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Spoke cavity power coupler conceptual design work for the HEL-JTO beam exp.

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Objectives:
- Create a low-cost, modest-power RF coupler for a SRF spoke cavity beam test of electrons test to be done at LANL

Deliverables:
- Develop a detailed design concept of a workable coupler for the beam test
- Deliver a technical design report

Work Performed:
- Created a coupler parameter sheet as to what is being designed
- Developed a conceptual design
- Evaluated conceptual design using CST MWS transient analysis
- Improved design over successive runs to establish final design
- Evalauted potential for multipacting behavior in final design
- Generated an estimate of the external Q of the coupler
- Generatde a detailed 3D assembly model highlighting design features
- Created a Technical Design report in the form of an Excel spreadsheet to maximize info transfer while minimizing writing.

Design Highlights and Commentary:
Developing the design for this magnetically-coupled SRF spoke cavity testing coupler was basically straightforward since the cavity coupling port needed to be one of the 1.22" ID ports, and the power level was limited by the available RF to less than 400 W TW power. In addition, the coupler would be immersed in bath cryostat filled with liquid helium, and ultimately used in a pulsed mode to accelerate beam, thereby significantly relaxing the thermal loads on the coupler.

Combining the above considerations with the level of resources available for this task, emphasis was placed on rapidly developing a robust, reliable design that would use commercially-available components as available to save design, engineering, and fabrication costs. Analysis was also kept to a minimum. As such, the design incorporates the following features:

- Use of a commercially-available Type-N ceramic feedthrough. For the power and frequency range of the test, with the feedthrough immersed in LHe, it was felt the Type-N feedthrough would provide a robust, low-cost vacuum window solution.

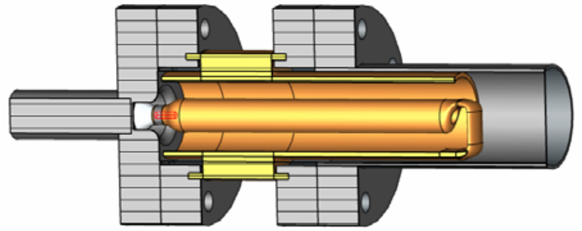
- The coupler outer conductors would be solid OFE copper that is brazed into two 2.75" CFF, with the cavity-sde flange being rotatable to allow minor Qx adjustments by rotating the coupler. The braze joint shown has the copper brazed into a groove in the SST to ensure maximum strength for successive thermal cyclings. The outer wall of the copper between the two flanges serves as the heat sink for depositing coupler heat to the liquid helium.

- The inner conductor would be solid OFE copper brazed to the outer conductor at the top to ensure maximum thermal conductivity from the outer thermal sink area to the base of the feedthrough. A mass-reducing hole is placed down the center of the inner conductor to decrease thermal mass and weight.

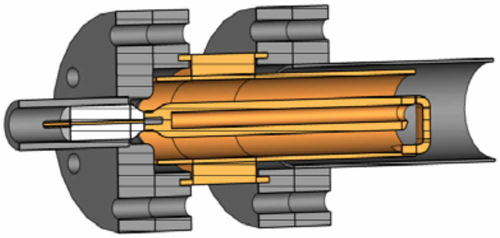
- This assembly would be mated to the Type-N feedthrough by pushing the pin from the feedthrough into a spring-loaded connector on the base of the inner conductor, then bolting the flanges together.

- If the coupling needs to be greatly reduced, an additional 1/2" CFF can be insered between the coupler and cavity flanges. Increasing the coupling can be done with a 3 stub tuner.

Further details are included in the balance of this report.



Baseline final design graphic sectioned to show detail

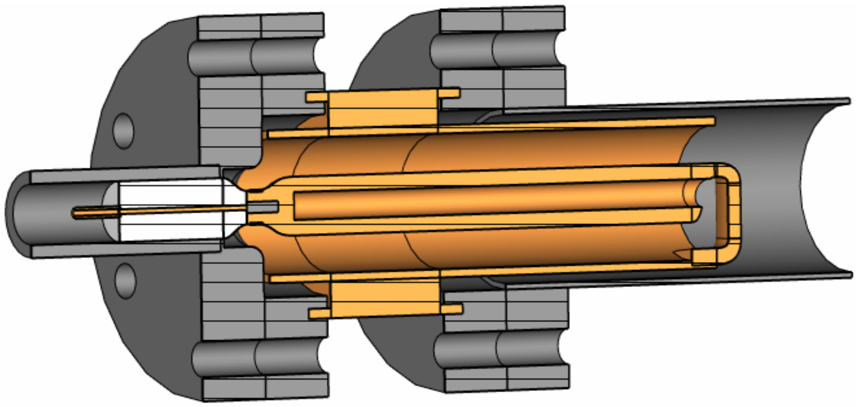


Baseline final design graphic half section

Overall parameter sheet for coupler design process

orig 9/21/2007
vers 10/3/2007

parameter	units	value	comments
cavity type		λ/s 2 gap spoke	
cavity mode		0	cavity "0" mode
operating temp	K	4.0	
frequency (cavity, no coupler)	MHz	454.236	
frequency (cavity, with coupler)	MHz	445	
wavelength	cm	65.999	free space
$\lambda/2$	cm	33.000	
$\lambda/4$	cm	16.500	
impedance	Ohms	50	match xmission line
window/feedthrough		Type N	Kyocera or Ceram Tec
pulsed or CW		pulsed	assume CW for startup
pulse length	usec	5	1 usec beam length
rep rate	Hz	10	total guess…
duty factor	%	0.0050	
coupling		magnetic	loop
adjustability		limited	manual adj for Qx set
adjustment range	inches	+/- 0.5	
port flange to c-stat wall	inches	10.66	max length of coupler body
port flange	inches	2.75	Conflat
port length	inches	2.81	corrected by FK 9/25
port diam	inches	1.22	confirmed FK 9/25
outer cond outer diam	inches	1.095	1/16" radial clearance
outer cond inner diam	inches	0.97	1/16" radial wall thickness
inner cond outer diam	inches	0.422	
P operating TW ave	W	200	
P operating SW ave	W	800	
P max TW ave	W	400	600 W amp w/ 1.7 dB loss
P max SW ave	W	1600	
P design TW ave	W	400	assume CW for now
P design SW ave	W	1600	
est. operating pk power on coupler	W	200	assuming VSWR < 1.1
est. operating ave power on coupler	W	1.00	
est. max pk power on coupler	W	400	assuming VSWR < 1.1
est. max ave power on coupler	W	2.00	
Type N coupler max voltage DC	volts	1500	from CeramTec specs
Type N coupler max current DC	amps	3.6	from CeramTec specs
Type N coupler peak power	W	22,500.0	based on max DC voltage
Type N coupler ave power	W	324.0	based on max DC current
cavity Qo at 4K		4.54E+09	
peak beam power at 4K	W	200	
cavity wall power at 4K	W	1.25	
cavity beam loaded Q		2.84E+07	
baseline design geometry Qx		2.09E+07	needs to be confirmed



Baseline final design graphic half section

Multipacting assessment using scaling

orig 9/27/2007
vers 10/3/2007

Multipacting band scaling - based on original work by E. Haebel, CERN

frequency (MHz)	350	**454.26**
diameter (mm)	100	**30.99**
impedance (Ohm)	50	**50**
MP order	TW (kW)	**TW (kW)**
7	32	**0.837**
6	36	**0.942**
5	60	**1.570**
4	118	**3.088**
3	152	**3.978**
2	300	**7.852**
1	428	**11.201**

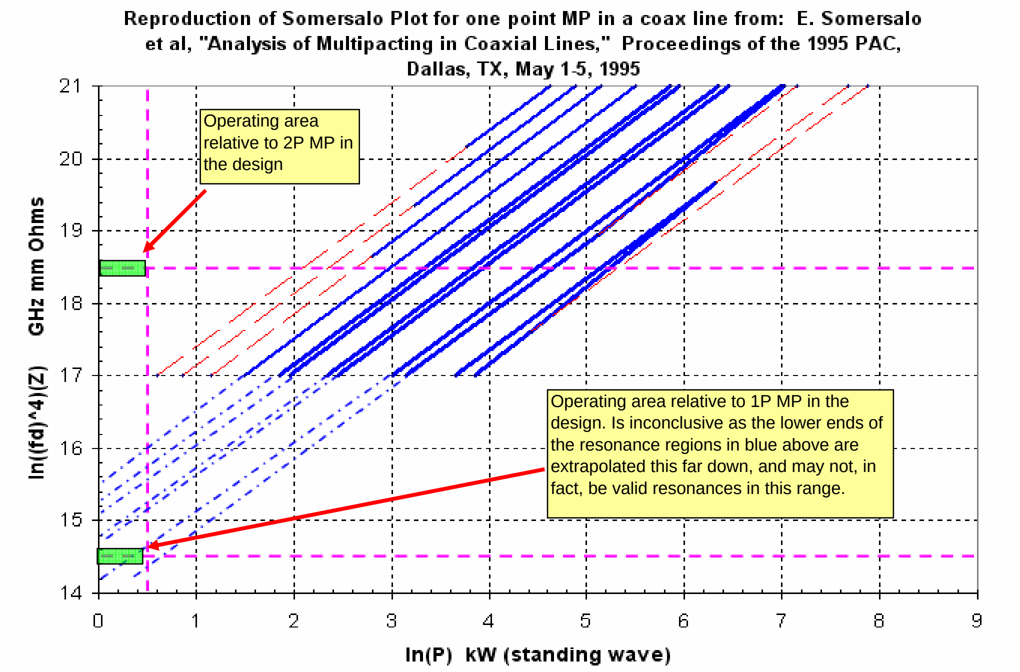
**For operation at less than or equal to 400 W,
MP below about the 8th-9th order should not be supported**

diameter (mm)	**100**	**100**	**75**	**75**	**50**
impedance (Ohm)	**75**	**50**	**75**	**50**	**50**
MP Order	**multipacting power band average power (kW)**				
7	48	32	15	10	2
6	52	36	16	11	2
5	88	60	29	19	4
4	176	118	56	37	7
3	234	152	72	48	10
2	448	300	146	97	19
1	640	428	203	136	27

**scaled bands at 350 MHz for travelling-wave
power from ADTF spoke cavity coupler report**

coupler	**(GHz)** **f**	= 2b **(mm)** **d**	**(Ohm)** **Z**	**one-point** **ln(fd)^4*Z**	g= b-a = d/2(1-exp(-Z/60)) **two-point** **ln(fd)^4*Z^2**	**(fd)^2**	for Hatch **MHz-cm** **(fg)**
CERN LEP	0.352	103	75	18.680	22.997	1314.50	1293.42
CERN LHC	0.4	103	75	19.191	23.509	1697.44	1469.80
KEK TRISTAN	0.508	150	50	21.245	25.157	5806.44	2154.18
KEK B fac	0.508	150	50	21.245	25.157	5806.44	2154.18
HERA	0.5	100	50	19.560	23.472	2500.00	1413.50
APT 4"	0.7	100	50	20.906	24.818	4900.00	1978.91
APT 6.13"	0.7	150	50	22.528	26.440	11025.00	2968.36
LANL spoke coupler des	**0.45426**	**30.99**	**50**	**14.490**	**18.402**	**198.18**	**397.97**

These values of the fd parameters combined with the low operating power levels indicate 2P MP will not be supported, and the graphical results for 1P MP are inconclusive.



Reproduction of Somersalo Plot for one point MP in a coax line from: E. Somersalo et al, "Analysis of Multipacting in Coaxial Lines," Proceedings of the 1995 PAC, Dallas, TX, May 1-5, 1995

Operating area relative to 2P MP in the design

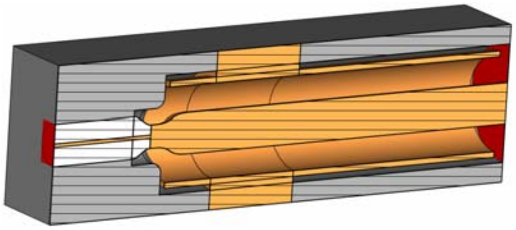
Operating area relative to 1P MP in the design. Is inconclusive as the lower ends of the resonance regions in blue above are extrapolated this far down, and may not, in fact, be valid resonances in this range.

Coupler electromagnetic transient analysis on CST MWS

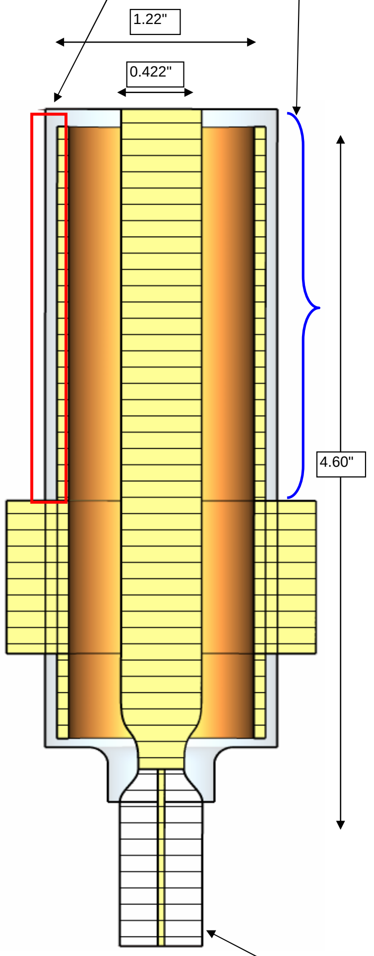
orig 9/27/2007
vers 10/3/2007

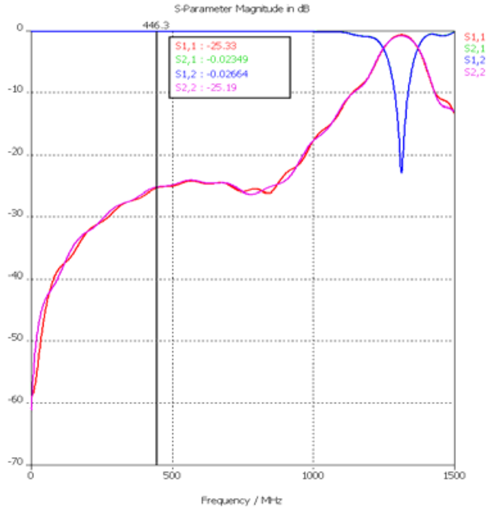
Simplified model for analyzing coupler parameters.

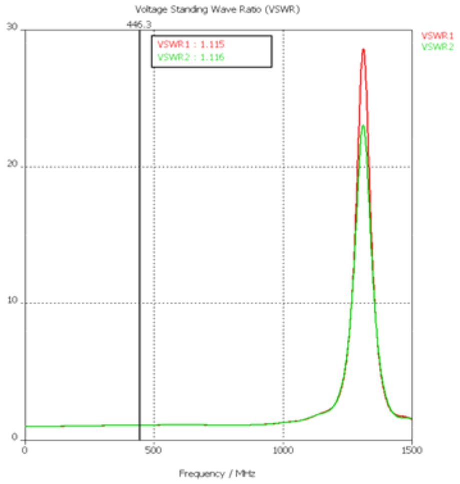
The stopband at ~1300 MHz is due to a quarter-wave resonance that is being set up between the outer electrical conductor and the vacuum wall (highlighted in red below). The distance between the cavity and the base of the outer conductor (blue below) needs to be short for higher (>400 MHz) frequency applications.

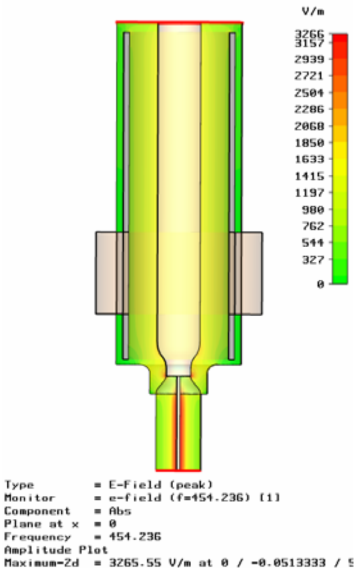


simplified RF model for transient RF analysis

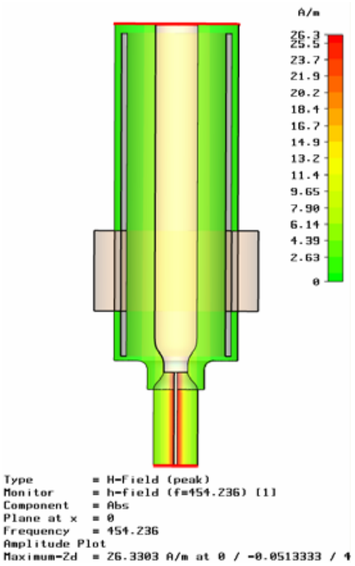








```
Type         = E-Field (peak)
Monitor      = e-field (f=454.236) [1]
Component    = Abs
Plane at x   = 0
Frequency    = 454.236
Amplitude Plot
Maximum-2d   = 3265.55 V/m at 0 / -0.0513333 /
```



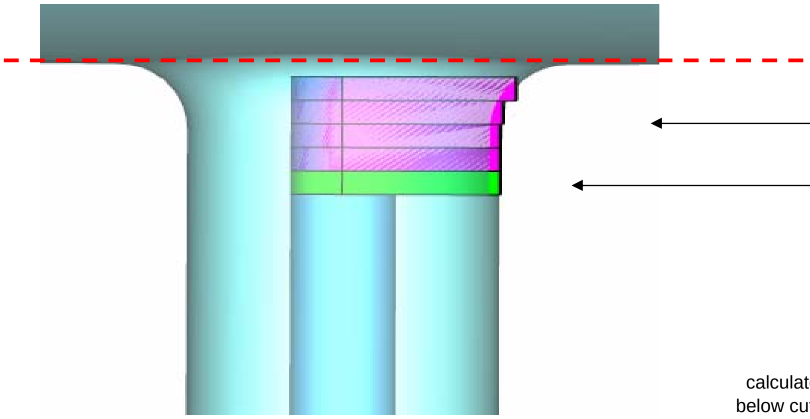
```
Type         = H-Field (peak)
Monitor      = h-field (f=454.236) [1]
Component    = Abs
Plane at x   = 0
Frequency    = 454.236
Amplitude Plot
Maximum-2d   = 26.3303 A/m at 0 / -0.0513333 /
```

A certain amount of uncertainty in the calculated S parameters comes from not knowing what the geometry is inside the Type N ceramic feedthrough, as it's not displayed in the catalog. It appears this component dominates the transmission characteristics.

Type N feedthrough, Ceramtec #NW35CF or equivalent

Coupling analysis using CST MWS Qx calculating solver

orig	9/27/2007
vers	10/3/2007



cavity flush line

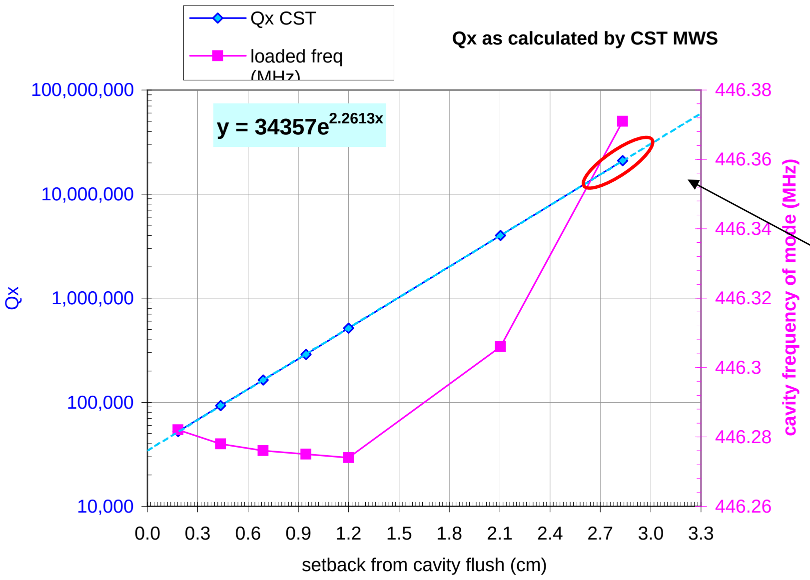
green is PEC, purple is normal/vacuum

0.254 cm width each

position	setback depth (mm)	Qx CST	loaded freq (MHz)	ln (Qx1/Qx2)	z1-z2	calculated below cutoff attenuation factor (BCAF) α (dB/cm)
	0					
5	0.183	5.24E+04	446.282			
4	0.437	9.29E+04	446.278	0.5715	0.2540	9.7651
3	0.691	1.63E+05	446.276	0.5633	0.2540	9.6245
2	0.945	2.88E+05	446.275	0.5699	0.2540	9.7375
1	1.199	5.14E+05	446.274	0.5773	0.2540	9.8643
	2.104	4.00E+06	446.306	2.0532	0.9050	9.8461
	2.833	**2.09E+07**	**446.371**	**1.6537**	**0.7290**	**9.8448**

target Qx	2.00E+07	
setback (cm)	2.8333	
setback (in)	1.1155	
TM01 BCAF	13.465	dB/cm
TE11 BCAF	**10.293**	**dB/cm**
ave calc BCAF	**9.7804**	dB/cm
difference	4.98008	%

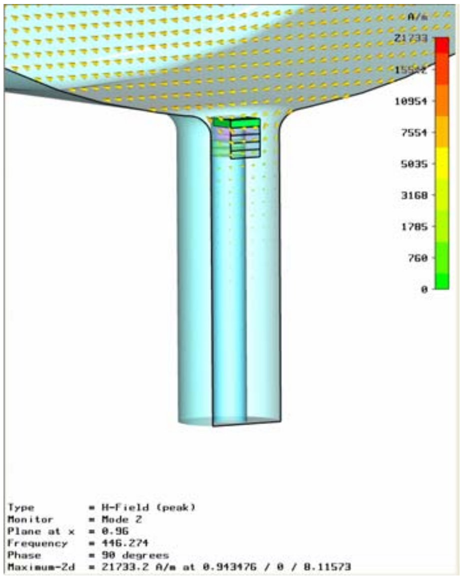
There is reasonably good agreement between the calculated TE11 below cutoff attenuation factor and the average value determined by the MWS runs, considering the TE11 field patters are distorted by the presence of the antenna loop.



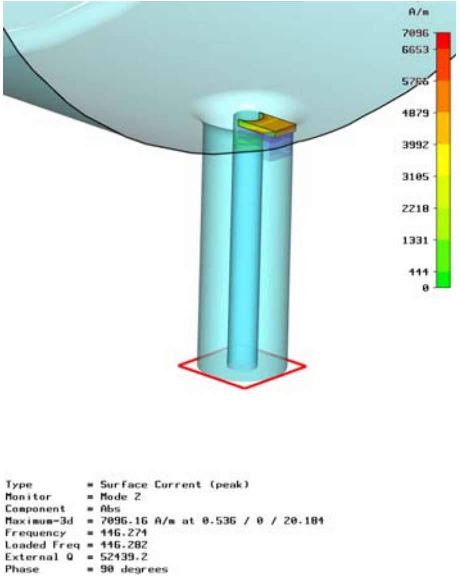
Projected operating range for Qx

Comments on External Q analysis: The analysis was done using the Qx calculation function in MWS, vers 2006B.03. While doing this was straightforward, it was not checked against a proven alternative calculational route like a Balleyguier analysis modified for magnetic coupling loops. While the Qx values produced by MWS appear to be reasonable, and the slope is consistent with the cutoff for a 1.27" diam port, it is recommended that the above plot be confirmed with a measurement on the cavity done at LANL, instead of by doing additional analyses. This is proposed for efficiency purposes, as addtional analysis work would easily take 3-4 days, where a measurement in the lab would take ~0.5 days, and would be more rigorous. **In addition, the design value needs to be confirmed by LANL for adequacy for beam loading and cavity operation bandwidth.**

Field plots around coupler loop

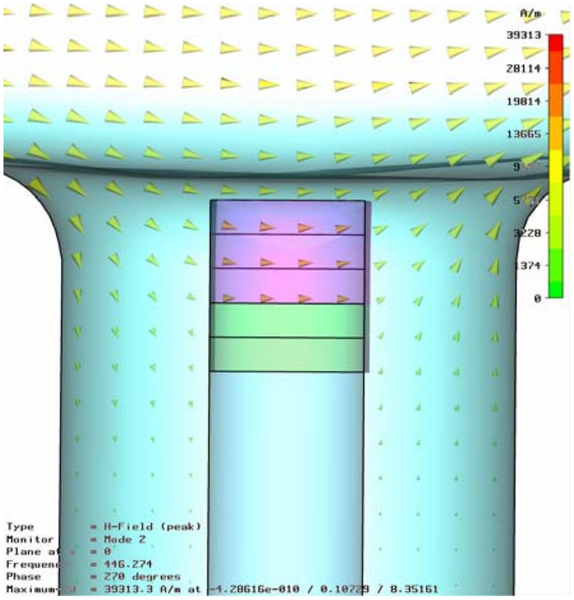


```
Type         = H-Field (peak)
Monitor      = Mode 2
Plane at x   = 0.96
Frequency    = 446.274
Phase        = 90 degrees
Maximum-2d   = 21733.2 A/m at 0.943476 / 0 / 8.11573
```

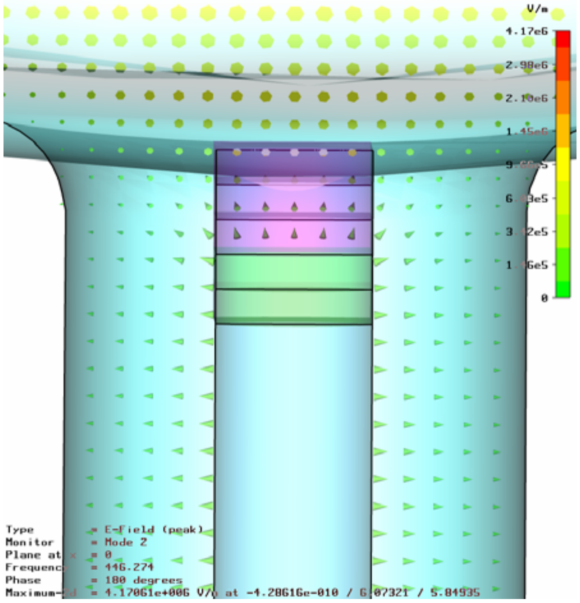


```
Type         = Surface Current (peak)
Monitor      = Mode 2
Component    = Abs
Maximum-3d   = 7096.16 A/m at 0.536 / 0 / 20.184
Frequency    = 446.274
Loaded Freq  = 446.282
External Q   = 52439.2
Phase        = 90 degrees
```

Magnetic and electric field patterns in the coupling port are analagous to TE11 mode patterns except near loop



```
Type         = H-Field (peak)
Monitor      = Mode 2
Plane at x   = 0
Frequenc     = 446.274
Phase        = 270 degrees
Maximum-2d   = 39313.3 A/m at -4.28616e-010 / 0.10729 / 8.35161
```



```
Type         = E-Field (peak)
Monitor      = Mode 2
Plane at x   = 0
Frequency    = 446.274
Phase        = 180 degrees
Maximum-2d   = 4.17061e+006 V/m at -4.28616e-010 / 6.07321 / 5.84935
```

Detailed design, rendered in CST MWS and exported

orig 9/27/2007
vers 10/3/2007

exported file: **spoke FEL STEP export model v2b.stp**

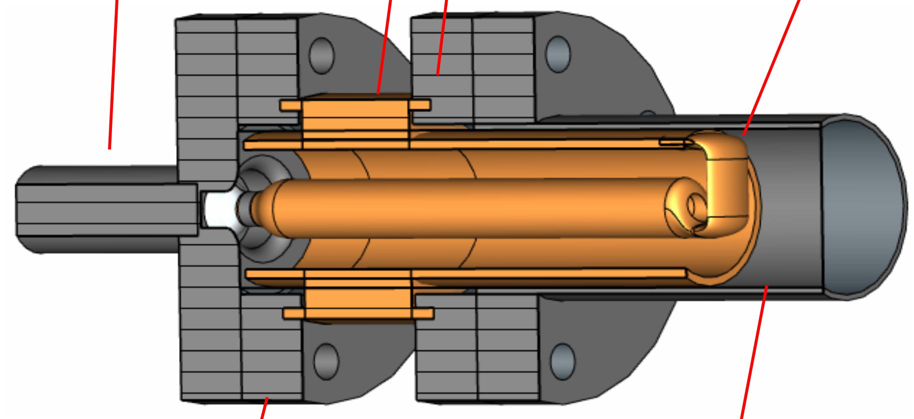
Cu heat sink to cool outer and inner conductors

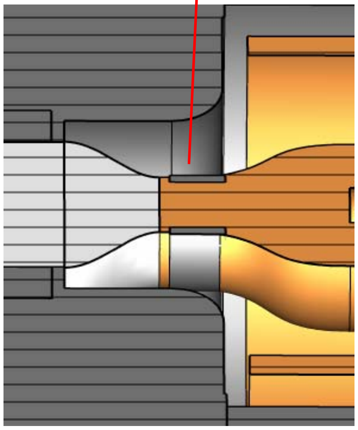
Cu sink brazed into SST flanges in captured joint to increase strength for cooldown

Type N feedthru, CeramTec #NW35CF or equivalent

Cu outer and inner conductor continuous piece to ensure high thermal conductivity. Loop bridge brazed in place.

SST spring clip to ensure firm clamping and to serve as demountable joint between feedthrough and antenna



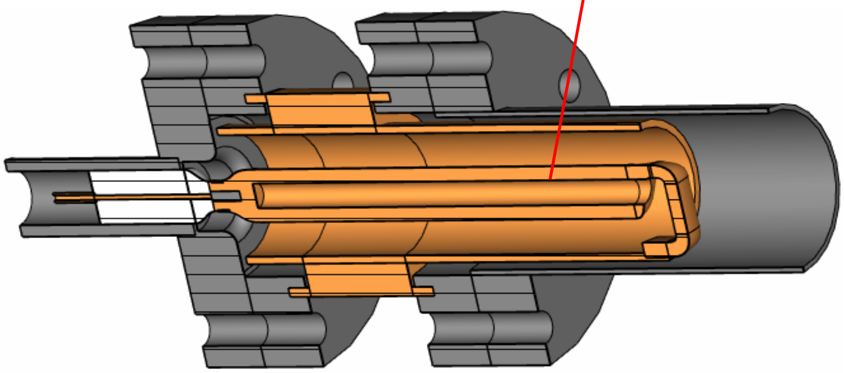


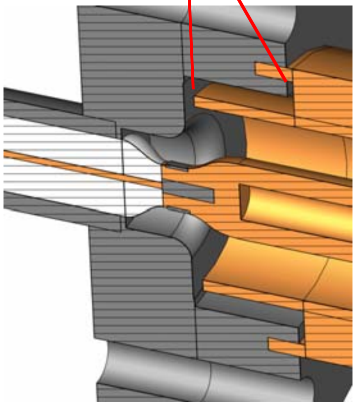
2.75" Conflat flanges

Niobium port from cavity

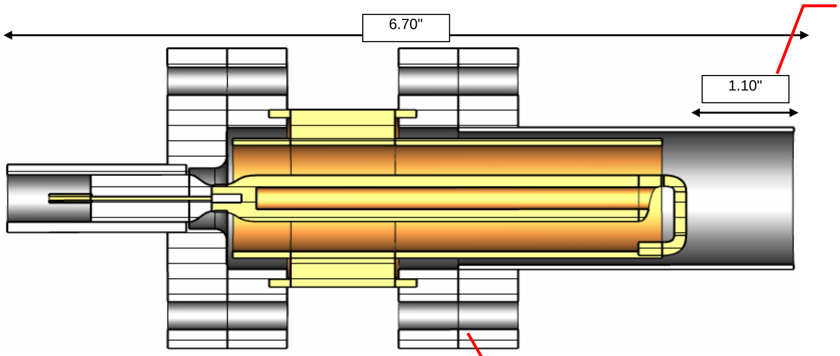
Gaps not crucial to match, and are a low-field region

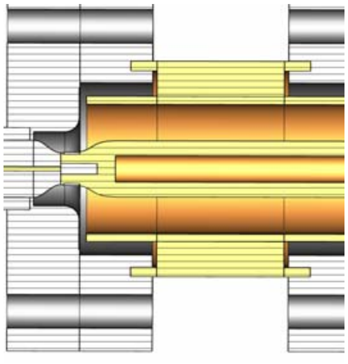
mass relief hole drilled down center of inner conductor





Initial esign depth for Qx=~2e7. Adjustments can be made prior to final design activities.





If the Qx needs to be decreased, add spacer a Conflat flange here. To increase Qx, use of 3-stub tuner is proposed.