Coaxial Couplers

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70 YEARS OF DISCOVERY

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U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

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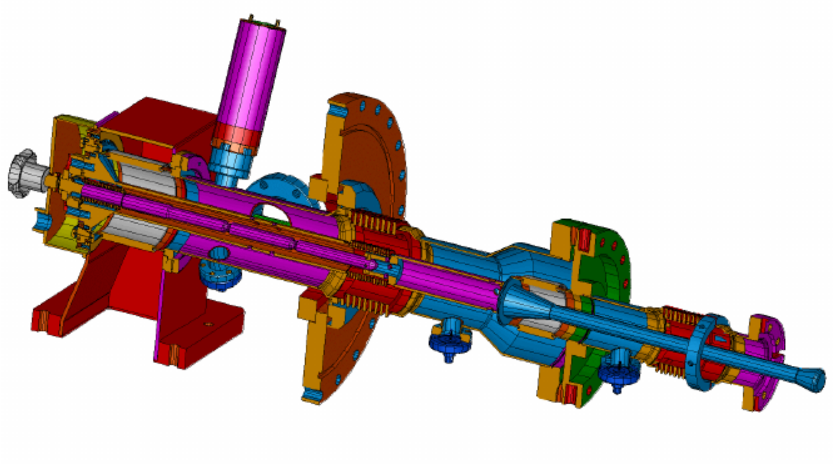
- Examples of couplers
- Major issues in Coaxial Coupler design
- Summary

Characteristics of Coaxial Couplers

Compared to the other type of RF power coupling method, waveguide, **coaxial couplers** have the **advantages** of :

- Compact in size
- Easy to modify design
- Easy to add motion
- Smaller heat leak



TTF 3 input coupler
S. Bauer, ERL04

However, the **coaxial couplers** are **not ideal** for:

- High RF power handling, especially at high frequencies
- Sufficient cooling from easy design
- Fast pump down

Characteristics of Coaxial Couplers, cont'd

- Coupling type
  - Electric – probe antenna
  - Magnetic – hook/loop antenna
- Quality factor
  - Fixed external Q version – Tristan, bERLinPro, KEK, SNS, BNL
  - Variable external Q version – TTF3, XFEL, ILC, LCLS-II
- Operation
  - CW – high average power, needs longer time to condition, gas discharge needs shut down of RF to recover
  - Pulsed – lower average power, less discharge, transient conditions
- Function
  - Fundamental mode power input (FPC)
  - Higher order mode damping
  - Pick-up signal for LLRF control

Examples in Application – FPCs more than 10yr old

J. Delayen, USPAS, June 2008
S. Belomestnykh, SRF13

CW Type:

	Frequency	RF window	Q_{ext}	Max power	Comments
LEP2 /SOLEIL	352 MHz	Cylindrical	2e6/1e5 fixed	Test: 565 kW / 380 kW Oper: 150 kW	Traveling wave @ Γ=0.6
LHC	400 MHz	Cylindrical	2e4 to 3.5e5	Test: 500 kW 300 kW	Traveling wave Standing wave
HERA	500 MHz	Cylindrical	1.3e5 fixed	Test: 300 kW Oper: 65 kW	Traveling wave
TRISTAN /KEKB/ BEPC-II	509 MHz	Disk, coax	1e6/7e4/1.7e5 fixed	Test: 800 kW Oper: 300 kW 360 kW	Traveling wave Forward power
APT	700 MHz	Disk, coax	2e5 to 6e5	Test: 1 MW 850 kW	Traveling wave Standing wave
Cornell ERL injector	1300 MHz	Cylindrical	9e4 to 8e5	Test: 61 kW	Traveling wave

Examples in Application – FPCs more than 10yr old

J. Delayen, USPAS, June 2008
S. Belomestnykh, SRF13

Pulsed Type:

	Frequency	RF window	Q_{ext}	Max power	Comments
SNS	805 MHz	Disk, coax	7e5 fixed	Test: 2 MW Oper: 550 kW	1.3 msec, 60 Hz 1.3 msec, 60 Hz
J-PARC	972 MHz	Disk, coax	5e5 fixed	Test: 2.2 MW 370 kW	0.6 msec, 25 Hz 3.0 msec, 25 Hz
FLASH (FNAL)	1300 MHz	Conical (cold) WG planar (warm)	1e6 to 1e7	Test: 250 kW Oper: 250 kW	1.3 msec, 10 Hz 1.3 msec, 10 Hz
FLASH (TTF-II)	1300 MHz	Conical (cold) WG planar (warm)	1e6 to 1e7	Test: 1 MW Oper: 250 kW	1.3 msec, 10 Hz 1.3 msec, 10 Hz
FLASH/XFEL/ILC (TTF-II)	1300 MHz	Cylindrical (cold and warm)	1e6 to 1e7	Test: 1.5 MW 1 MW Oper: 250 kW	1.3 msec, 2 Hz 1.3 msec, 10 Hz 1.3 msec, 10 Hz
KEK STF Baseline ILC cavity	1300 MHz	Disk, coax (cold and warm)	2e6 fixed	Test: 1.9 MW 1 MW	10 μsec, 5 Hz 1.5 msec, 5 Hz
KEK STF Low loss ILC cavity	1300 MHz	Disk, coax (cold and warm)	2e6 fixed	Test: 2 MW 1 MW	1.5 msec, 3 Hz 1.5 msec, 5 Hz

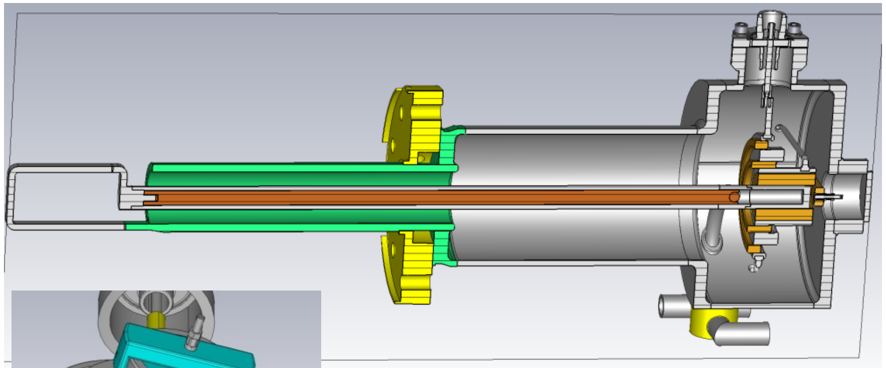
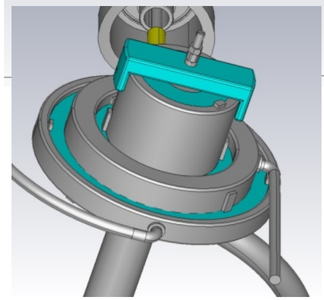
Examples in Application – More recent FPCs

	Site	Cavity Type	Freq.	Power	Status
BEPC-II	IHEP	Elliptical single cell (SC CW)	500 MHz	Test: 420 kW Operation: 150 kW	Beam Operation
C-ADS	IMP	Spoke (SC CW)	325 MHz 162.5 MHz	Test: 10 kW Operation: 10 kW	Beam commissioning
LHC crab	CERN	DQW/RFD (SC CW)	400 MHz	Operation: 100 kW	Construction
MICE Cooling	LBNL	Pill-Box like (NC Pulsed)	201 MHz	Peak: 2MW Duty factor: 0.1% Pulse length: 1ms	RF commissioned
APEX Gun	LBNL	Single cell (NC CW)	186 MHz	Operation: 87.5 kW	Beam Operation
APEX Buncher	LBNL	2-Cell (NC CW)	1300 MHz	Operation: 7.4 kW	Beam Operation
FRIB	MSU	Half wave (SC CW)	322 MHz	Test: 20 kW 20% duty cycle Operation: 5 kW	Construction
LCLS-II	SLAC	9-cell (SC CW)	1300 MHz	Test: 4 kW Operation: 4 kW	RF commissioning
cERL Injector	KEK	2-cell (SC CW)	1300 MHz	Test: 50 kW Operation: 50 kW	Beam Operation

Ref for previous slide

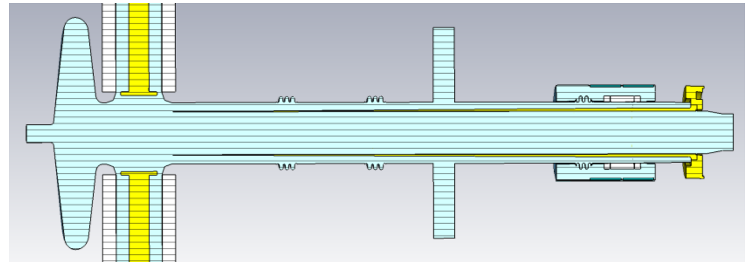
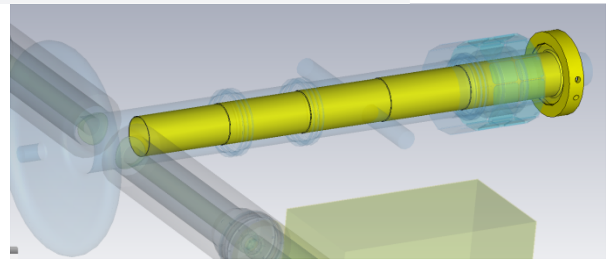
- T. Huang, *FPCs Development at IHEP*, WWFPC Mini-workshop, CERN, 2016
- E. Montesinos, *Last year experiences at CERN with FPC and future perspectives*, WWFPC Mini-workshop, CERN, 2016
- H. Qian et. al., *DESIGN OF A 1.3 GHZ TWO-CELL BUNCHER FOR APEX*, IPAC14
- F. Sannibale, *APEX Phase-II Commissioning Results at the Lawrence Berkeley National Laboratory*, IPAC16
- T. Luo et. al., *PROGRESS ON THE MICE RF MODULE AT LBNL*, IPAC16
- Z. Zheng, Multipacting Free Coupler Design and Commissioning for FRIB, TTC17
- N. Solyak, Coupler Performance at FNAL CM02, PIPII Technical Meeting, 2017
- E. Kako et. al., *HIGH POWER TESTS OF CW INPUT COUPLERS FOR cERL INJECTOR CRYOMODULE*, IPAC12
- S. Sakanaka et. al., *Construction and Commissioning of Compact-ERL Injector at KEK*, ERL13

Examples in Application – Higher Order Mode Couplers

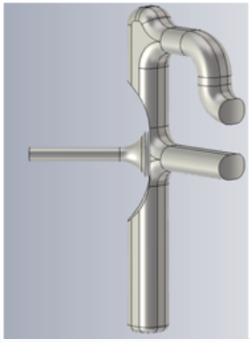



56 MHz SRF cavity for RHIC
Q. Wu et al., SRF15

704 MHz booster cavity for LEReC

TESLA type for LCLS-II
Solyak et al., SRF15




- HOM damping with coaxial couplers usually have antennae with filters built together.
- Type of coupling depends on the location of HOM coupler w.r.t. the cavity

Major Issues

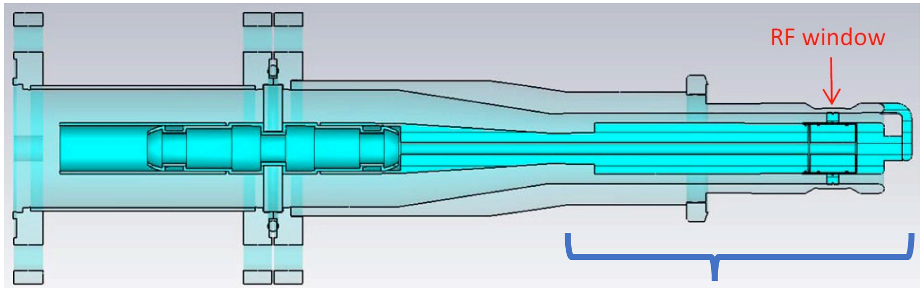
Physical
- RF transmission
- Unwanted RF modes
- Induce RF perturbation to beam
- Multipacting
- Discharge
- Sputtering

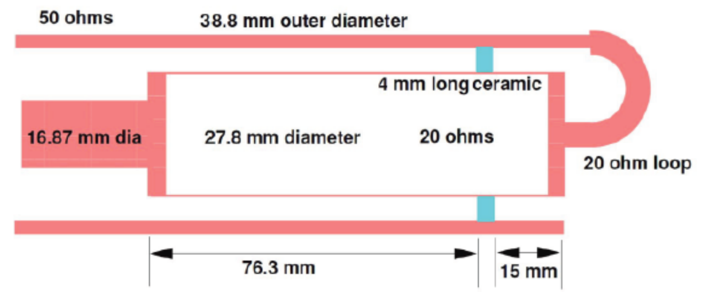
Mechanical
- Stress
- Connection
- Motion
- Installation tolerance
- Pumping

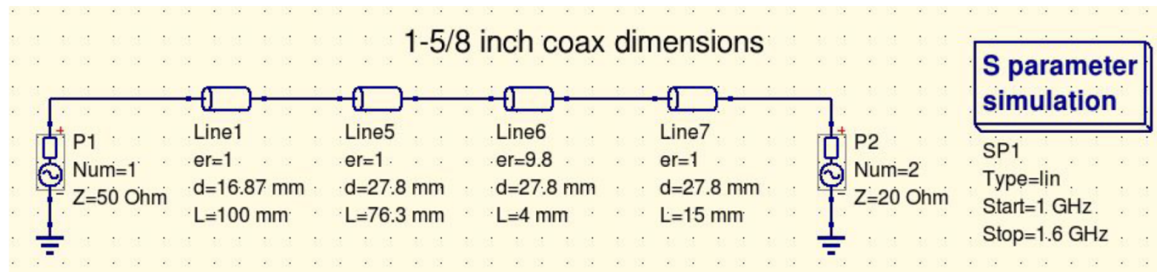
Thermal
- Heat dissipation
- Cooling design
- Material selection
- Plating

Solutions:
- Intensive simulation (CST, ACE3P, ANSYS, HFSS, etc.)
- Bellows
- Coating (TiN)
- Novel structure
- Conditioning
- Etc.

Major Issues – Matching



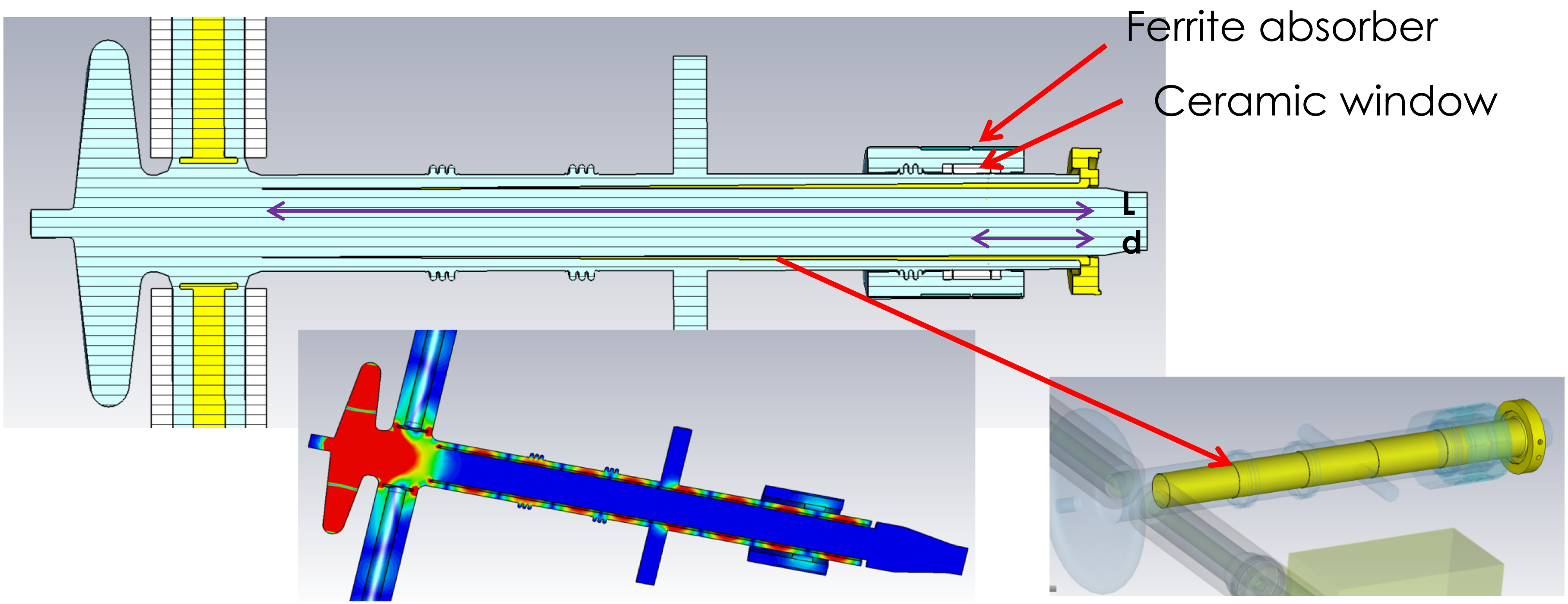




J. Staples et al., CBP tech note, 2013
Qian et al., IPAC14

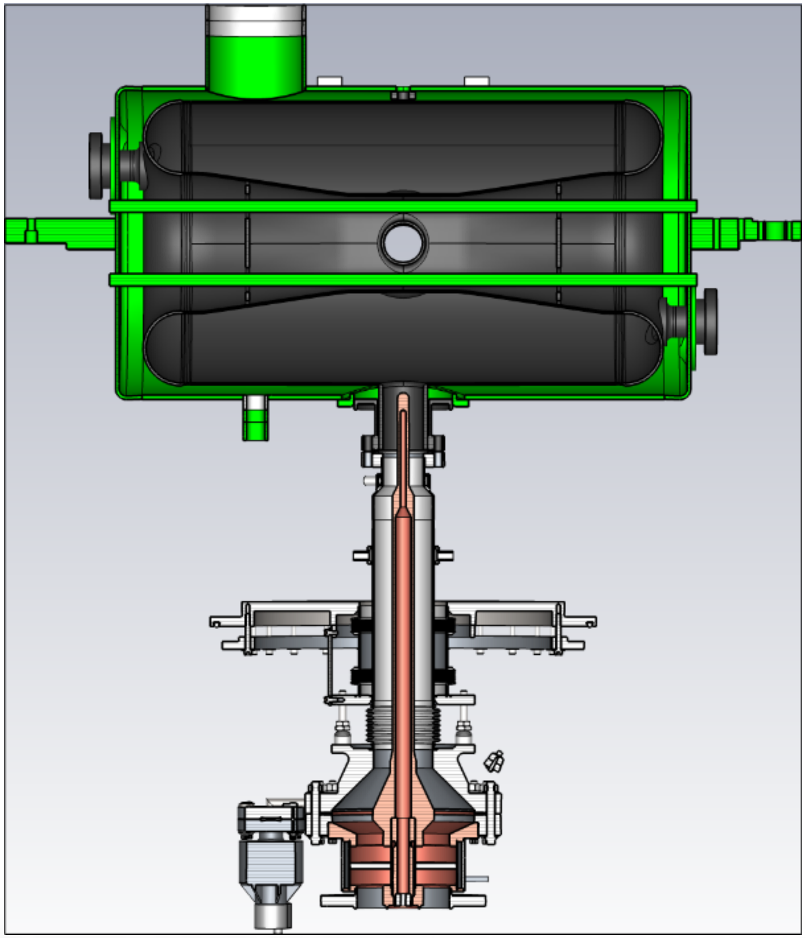
- APEX Buncher Cavity. Transition structure from 20 Ohm to 50 Ohm.
- No commercial feedthrough is available at the frequency and power level of APEX buncher cavity. Thus LBL design this low-Z coupler in house.

Major Issues – Matching



- LEReC HOM damping added for existing 704 MHz half-cell cavity
- Minimize the damping to TM010 fundamental mode @ 704 MHz, $d \sim \lambda_{010}/4$, $L \sim N/2 * \lambda_{010}$
- Maximize the damping to TM020 1st HOM @ 1.489 GHz, $d \sim \lambda_{020}/2$, $L \sim (N/2+1/4)\lambda_{020}$

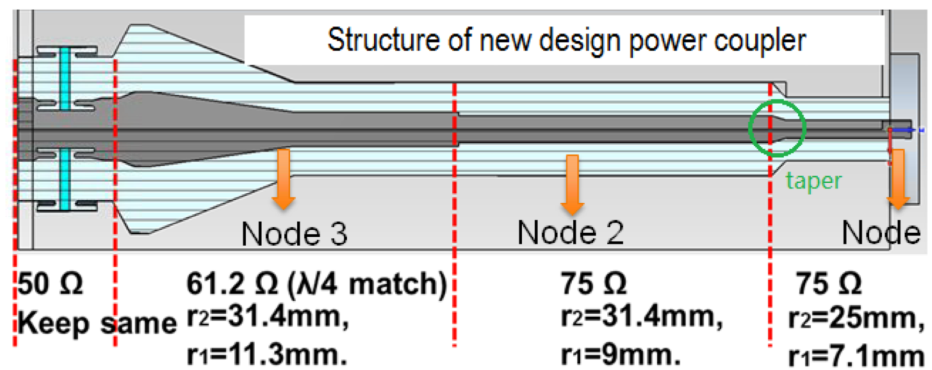
Major Issues – Multipacting



Z. Zheng et al., TTC17

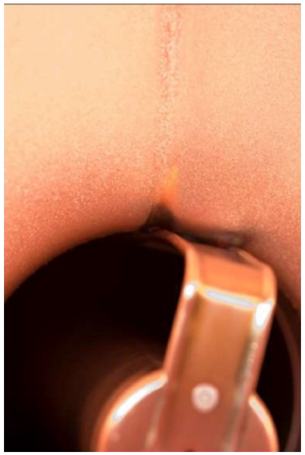
- FRIB half-cell 322 MHz FPC
- Multipacting caused by coaxial structure
- Solution: Increase coupler impedance to increase RF power to avoid multipacting

1-point	$P{\sim}(fd)^4Z$
2-point	$P{\sim}(fd)^4Z^2$



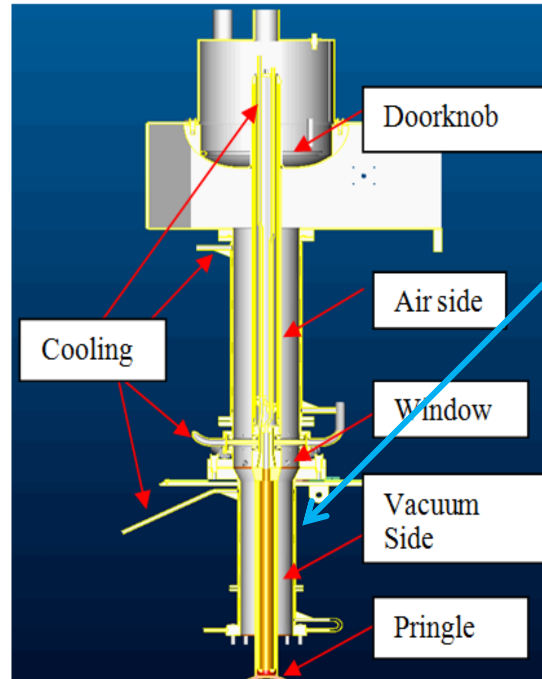
Multipacting-free design saved 22 hours conditioning time compared to original design couplers

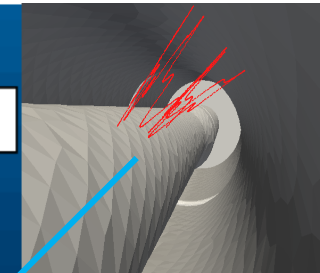
Major Issues – Multipacting

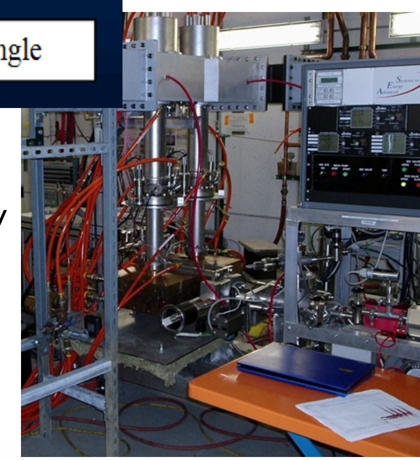


- MICE cooling cavity FPC
- Multipacting between cooling strip and cavity
- Solution: leaving cooling tubes only

Courtesy of T. Luo, LBNL



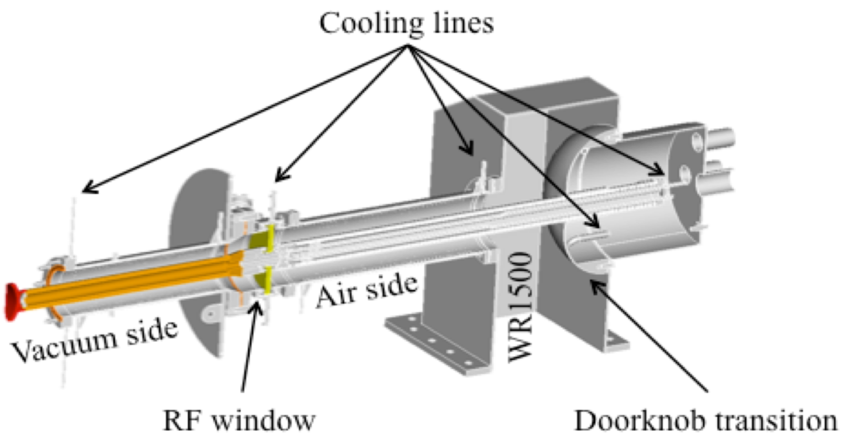




- BNL ERL Gun cavity
- Multipacting at coaxial structure
- Solution: RF conditioning

W. Xu, WWFPC Mini-workshop 2016

Major Issues – Cooling



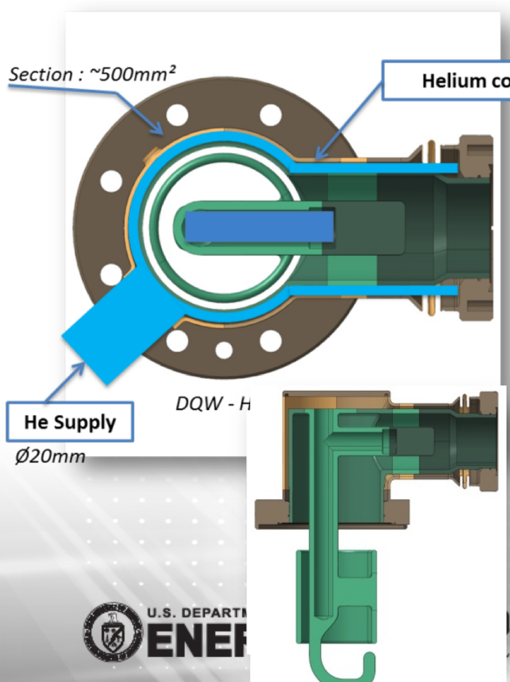
ERL Gun cavity @ BNL

Courtesy of W. Xu, BNL

RF power input is 500 kW per coupler

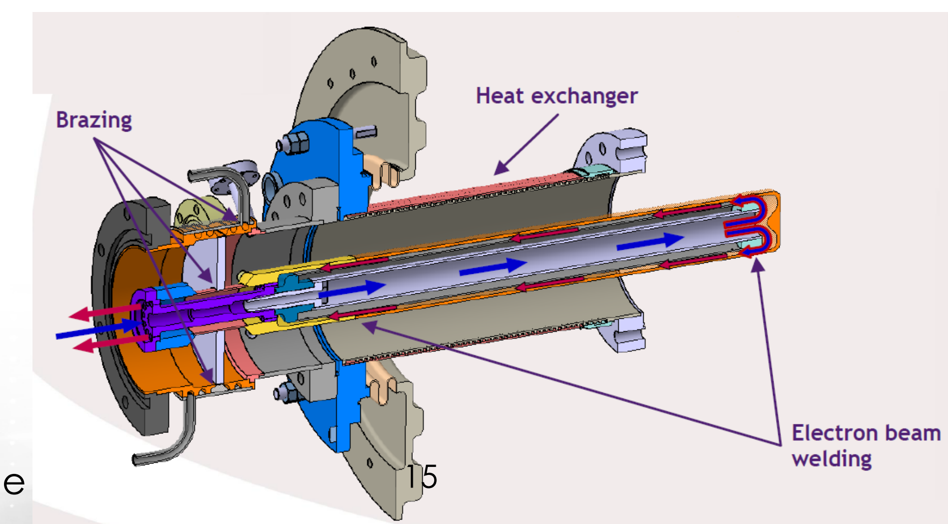
Water cooling for the inner conductor and air side, 5 K helium gas cooling at the vacuum side outer conductor.

- ESS 352 MHz FPC
- 2 water cooling sytems:
  - Window
  - Antenna (double enclosure)



- LHC Double quarter wave crab cavity HOM coupler
- 2K helium cooling

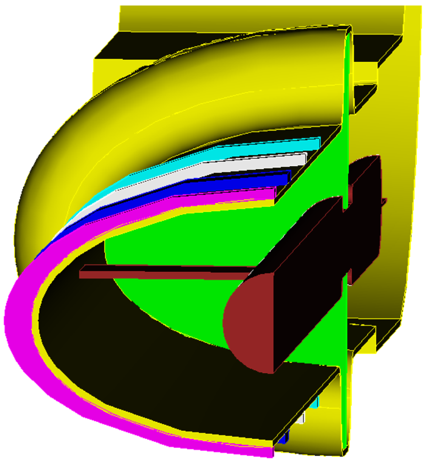
T. Capelli, Crab Cavity HOM Review 2015



E. Rampnoux, WWFPC Mini-workshop 2016

Major Issues – Cooling

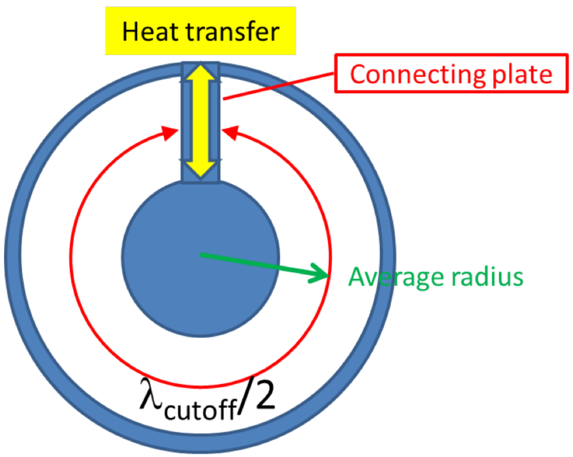
Another approach is to have cooling of the center conductor from physical connection to the outer conductor, which is easily cooled by ambient conditions…

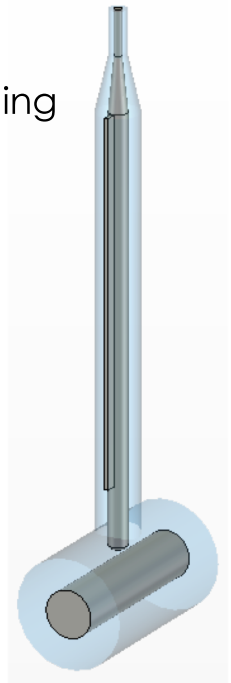


X. Chen, TTC17

- Use TE11 mode to transfer RF power down the coaxial structure. In TE11 coaxial mode the horizontal plane is a perfect electric boundary condition.
- Therefore, we can insert a metal plate without compromising the RF performance.
- This plate can be used to thermal anchor the temperature of the inner conductor.

C-Shape Waveguide (CWG): deforming coaxial-waveguide coupler

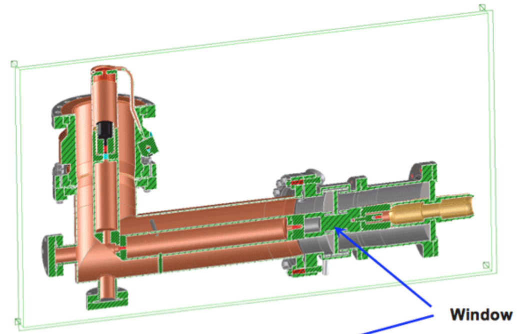


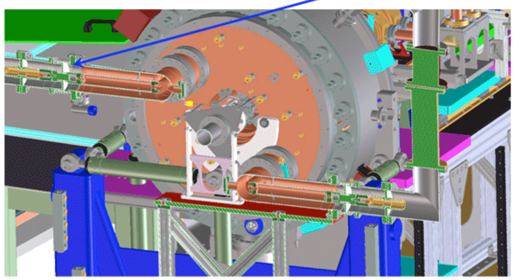


Connecting inner and outer conductors
Effective cooling of inner conductor through connecting plate.

M. Sawamura, SRF13
B. Xiao, SRF15

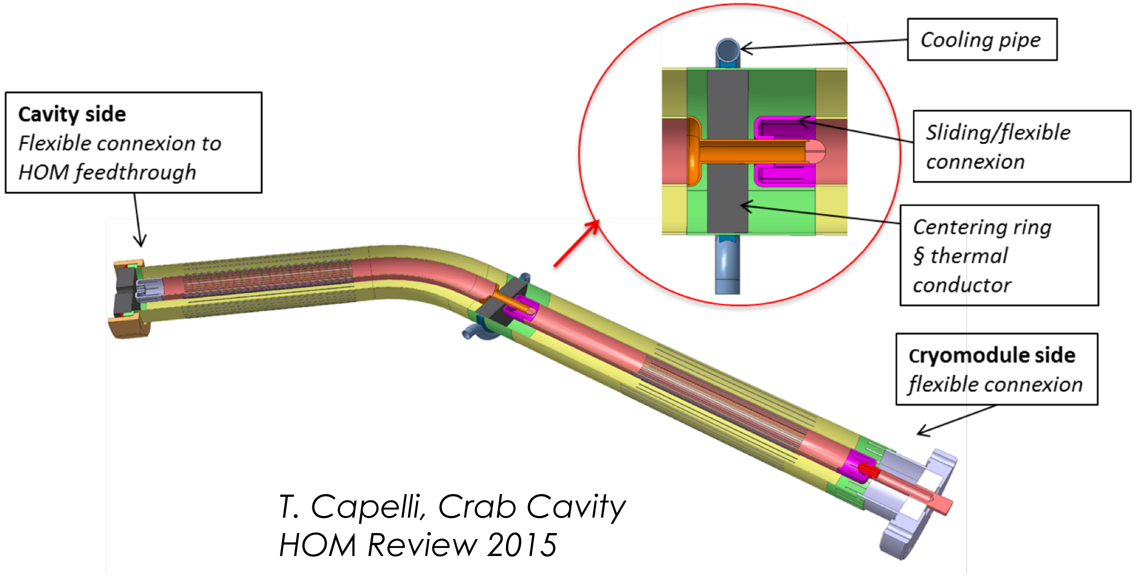
Major Issues – Window





- APEX gun cavity
- Crack window due to discharge
- Elbow shape to shield RF window from dark current.
- PS. This design also used TiN coating and permanent magnet to suppress multipacting

Courtesy of T. Luo, LBNL



T. Capelli, Crab Cavity HOM Review 2015

- LHC crab cavity HOM coupler window
- Special design for flexible mechanical connection and transmission of 1kW RF power at 400 MHz.

Single window	Easy design, easy cooling, Vulnerable cavity vacuum
Double window	Better protection to cavity, Hard design, hard cooling

Summary

- Coaxial couplers are widely used in both SC and NC RF resonators
- Compared to waveguide coupling, coaxial couplers are compact and easy to modify, but not ideal for handling large RF power.
- From various issues listed in this presentation, and much more details depends on each design, coaxial couplers are **not** easy to design. Sometimes the design is as complicated as the cavity, if not more.
- Best solution for one cavity varies with the details of the entire cryomodule system and beam dynamics requirements.