STRATEGIES FOR WAVEGUIDE COUPLING FOR SRF CAVITIES*

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Abstract

Despite widespread use of coaxial couplers in SRF cavities, a single, simple waveguide coupling can be used both to transmit generator power to a cavity, and to remove a large class of Higher Order Modes (HOMs, produced by the beam). There are balances and tradeoffs to be made, such as the coupling strength of the various frequencies, the transverse component of the coupler fields on the beam axis, and the magnitude of the surface fields and currents. This paper describes those design constraints, categories of solutions, and examples from the CEBAF Energy Upgrade studies.

1 USE OF COUPLERS

Fundamental power couplers form an important part of the design of any RF accelerating cavity, and have a history of difficult development in superconducting $\beta \approx 1$ designs[1]. Although waveguide couplers are relatively uncommon in this arena, they offer some intriguing advantages, including simplicity and the ability to operate while flexing mechanically.

The intended operation of a coupler is clear—it has to convert the TM_{01} mode of the circular beampipe (and possibly higher order modes as well) to the TE_{10} rectangular waveguide mode, eventually connected through a window and cold-warm transition to the power source.

Much of the following discussion depends on the propagation of various modes down the circular beampipe. Table 1 shows the calculation of attenuation

$$A = 20/\ln 10 \cdot \sqrt{(p/a)^2 - (2\pi f/c)^2}$$

for the cavities (designed at Cornell) used at Jefferson Lab, which have tube radius $a = 3.5$ cm. Most $\beta = 1$ cavities have similar behavior in this regard, although there will certainly be small differences due to the HOM band structure and the relative size of the beampipe. Note that the TM_{110} cavity mode couples to both the TM_{11} ($p = 3.832$) and TE_{11} ($p = 1.841$) waveguide modes, but the former decays more rapidly and is unimportant for pipes longer than 2 cm.

It is possible to ignore HOM properties of the coupler, and assert that separate HOM filter/absorbers will be used (this is the approach of Jefferson Lab's baseline design for its energy upgrade). That places stringent requirements on the HOM damping system. In particular it leaves intact a relatively tight ratio between the fundamental (which must not be absorbed) and the lowest frequency HOM (which must be absorbed). The Cornell/Jefferson Lab cell shapes set a ratio of 1.72 to 1.50 GHz for this requirement. The community's history of HOM absorbers (often designed to these tight frequency selectivity requirements) has been less than trouble-free. One might hope that moving the required absorption band edge from 1.7 GHz to 2.7 GHz could make for a simpler, more reliable filter.

Table 1: Mode attenuations in beampipe

mode	freq. (GHz)	p	attenuation (dB/cm)
TM_{010}	1.497	2.405	5.31
TE_{111}	1.72–1.97	1.841	2.83–3.33
TM_{110}	2.08–2.12	1.841	2.44–2.77

Note that the Q_{ext} required for HOM modes can be 100 times lower than the design point for Q_{ext} of the fundamental: Storage rings typically need Q_{ext} less than 10^4 for HOMs and 10^5–10^6 for the fundamental, and linacs typically need Q_{ext} less than 10^5 for HOMs and 10^6–10^7 for the fundamental.

2 A $\lambda/2$ STUB DESIGN

Cornell designed and tested a waveguide coupler for use in a storage ring. The basic design used a stub slightly shorter than $\lambda/2$, as shown in Figure 1[2, 3, 4]. The second stub is used for HOM purposes: the HOM coupler in that design was incapable of damping modes below 1.9 GHz, and there are cavity TE_{111} modes in the 1.7 to 1.9 GHz range that needed damping. The second stub enhanced coupling to these modes.

This coupler length has some interesting advantages: the fundamental can be rejected by a factor of $\sin(2\pi x/\lambda) \ll 1$. This condition does not hold for non-π TM_{010} modes and HOMs, since λ is appreciably different at other frequencies (1.7 vs. 1.5 GHz in the latter case). The resulting strong coupling to the former mode set is of great interest in a storage ring application, where the stub-on-stub design was demonstrated to give a factor of two reduction in Q_{ext} for the $4\pi/5$ TM_{010} mode[3].

Figure 2 shows the electric fields of this coupler in the direction of the beam axis, as computed by HFSS[7]. Examination of these shows the large resonance (14× amplitude) set up between the beamline and the end of the stub. The curve labelled "Real" is the component of a traveling wave

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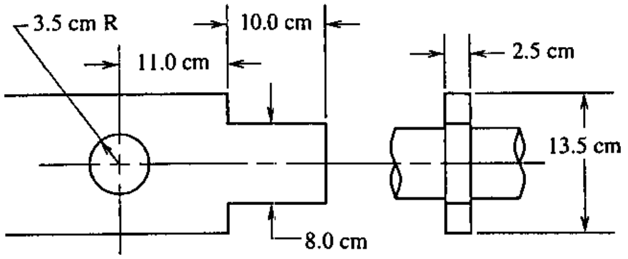

Figure 1: Schematic (interior dimensions) of $\lambda/2$ stub-on-stub FPC used by the Cornell/JLab cavity system.

that is in phase with the evanescent fields in the beampipe. It is also the standing wave pattern when the cavity is filled, as would occur in steady state on resonance. The curve labelled "Imag" is the component of a traveling wave that is in quadrature with the evanescent fields in the beampipe. It is also the standing wave pattern when the cavity is empty, as would occur off resonance.

This design also provides a mechanism to tune Q_{ext} by mechanical deformation of the stub. A bow in the wide face of the waveguide will change λ, which in turn makes a large change in $\sin(2\pi x/\lambda)$ and therefore Q_{ext}. For large changes in Q_{ext}, this might make sense. The complexity of producing a reliable cold mechanism makes this unattractive for performing small adjustments, where an external three-stub tuner can perform adequately.

When the cavity shape was incorporated in Jefferson Lab's design for its Nuclear Physics accelerator, CEBAF, the Q_{ext} tunability was used to shift from the (storage ring) design point of 3×10^5 to the (recirculating linac) design point of 6×10^6. This factor of 20 reduction of $\sin(2\pi x/\lambda)$ made for touchy bench adjustments and increased concerns about how stresses in assembly and cooldown could affect Q_{ext}. In retrospect, it might have been better to obtain some or all of the gross increase in Q_{ext} by increasing the length of beampipe between the coupler and end cell iris.

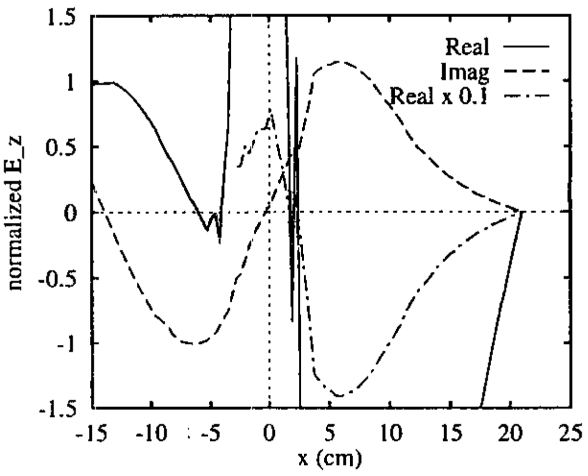

Figure 2: Electric fields in the centerline of $\lambda/2$ stub-on-stub FPC used by the Cornell/JLab cavity system.

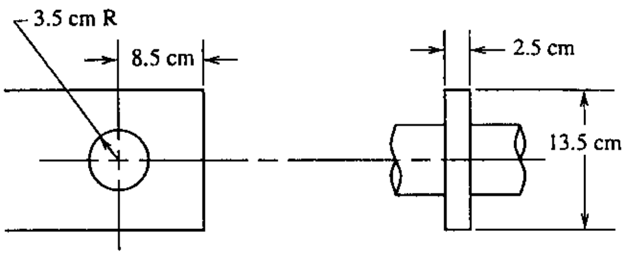

Figure 3: Schematic (interior dimensions) of $\lambda/4$ stub FPC proposed for the CEBAF energy upgrade cryomodule.

The coupler fields are quite asymmetric in the $\lambda/2$ stub design. The resulting beam kick was cancelled (to first order) in the CEBAF accelerator by arranging the feeds in a $+ + - - - - ++$ pattern for the 8-cavity cryomodule. Further study of coupler kicks[5] has in some cases placed extra restrictions on the setup of cavity gradients[6]. The use of the stub to reject the fundamental mode also leads to high fields in the coupler, and the stub must be well cooled to keep it superconducting.

3 A $\lambda/4$ STUB DESIGN

The same waveguide–beamline topology can result in a near-zero coupler kick, if the stub is $\lambda/4$ long, as shown in Figure 3. Figure 4 shows E_z along the length of the coupler axis, again computed by HFSS.

For a given intensity of fundamental evanescent fields in the beampipe at the coupler location, this coupler design has a factor of 10 lower peak field in the coupler region. It passes a factor of 10 more wave intensity to its waveguide port than the $\lambda/2$ stub design. To keep Q_{ext} the same, therefore, one could either put more beampipe between the cavity and the coupler, or add a matching iris on the rectangular waveguide section.

While the use of a matching iris may sound silly, a super-

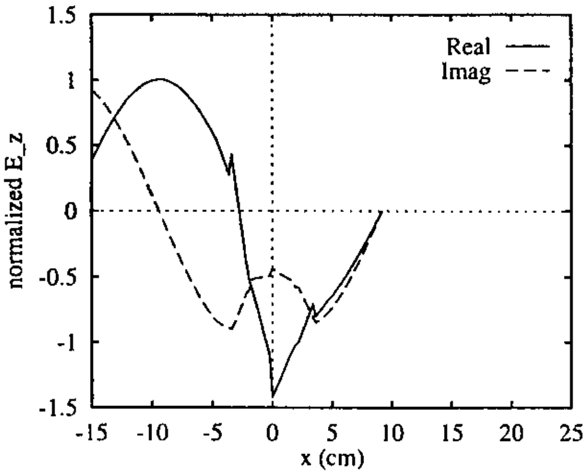

Figure 4: Electric fields in the centerline of $\lambda/4$ stub FPC proposed for the CEBAF energy upgrade cryomodule.

conducting filter constructed out of H-plane steps in waveguide width can form an effective *narrowband* iris. An example design sets up a VSWR of 10 at 1.5 GHz, but less than 1.2 at 1.72 GHz and above[8]. It takes only 56 cm of waveguide length, zero beamline space, and does not induce asymmetric coupler fields.

4 POLARIZATION OF RF COUPLING

Normally the two polarizations of dipole (and higher rotational order) modes have slightly different frequencies, due to broken cylindrical symmetry by manufacturing defects and couplers. In the worst case, a single HOM coupler in the presence of otherwise degenerate polarizations will break the degeneracy in such a manner as to couple only one of the two polarizations. Conversely, a single coupler can function effectively if the nodal planes are pinned at a 45° angle from the coupler plane.

The lowest frequency mode (which is the hardest to separate from the fundamental in conventional HOM filters) is normally the TE_{111} dipole mode, so any attempt to extract this mode from the fundamental power coupler (waveguide or not) has to deal with polarization. The HOM coupler in the Cornell/Jefferson Lab cavity-coupler system is designed to polarize the TE_{111} mode in the ideal direction. Most measurements of mode Q's verify the success of this plan. This effect was not checked during manufacturing, however, and in two cases (in Jefferson Lab's Free Electron Laser) one of those modes shows very high Q_{ext}[9].

Some studies have shown [10] that polarized cells can be used to damp both polarizations with a single coupler. To date, no beam testing or production manufacturing of such cells has been attempted, so the cost and performance impact can not be fully characterized. The polarizing effects of the $\lambda/4$ stub waveguide coupler discussed here are rather small, so there is hope that an intentional disturbance (such as an elliptical section of beampipe near the coupler) could swamp both residual manufacturing and inherent coupler polarization, without the complexity of polarized cells.

5 RF WINDOWS

The design of windows is tightly bound to that of the coupler itself. In the original Cornell/JLab design, a cold window (originally Kapton$^{\text{TM}}$, later ceramic) was used, primarily to keep the cells under clean vacuum during cryomodule assembly. That window had to meet a set of extreme design goals:

- Low VSWR over a wide frequency range (because of the HOM damping needs)
- Tolerance of high radiation flux (it's only 8 cm from the beamline)
- Low RF losses at the fundamental (since dissipation is taken by the 2 K helium circuit)
- Particulate free during assembly and operation (to avoid damaging cavity performance)

Meeting all of these needs simultaneously turned out to be a larger challenge than anticipated. Among other problems, many of the windows installed at CEBAF have developed pinholes during the years of operation[11].

The baseline design of the cryomodules for CEBAF's energy upgrade uses a single ceramic window at room temperature. The coupler system, window included, is not used for HOM damping, so the window can be implemented with a narrowband design (allowing a thicker ceramic with better puncture resistance). It still forms part of the beam vacuum envelope, and must be manufactured and assembled free of particulates.

6 CONCLUSIONS

The ultimate simplicity of a waveguide coupler makes it a worthy competitor to a conventional coaxial coupler. The Cornell/Jefferson Lab experience has led to clearer understanding of how to use waveguide couplers to meet design goals. A coupler based on this work is now in the prototyping phase at Jefferson Lab.

7 REFERENCES

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