HEPL 994
August, 1989

HOM Couplers for a 1 mA Linac FEL Driver*

Alfred Baron and Ernst Haebel[1]

High Energy Physics Laboratory
Stanford University
Stanford, California 94305-4085

(Presented at the 4th Workshop on RF Superconductivity,
KEK, Japan, August 14-18, 1989)

* Work supported by ONR Contract Number N00014-86-K-0118.
1 On leave from CERN, Geneva, Switzerland.

HOM COUPLERS FOR A 1 mA LINAC FEL DRIVER*

Alfred Baron and Ernst Haebel[1]

High Energy Physics Laboratory
Stanford University
Stanford, California 94305-4085
U.S.A.

Abstract

HOM couplers have been designed for a 1 mA linac FEL driver with beam recirculation capability. The linac consists of 4-cell structures resonant at 1.3 GHz. CERN's widened beamtube concept with multimode endcell compensation has been adopted in its DESY version together with a coaxial coupler geometry to obtain compactness and low cost. Because it is easily tuned and cooled and is particularly short, CERN's one post coupler has been selected and adapted for use at 1.3 GHz. With optimized geometry the transfer curve is composed of two suitably placed low Q resonances and only one parasitic notch of 8 dB depth located above 4 GHz. There the fundamental mode monitor probes, which have been given a strongly enhanced high frequency coupling characteristic provide adequate cavity damping.

* Work supported by ONR Contract Number N00014-86-K-0118.

[1] On leave from CERN, Geneva, Switzerland.

(1) Introduction

At HEPL, work is underway to design an improved 1 mA superconducting (sc) linac FEL driver with recirculating capability. We seek a compromise between the number of cells per cavity and the number of cavities. Costs are clearly lower for fewer cavities, but design becomes more difficult as the number of cells per cavity increases. In particular, with many cells per cavity, it is difficult to maintain sufficient mechanical rigidity, high enough accelerating gradients, homogeneous excitation of all cells and sufficient damping of higher order modes (HOMs) with beam tube couplers. We have a coupling scheme which will allow four cells per cavity.

(2) Cavity and Beam Tube Geometry

The DESY version [1] of CERN's widened beam tube concept with multimode endcell compensation [2] has been adopted. Figure 1 shows an outline of half the cavity with details of the beam tube geometry including the two diameter reductions to the final beam pipe dimensions. Figure 2 shows the boundary used for URMEL calculations (20,000 mesh points on a CRAY computer.)

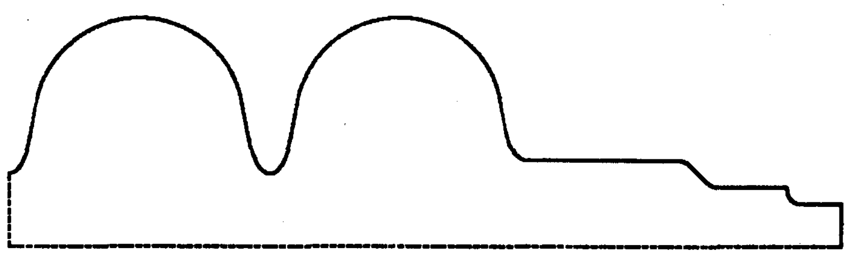

Figure 1. Cavity Shape.

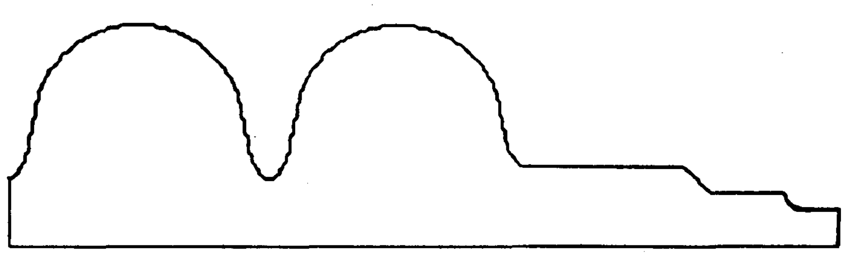

Figure 2. Cavity Shape used by URMEL

The dipole field calculations were subjected to particularly close scrutiny since the cavities will be used in a linac with beam recirculation. We determined that the positions of the E_r field nodes on the beam tube walls were well defined up to a frequency of 4.2 GHz.

This was done by comparing calculations having a constant mid-plane boundary condition but with different beam tube boundary conditions (i.e.: I-EE and I-EM modes were compared, as well as I-ME and I-MM). We limited quantitative coupler design work to frequencies below 4.2 GHz but also made certain that our couplers would be effective at higher frequencies (see Fig. 6).

(3) HOM Coupler Geometry

We have chosen a coaxial coupler geometry. Frequently wave guides are used [3] since their high pass characteristics may be employed to suppress coupling to the fundamental mode. However, a coaxial coupler may be made much more compact than a guide. These couplers will be terminated at room temperature since the dipole mode signal will be used as a diagnostic for beam steering. As a result, we can tolerate several watts of fundamental output without difficulty (for as much as 10 watts output we have a 60 MHz bandwidth in the fundamental mode rejection filter).

We have selected the one-post coupler design from CERN [4] and modified it for use at 1.3 GeV. It is very compact and is easy to cool. In addition, the filter is demountable with a flange that carries no fundamental mode current. Filters can be separately tuned with a rejection characteristic that is independent of the mounting procedure.

Two coupler models were constructed with diameters of 30.5 and 38 mm. An outline of the larger coupler is shown in Figure 3 and its transfer curve (measured as described in [5]) in Figure 4. It has two suitably placed low Q resonances and one parasitic notch of 8 dB depth at 4.05 GHz. This notch may be shifted to higher frequencies by reducing the coupler diameter. It is located at 4.4 GHz for the 30.5 mm diameter model. In any event, this notch is not a problem since another pair of couplers take over HOM damping in this frequency range.

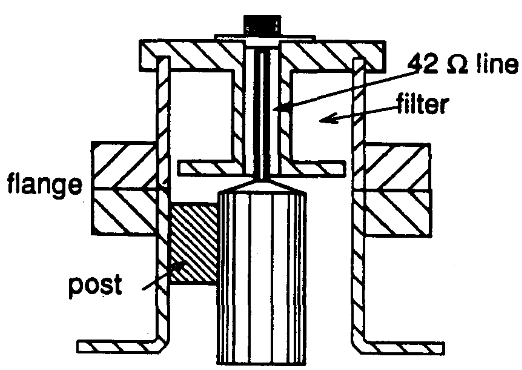

Fig. 3. Schematic of HOM Beamtube Coupler

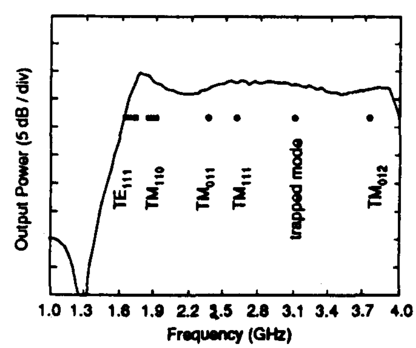

Fig. 4. Measured Response of HOM Coupler

We will use fundamental mode monitor probes for additional HOM coupling. The simple geometry shown in fig. 5 produces a double resonance transfer curve with peaks at 3.1 and 4.6 GHz. Within this frequency region (and at higher frequencies) the probe has an input resistance comparable to, or greater than, the HOM coupler. Calculated transfer curves, for both HOM coupler and probe are shown in figure 6. The equivalent circuits used for the calculation are shown in figure 7.

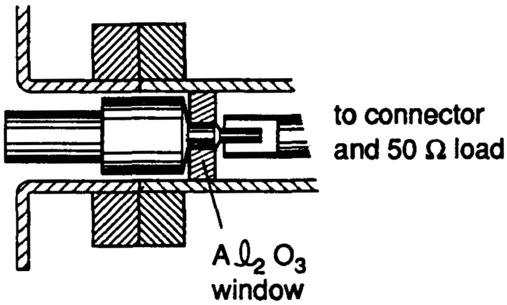

Fig. 5. Schematic of Fundamental Probe

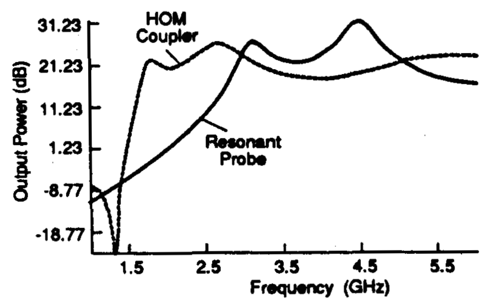

Fig. 6. Calculated Response of HOM Coupler and Probe

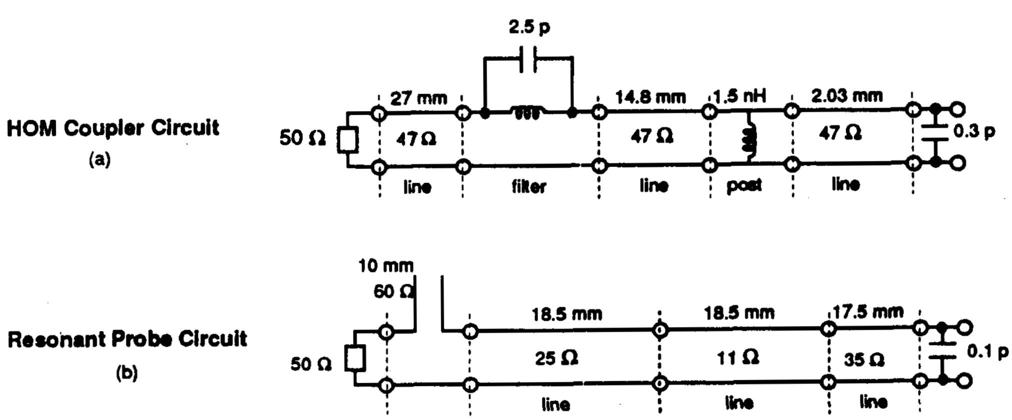

Figure 7. Equivalent Circuits for HOM Coupler and Probe.

(4) Coupler Location on the Beam Tube

URMEL output shows that only dipole modes with frequencies less than twice the fundamental have sizeable (R/Q)' values. These modes do not propagate into the beam tube and the HOM coupler is mounted close enough to the end cell to damp them sufficiently. Higher frequency modes will propagate into the beam tube and, though they have relatively small (R/Q)' values, coupling to some of them may still be too small. This is because the modes form standing waves and an E_r field node may fall on the coupler position. In addition, some modes simply have small beam tube fields [6].

We have identified four dipole modes with frequencies between 2.5 at 4.2 GHz that have low beam tube fields. Two of them (at 3055 and 3060 MHz) are particularly dangerous,, having both low fields and a node near the HOM coupler position (261 mm from the cavity midplane). Therefore we have placed our resonant probes onto the E_r maximum of these modes at 22 mm outwards and, to avoid mechanical overlap, rotated 90° from the HOM coupler. (At this position we expect the monitor probes to have a fundamental Q_{ex} of 2 E 10).

(5) Cavity Damping and Beam Breakup Currents

External Q values (Q_{ex}) are given in tables 1 and 2 below. Since we do not yet have a cavity to measure, these values were calculated using

$$Q_{ex} = \frac{\omega U}{P_{ex}}$$

where ω (the mode frequency) and U (the field energy in the cavity) are given directly by URMEL. The power removed by the couplers (P_{ex}) may be calculated using a displacement current.

$$I_d = \omega \varepsilon_0 E_r S$$

where S is the effective area of the coupler antenna and E_r is the field given by URMEL at the coupler location. The power is then given by:

$$P_{ex} = \frac{1}{2} I_d^2 R_s$$

where R_s is the input resistance of the coupler calculated using the circuit model given above.

Note that this calculation is sensitive to the value chosen for the effective area of the coupler. Q_{ex} values vary with the square of the effective area and, therefore, the fourth power of the radius. We have used effective radii of 12 and 8 mm for the HOM coupler and probe, respectively. The actual antenna radii in these devices are 9 mm and 6 mm respectively. However, these are clearly lower limits since the outer diameters are substantially larger (38 mm and 20 mm) and the antennas are extended somewhat into the beam tube further increasing their coupling. This method of approximation has been used

URMEL Name	f (MHz)	Mode	(R/Q)' (Ohms)	Q_{ex} HOM Coupler	Q_{ex} Probe	I_{s2} (mA)	
1 ME 2	1695	TE_{111}	18.2	2.8 E4	-	34	
1 EE 2	1751	TE_{111}	15.1	1.8 E4	-	62	
1 ME 3	1826	TM_{110}	3.8	2.3 E4	-	185	
1 EE 3	1863	TM_{110}	19.8	3.5 E4	-	22	
1 ME 4	1892	TM_{110}	13.7	1.0 E5	-	11	lowest I_{s2}
1 EE 4	1906	TM_{110}	1.38	4.3 E5	-	26	
1 ME 7	2534	TM_{111}	25.2	1.9 E4	4.8 E6	19	highest (R/Q)
1 EE 10	3055	-	.025	1.0 E8	1.5 E7	24	"trapped" mode
1 ME 11	3060	-	.415	1.7 E7	5.9 E5	33	"trapped" mode
1 EE 20	4175	-	.732	6.8 E5	5.3 E4	144	
1 ME 20	4177	-	.360	8.8 E6	3.0 E5	57	

Table 1. Dipole Modes With Lowest Beam Breakup Currents

URMEL Name	f (MHz)	Mode	R/Q (Ohms)	Q_{ex} Probe	Q_{ex} 2 HOM Couplers
0ME2	1300	TM_{010}	231.8	2.3 E10	-
0EE4	2347	TM_{011}	24.8	-	3.5 E4
0ME4	2360	TM_{011}	55.8	-	7.1 E4
0ME 11	3703	TM_{012}	14.6	-	4.6 E4

Table 2: Q_{ex} of longitudinal modes with high (R/Q)

previously [2] and subsequent results lead us to believe that our Q_{ex} values are in fact conservative estimates.

For dipole modes we have also calculated a two pass recirculation beam break up current limit, I_{s2}. This is given as

$$Q\,I_{s2} = \frac{\gamma}{R_{12}}\,\frac{1}{K}$$

$$K = 2\,\frac{\omega}{c}\,\frac{e}{mc^2}\left(\frac{R}{Q}\right)'$$

where we have taken γ/R_{12} to be 2 m^{-1} as used in [7]. In all cases, we have a comfortable margin error over the 1 mA current planned for this machine. A short derivation of the above expression is given in an appendix.

(6) Conclusion

We have carefully designed a coupling scheme that should provide more than adequate damping for higher order modes in a 4 cell accelerating cavity. This scheme uses compact HOM couplers mounted close to the cavity in conjunction with the fundamental monitor probes. The monitor probe has been given an enhanced high frequency coupling characteristic via some simple design modifications and couples to modes having E_r zeros at the HOM coupler location.

(7) Acknowledgements

The authors would like to thank H. A. Schwettman (HEPL) for his continued interest and stimulating discussions. Also many thanks to W. R. Fowkes, B. Tice and H. Hoag (SLAC) for their generosity in allowing us to use SLAC resources and their useful suggestions. Finally, we would like to thank G. Wilson for her patient help preparing this manuscript.

(8) References

[1] H. P. Vogel, DESY-M-85-09.

[2] E. Haebel, P. Marchand, J. Tuckmantel, Proceedings of the Second Workshop on RF Superconductivity, Geneva, Switzerland, July (1984), Part 1, p. 281.

[3] J. C. Amato, Proceedings of the Third Workshop on RF Superconductivity, ANL-PHY-88-1, Vol. II, p. 589.

[4] E. Haebel, CERN/EF/RF/87-4, November, 1987.

[5] E. Haebel, Proceedings of the Second Workshop on RF Superconductivity, Geneva, Switzerland, July 1984, Part 1, p. 299.

[6] A. Mosnier, private communication.

[7] C. M. Lyneis, R. E. Rand, H. A. Schwettman, A. M. Vetter, Nucl. Instr. and Meth., 204, (1983), pp. 269-284.

Appendix: Derivation ofthe Beam Current Stability Limit

Assume a cavity oscillates in a dipole mode with axial fields $\vec{E} = (E_x,0,0)$ and $\vec{B} = (0,B_y,0)$. A particle of charge e travelling along the axis with velocity v will experience a transverse force leading to a change in momentum given by

$$\Delta p_x = e \int (E_x - v B_y)\, dt$$

Assuming the fields are given by

$$E_x(z,t) = \hat{E}_x(z) \cos \omega t$$

and

$$B_y(z,t) = \hat{B}_y(z) \sin \omega t$$

where ω is the frequency of the dipole mode and t = v/z is taken to be zero in the center of the cavity, we may write

$$\Delta p_x = \frac{e}{v} \int \left[\hat{E}_x(z) \cos\left(\frac{\omega}{v} z\right) - v \hat{B}_y(z) \sin\left(\frac{\omega}{v} z\right) \right] dz$$

Integration by parts yields

$$\Delta p_x = \frac{e}{\omega} \hat{E}_x(z) \sin\left(\frac{\omega}{v} z\right)\Big|_{z_1}^{z_2} - \frac{e}{\omega} \int \left[\frac{\partial \hat{E}_x}{\partial z} + \omega \hat{B}_y \right] \sin\left(\frac{\omega}{v} z\right) dz$$

Maxwell's curl law may be used to give

$$\frac{\partial \hat{E}_x}{\partial z} + \omega \hat{B}_y = \frac{\partial \hat{E}_z}{\partial x}$$

So, taking $E(z_1) = E(z_2) = 0$, we may write

$$\Delta p_x = -\frac{e}{\omega}\int_{z_1}^{z_2} \frac{\partial \hat{E}_z}{\partial x} \sin\left(\frac{\omega}{v} z\right) dz$$

Exchanging orders of differentiation and integration gives

$$\Delta p_x = \frac{e}{\omega} \frac{\partial V}{\partial x}$$

where

$$V(x) \equiv -\int_{z_1}^{z_2} \hat{E}_z(x) \sin\left(\frac{\omega}{v} z\right) dz$$

Then taking a finite difference approximation to the derivative we have

$$\Delta p_x \approx \frac{e}{\omega} \frac{V(\xi)}{\xi}$$

where ξ is some small displacement in the x direction.

Now, for the change in angle through the cavity we may write

$$x' = \frac{\Delta p_x}{p_{\parallel}} = \frac{1}{\gamma \beta m c} \frac{e}{\omega} \frac{V(\xi)}{\xi}$$

Converting this to a change in position after one pass through the recirculation optics gives ($\beta = 1$)

$$x = R_{12}\, x' = \frac{R_{12}\, e}{\gamma \omega m c} \frac{V(\xi)}{\xi}$$

Then taking $P_{tr} = I_b V(x)$, (P_{tr} the power transfered from the beam to the mode) and choosing $\xi = x$ gives

$$P_{tr} = I_b V(\xi) = I_{s2} \frac{V(\xi)}{\xi} \xi$$

or

$$P_{tr} = I_b \frac{R_{12}\, e}{\gamma \omega m c} \left(\frac{V(\xi)}{\xi} \right)^2$$

The system becomes unstable when the power transfered to the mode becomes equal to the power dissipated. Using the usual definitions for Q and R/Q we may write

$$P_{diss} = \frac{\omega U}{Q}$$

and

$$\omega U = \frac{1}{2} \frac{V^2(\xi)}{R/Q}$$

Then equating the two powers and calling the limiting current I_{s2}, we have

$$I_{s2} \frac{R_{12}\, e}{\gamma \omega m c} \left(\frac{V(\xi)}{\xi} \right)^2 = \frac{1}{2} \frac{V^2(\xi)}{Q \cdot R/Q}$$

And algebra gives

$$I_{s2} \cdot Q = \frac{\gamma}{R_{12}} \cdot \frac{1}{K}$$

where

$$K \equiv 2 \frac{\omega}{c} \frac{e}{mc^2} \left(\frac{R}{Q} \right)'$$

and

$$\left(\frac{R}{Q} \right)' \equiv \frac{R}{Q} \cdot \frac{1}{\xi^2 \left(\frac{\omega}{c} \right)^2}$$