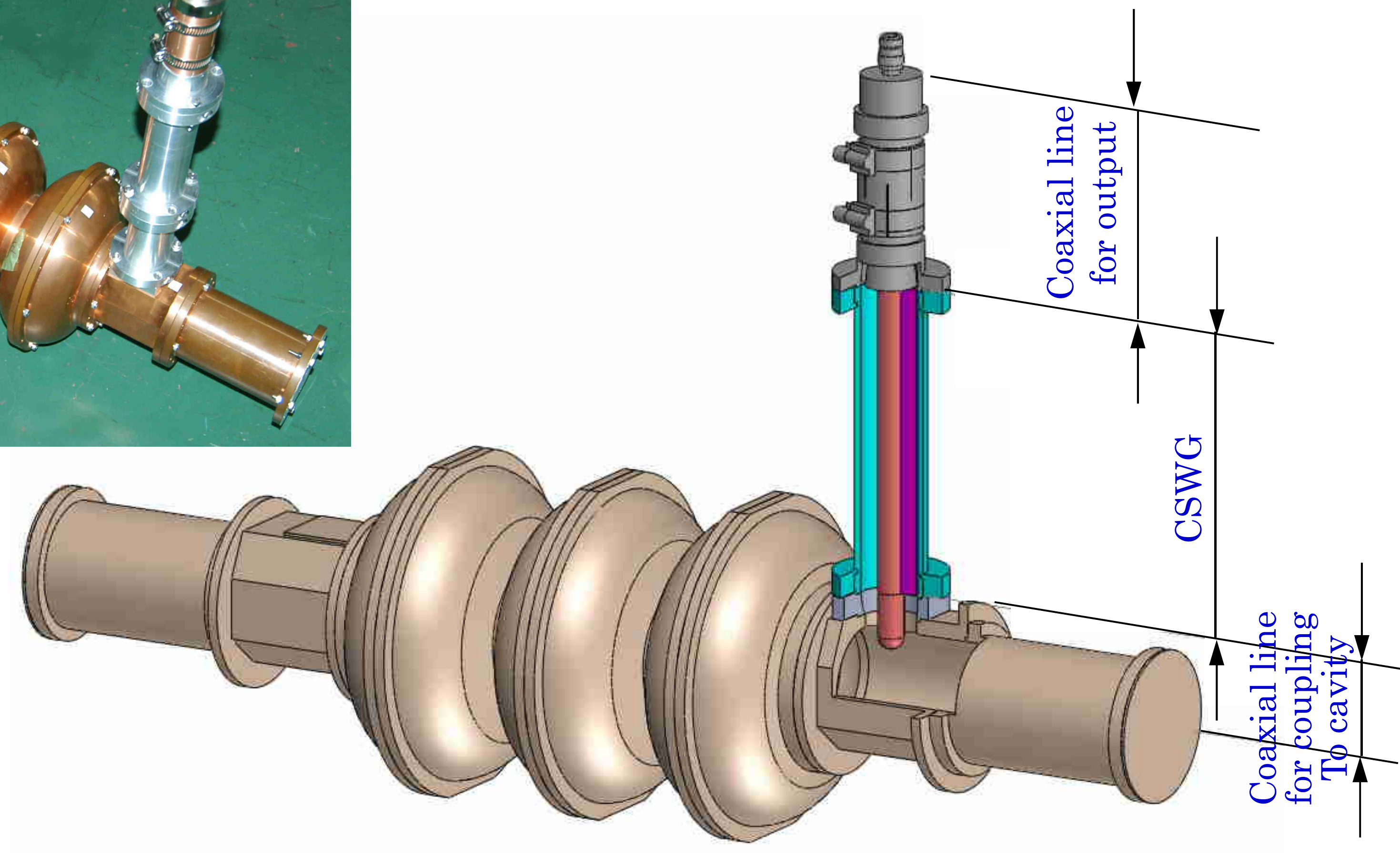


O.D. 42mm
I.D. 18mm
Length 560mm
Connection plate: Radial
Cutoff freq. 1783, 1959, 2180, 2444MHz

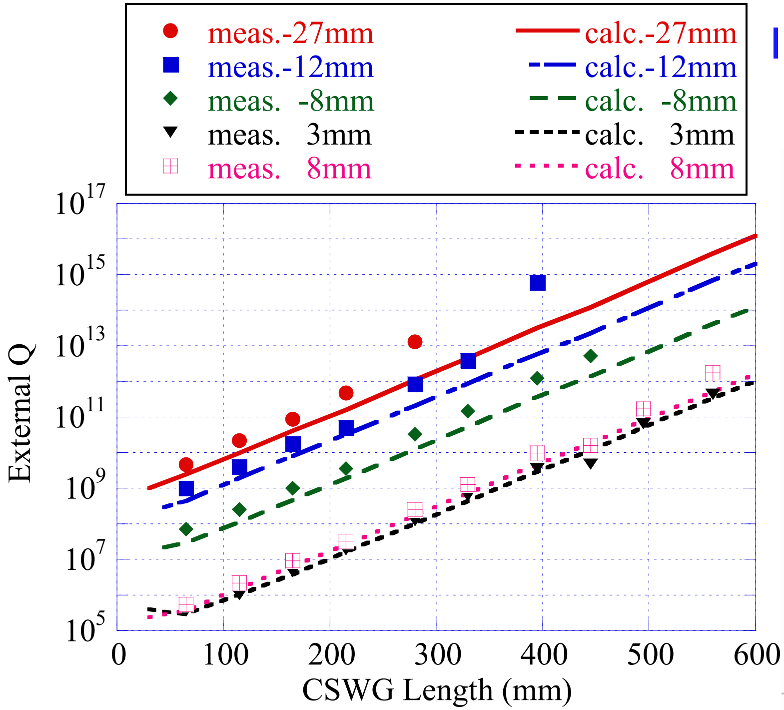
- Measurements well agree with calculations

CSWG-HOM Coupler with TESLA Cavity



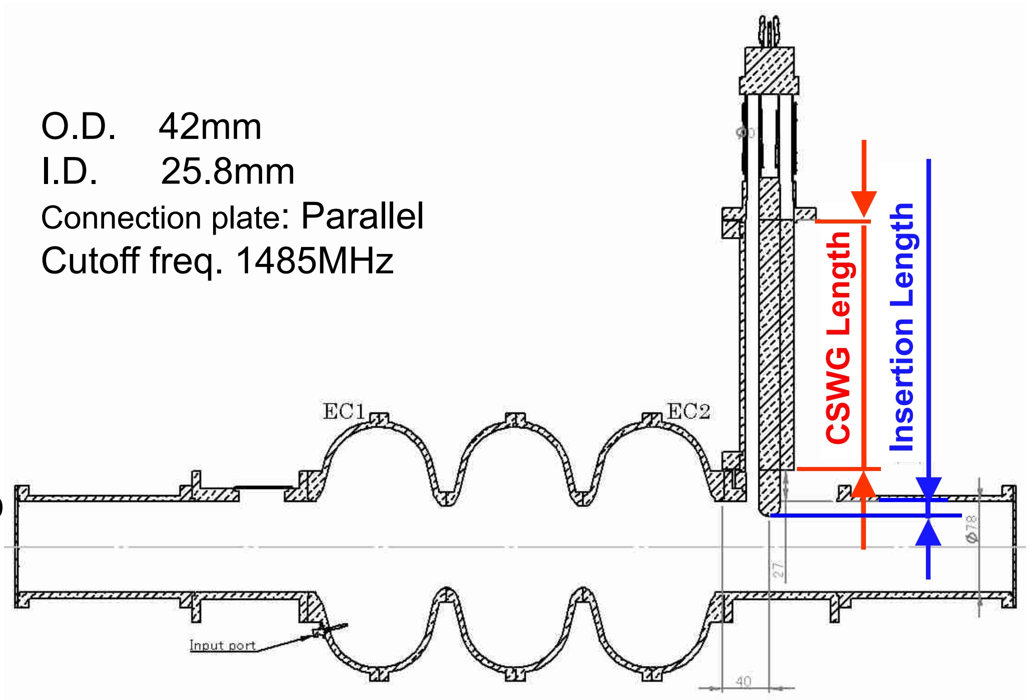


Q_{ext} of Acc. mode



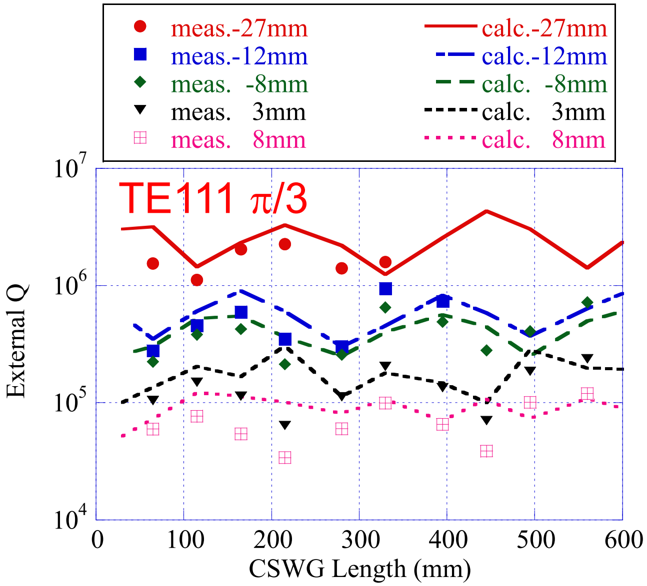
Insertion Length

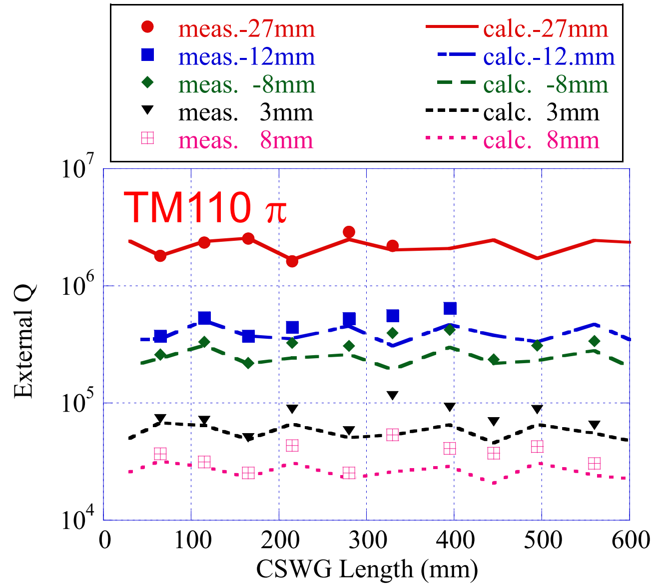
O.D. 42mm
I.D. 25.8mm
Connection plate: Parallel
Cutoff freq. 1485MHz



- Q_{ext} of Acc. mode increases
  - by increasing CSWG length
  - by extracting coaxial rod from beam pipe

Q_{ext} of HOMs



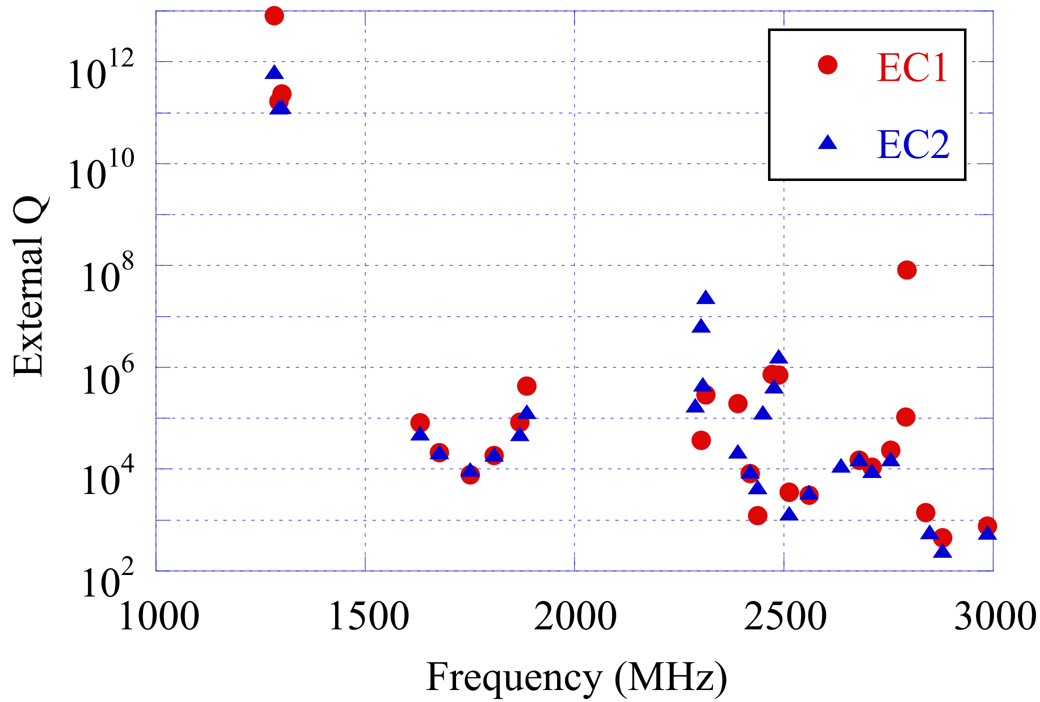


O.D. 42mm
I.D. 25.8mm
Connection plate: Parallel
Cutoff freq. 1485MHz

- Q_{ext} of HOMs
  - are independent on CSWG length
  - decreases by inserting coaxial rod into beam pipe

Q_{ext}	Acc. mode	HOMs	Choice
Insertion length	decrease	decrease	1) Suitable insertion length for Q_{ext} of HOMs low enough
CSWG Length	increase	Independent	2) Suitable CSWG length for Q_{ext} of Acc. mode high enough

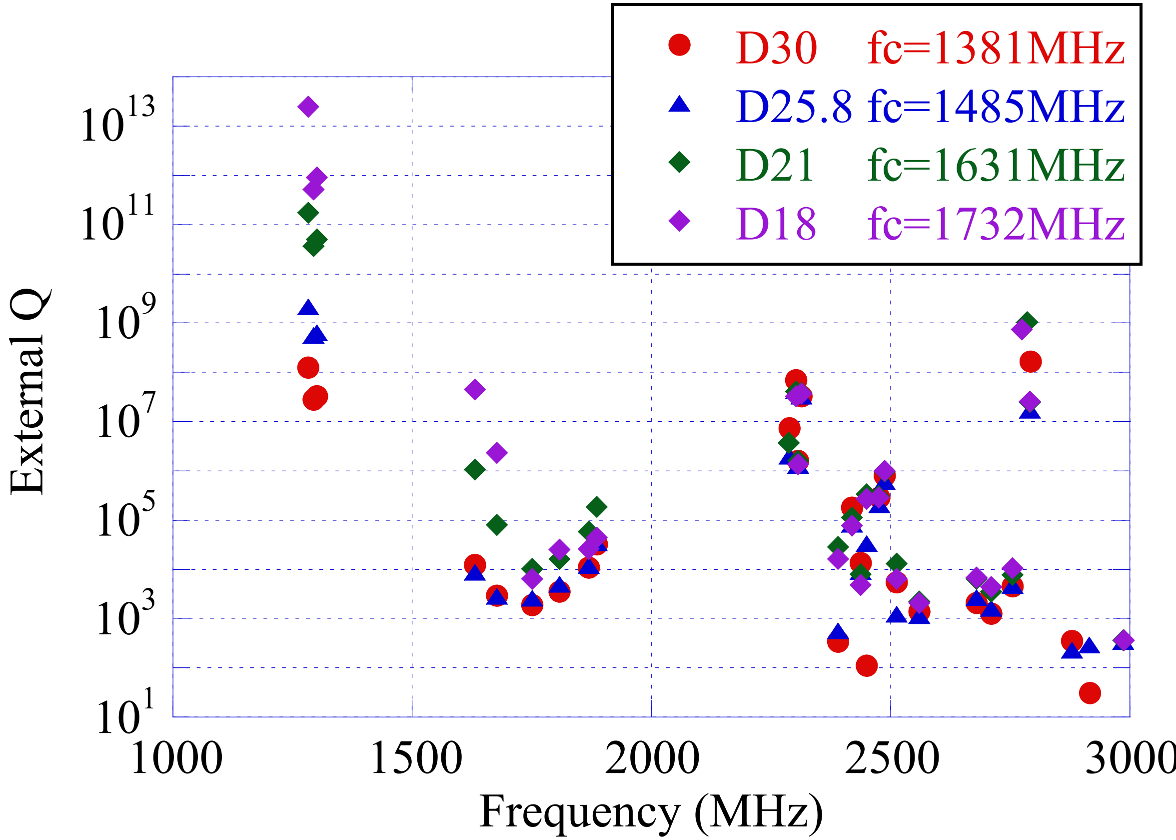
EC1 or EC2 side



O.D. 42mm
I.D. 25.8mm
Connection plate: Parallel
Cutoff freq. 1485MHz
Insertion length 3mm
CSWG length 495mm

- Q_{ext} for acc, mode shows more than 10^{11}
- TESLA cavity is asymmetric with two different shapes of the end cells to enhance the field amplitude of the trapped mode in one end cell
- Some HOMs show high Q_{ext}
- HOM coupler installed at either EC1 side or EC2 side can keep Q_{ext} less than 10^6 at least

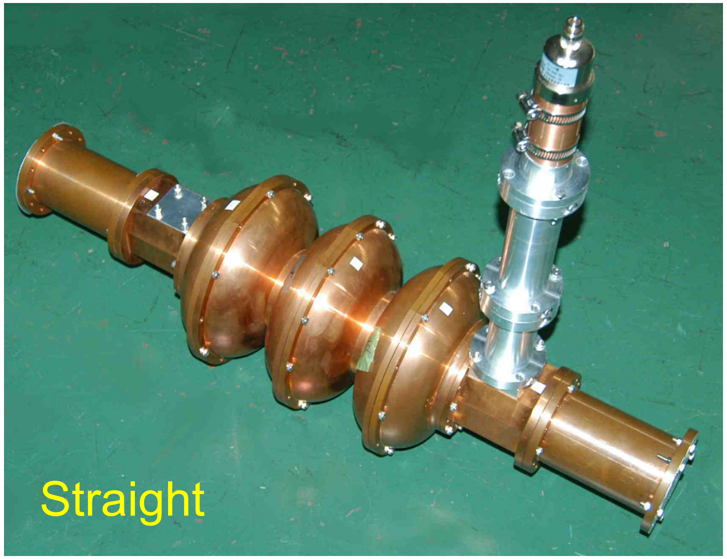
Cutoff Frequency

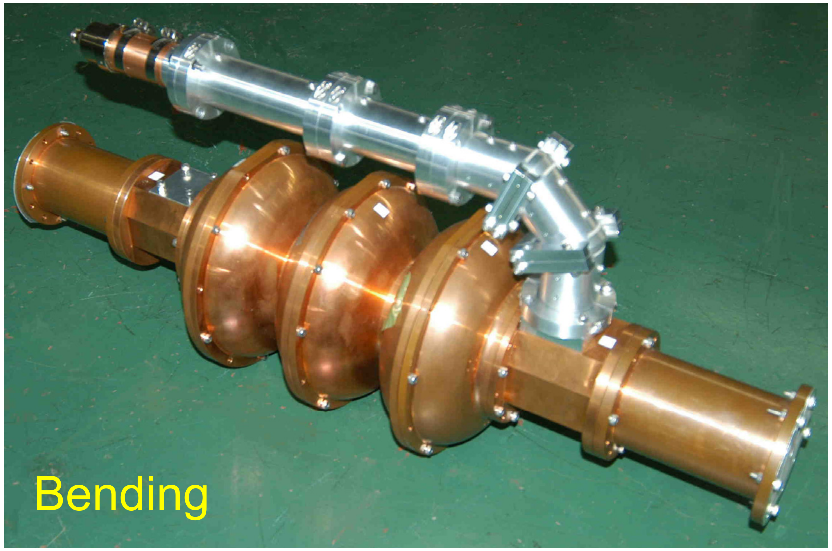


O.D. 42mm
Connection plate: Parallel
Insertion length 3mm
CSWG length 300mm

- As the cutoff frequency increases
  - Q_{ext} of acc. mode increases
  - Q_{ext} of low frequency HOMs increase
    - since the some HOM frequencies become lower than the cutoff frequency.

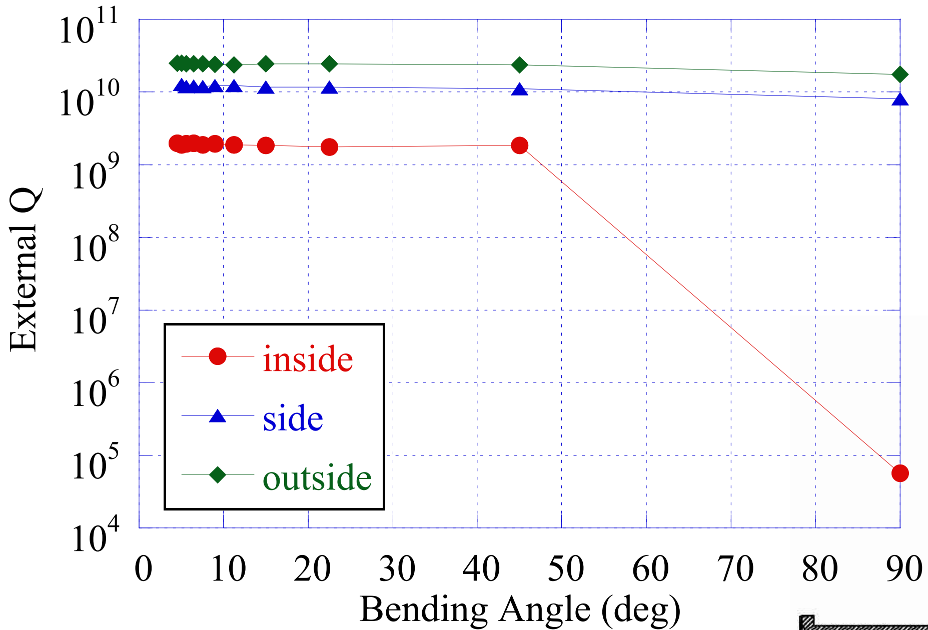
Bending CSWG type HOM Coupler

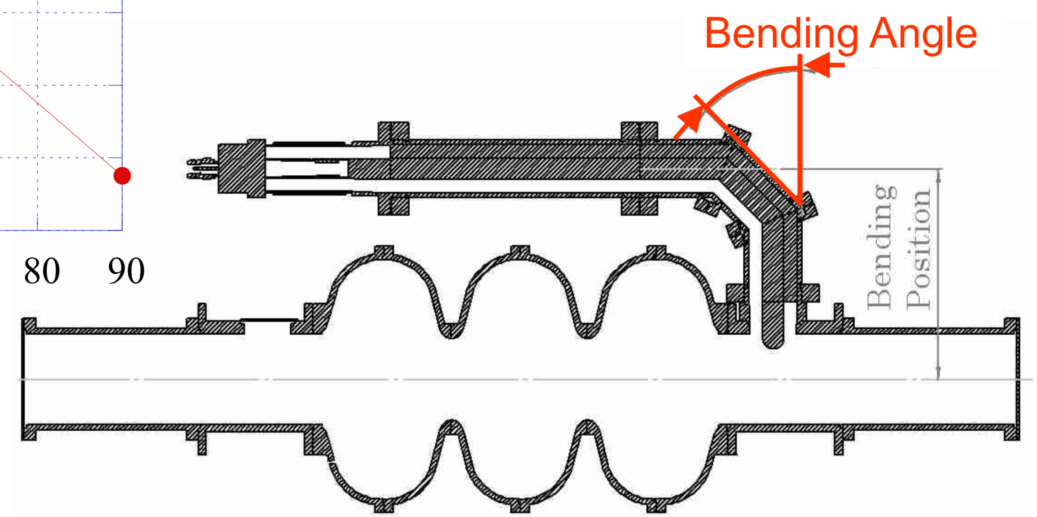




- CSWG type HOM coupler requires a long pipe so as not to affect the accelerating mode
- No bending of CSWG type HOM coupler requires large radial size of a cryomodule
- Bending CSWG type HOM coupler is practical

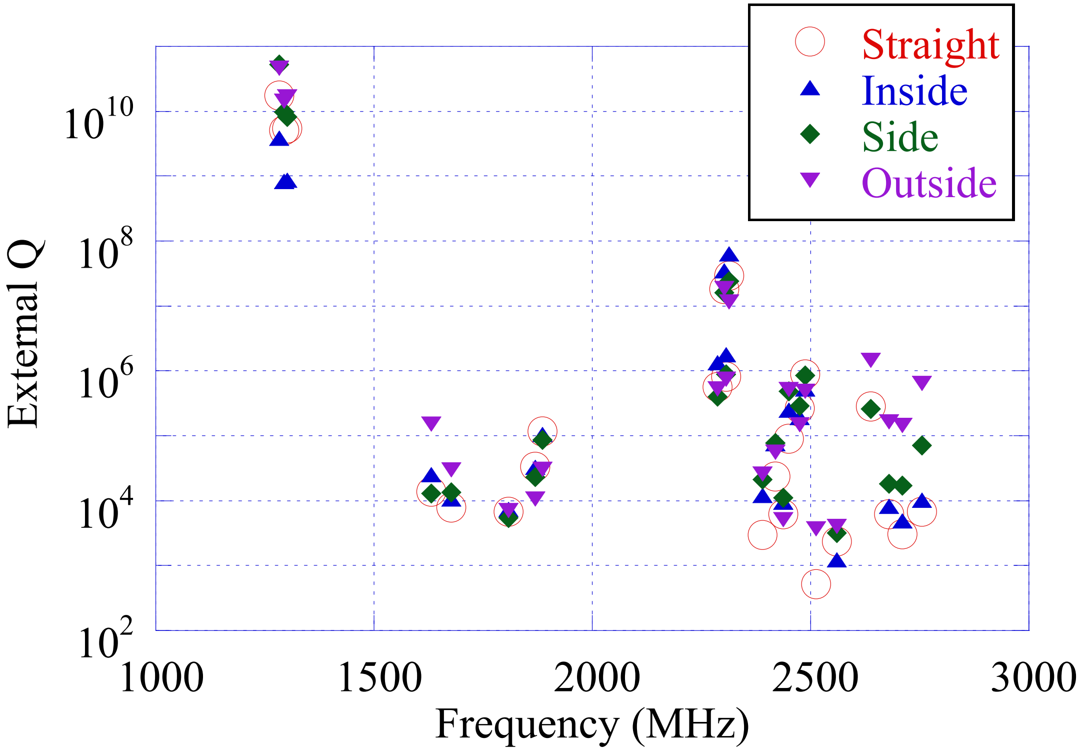
Bending Angle





- Q_{ext} are almost same regardless of bending angle
- except for the 90-degree bending of the inside connecting plate

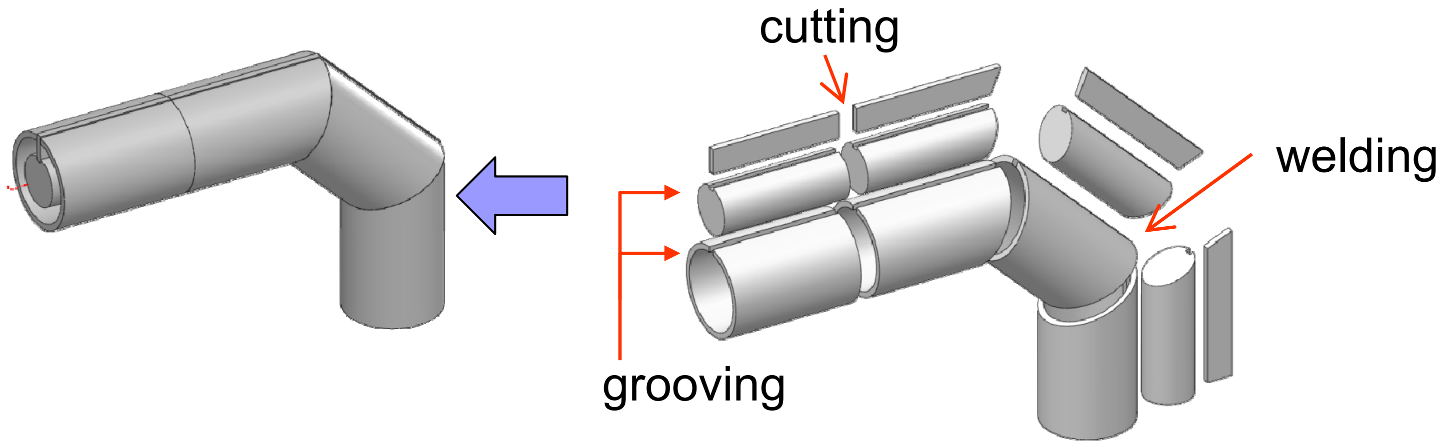
Q_{ext} for connection plate direction



O.D. 42mm
I.D. 25.8mm
Connection plate: Parallel
Insertion length 18mm
CSWG length 420mm
Bending angle 45deg

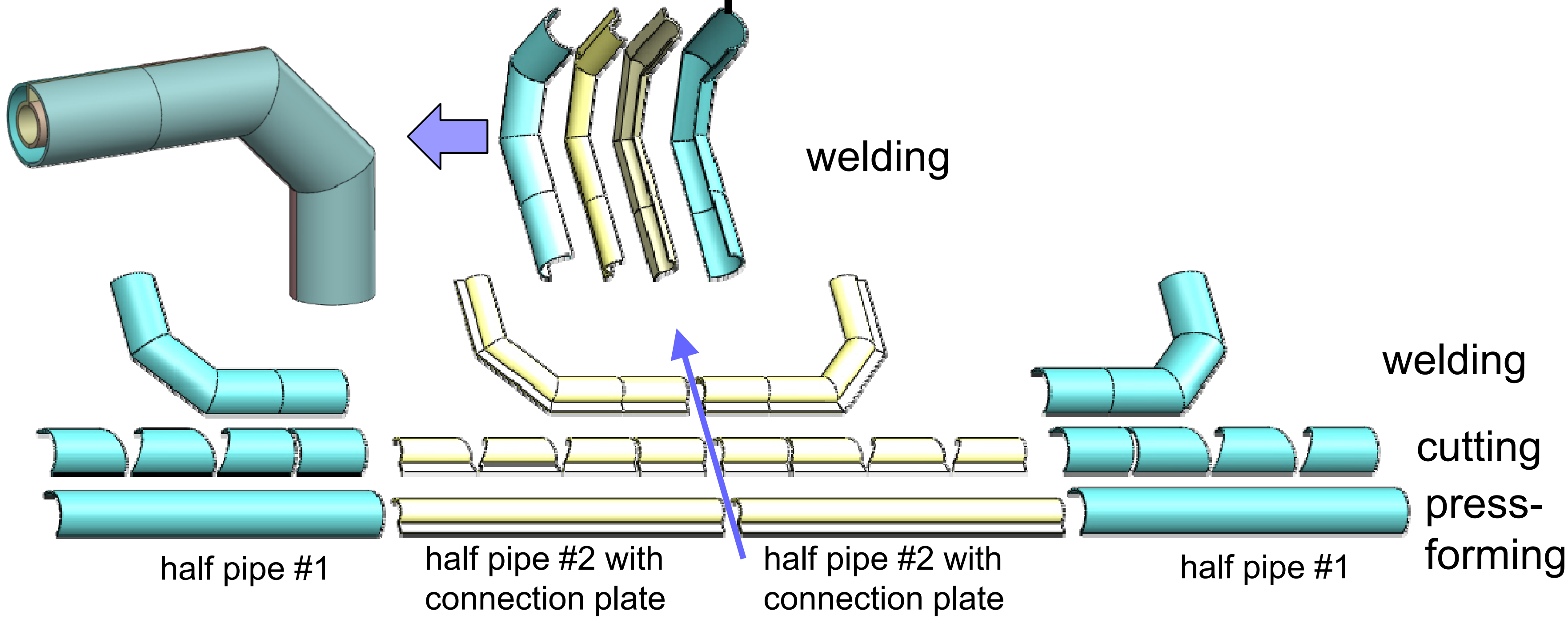
- Outside connection plate direction is preferable for the Acc. mode
- Suitable connection plate directions vary for HOMs
  - but the differences are little

How to Fabricate: plan #1



- Materials: pipe, cylindrical rod, and plate
- Processes: cutting, grooving, and welding
- Problems
  - Welding process is complicated
  - Lack of pipe of suitable size (expensive)
  - Groove width of pipe gets narrow under the influence of residual stress
  - Distortion due to welding

How to Fabricate: plan #2



- Press-forming of 2 kinds of half pipes
- Materials: plate
- Processes: press-forming, cutting, and welding
- Problems
  - Need to make 2 kinds of molds
  - It is possible to make whole bending parts with one press-forming.
    - This reduces the working process, but increases number of molds (bending and straight)

Summary

- CSWG has good features for HOM attenuator
  - High-pass filter
  - Easy cooling of inner conductor
  - Easy conversion to coaxial-line
  - Compactness
- CSWG type HOM Coupler realizes good damping properties
  - High Q_{ext} for acc. mode
  - Low Q_{ext} for HOMs
- Bending CSWG type HOM Coupler
  - Q_{ext} are almost same regardless of bending angle
    - except for the 90-degree bending of the inside connecting plate
  - Similar properties to straight CSWG
- Fabrication is under investigation

Thank you for your attention