# OPTIMIZING THE HIGH POWER INPUT TO THE LBL 400 MHZ PROTON RFQ*

D. Howard, R. Caylor, R. Gough, J. Lax, R. MacGill,
R. Richter, W. Ridgeway, J. Staples
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

## Abstract

Based on the initial design values and results of the recent alignment and low power testing of the novel 400 MHz RFQ produced at LBL, the RF input power requirement at design gradient with full beam loading is approximately 160 kilowatts.

As the quadrant size and design limit the RF drive loop dimensions, the drive port was chosen to accept commercially available equipment of 1 5/8 inches diameter. Available RF power sources provide 3 1/8 inch diameter coax at the output.

The interface between the two coax sizes was chosen to be a 1/4 wavelength tapered section with a constant Zo of approximately 50 ohms. The 1 5/8" end of the tapered section is mounted directly to the RFQ cavity body. The following items will be described:

- Method used to more evenly distribute the power handling limits.
- Gradients and relative safety factors along the length of the tapered section.
- Impedance matching sections.
- Limiting factors and their subsequent treatment.
- High power test results.

## Introduction

As the specified RFQ[1] operational duty factor is quite low, ~0.2%, the predominant factor in limiting the input power to the RFQ is the peak voltage gradients in the system. This simplifies our efforts as high average currents, and the problems of removing the associated heat, are not of great concern.

It is desirable to have the system input power, or gradient, limits located within the RFQ structure and particularly at the vane tips, as once the structure is "baked-in" reliable operation can be achieved.

The maximum power deliverable, in a coaxial, 50 ohm, very low average power environment, is determined by the line diameters and the operating Standing Wave Ratio. Conservative specifications, by Andrews Corporation, rate the maximum peak power in 1 5/8 inch and 3 1/8 inch coaxial lines, where the SWR is 1:1, as follows:

- 1 5/8 inch — 145 kilowatts
- 3 1/8 inch — 400 kilowatts

As is shown above, when operating with an SWR of 1:1, the 1 5/8 inch diameter coax peak power rating of 145 kilowatts is less than the 160 kilowatts required for normal operation. This places an unacceptable system power, or gradient, limit outside the RFQ structure, in the tapered section, at the cavity body. The option of a manifold and multiple drive loop assembly as a solution to this problem was discarded in favor of a solution that modifies the gradient levels in the tapered section. This redistribution of the gradient is achieved by operating the tapered section with an SWR in excess of 1:1, where the tapered section acts as a 1/4 wave transformer.

Since the maximum peak power ratings are defined when the SWR is 1:1, these ratings reflect the gradient limits due to the geometry of the coaxial line. The maximum peak power rating at a point along the line will be modified, up or down, dependent upon the resonant impedance of the line at the point in question.

The low impedance point on the transmission line is located near the cavity wall, in the 1 5/8 inch environment, where, an impedance value of less than the tapered section Zo of 50 ohms is determined by cavity condition and drive loop size. At this point, the modified maximum peak power rating, due to the change in impedance will always be greater than the "flat line" peak power rating provided the impedance remains lower than the tapered line impedance. This criteria is ensured during normal operation as cavity sparking, multipactoring, and the fill times associated with pulsed operation, present lower impedances to the drive loop. Conversely, the modified peak power rating at the high impedance point, located 1/4 wavelength away in the 3 1/8 line environment, will be reduced from the "flat line" condition.

Fig. 1. The RFQ and Drive Line Assembly

A matching section is attached to the high impedance end of the tapered line. This mechanically rigid section is of one piece, 3 1/8 inch, 50 ohm coaxial line, construction. The fixed lengths of line required to match the tapered line impedance to RF drive source are an integral part of the matching section and no tuning adjustments are available. As alluded to in the above paragraph, there may be significant voltages produced in the matching section when there is cavity sparking, multipactoring, or normal filling; caused by the increased SWR. To reduce the chance of sparking in the tapered line or matching sections during these times, the assembly has been designed to withstand 3 atmospheres pressure. The pressure and bleed ports are about the size of 1/8 inch pipe and are designed to interface with a dry nitrogen bottle and scfh flow gauge.

There are two insulators between the 3 1/8 inch port provided for the RF drive source and the RFQ cavity. To eliminate multipactoring in the drive line, the cavity vacuum insulator is located as close to the cavity body as possible. The second insulator is located at the input port and is pressure tight on the matching section side.

## SWR

The initial criteria for setting the SWR of the tapered section is equal peak power ratings at the input and output ports of the taper. As such, the calculation to define the SWR is based on the breakdown voltages at the ports. The breakdown voltage is based on the geometry of the taper and on S, the maximum gradient allowable in air, in volts per mil. The value for S and the dimensions of the tapered section are given below. The dimensions listed for the outer conductor give the inside diameters.

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†Author's Address: Washington State University, Pullman, WA.

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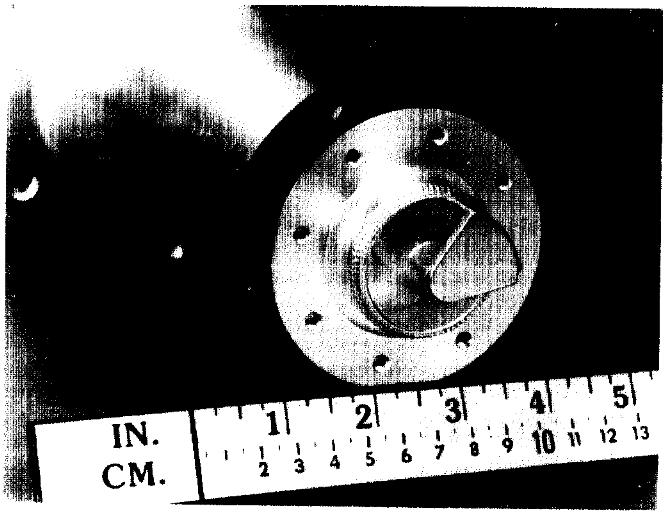


Fig. 2. Cavity Vacuum Insulator and Drive Loop

Tapered Section Dimensions – inches

| | |
|---|---|
| Length of tapered section | L: = 7.335 |
| Minimum inner conductor diameter | Idmin: = .658 |
| Maximum inner conductor diameter | Idmax: = 1.309 |
| Minimum outer conductor diameter | Odmin: = 1.515 |
| Maximum outer conductor diameter | Odmax: = 3.015 |

It is assumed that the diameters change at a constant rate. The diameters, at any point, n, along the line, can then be calculated as shown below. Where:

k is an integer to define the number of calculated points along the line $k := 71$ $n := 0 \,..k$

$$Id_n := \left[(Idmax - Idmin \cdot \frac{n}{k}\right] + Idmin$$

$$Od_n := \left[(Odmax - Odmin \cdot \frac{n}{k}\right] + Odmin$$

The breakdown voltage for any point, n, along the length of the tapered section can be calculated using the formula shown below. From TIMES WIRE and CABLE CO.

$S := 74$

$$Vbrkdwn_n := 1000 \cdot 1.15 \cdot \frac{S}{2.54} \cdot Id_n \cdot \log\left[\frac{Od_n}{Id_n}\right]$$

Since the tapered section is a constant Zo structure, the breakdown voltage, Vbrkdwn, is proportional to the Id or Od along the line.

For the taper to breakdown at two points on the line, the resonant impedance must vary as the square of Vbrkdwn, Id, or Od. Since SWR is the square root of the ratio of maximum and minimum impedances and the points in question are at the ends of the taper, the SWR required for simultaneous breakdown at the input and output ports is:

$$SWR := \frac{\max(Id)}{\min(Id)} \qquad SWR = 1.99$$

Andrews Corp. uses a safety factor of two in voltage when calculating the peak power ratings. With this as the criteria, and given the above SWR, the new peak power rating at the input and output ports of the tapered section is:

$$Pin := \frac{\left[\frac{\max(Vbrkdown)}{\sqrt{2} \cdot 2}\right]^2}{Zo \cdot SWR} \qquad Pin = 3.17 \cdot 10^5$$

## Ideal Voltage and Gradient Distribution

The calculated voltage distributions in a tapered section are a function of the frequency, length of the taper, Zo, and SWR. Where:

The impedance at the tapered section input in polar format:

$$zp := \frac{SWR - 1}{SWR + 1}$$

The impedance along the line in polar format:

$$Zp_n := |zp| \cdot e^{j \cdot \left[4 \cdot \pi \cdot \left[\lambda lo - \lambda 1_n\right]\right]}$$

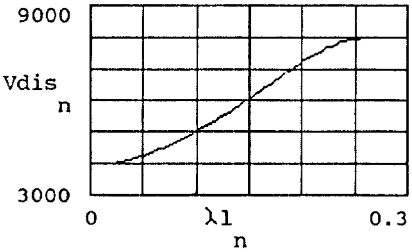
Where: $\lambda lo$ is the wavelength of the line and $\lambda l_n$ is the wavelength at point n, along the line.

In rectangular format:

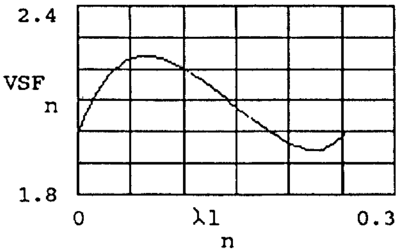
$$Zr_n := \frac{\left[1 + Zp_n\right]}{\left[1 - Zp_n\right]}$$

Peak voltage distribution vs. line position:

$$Vdis_n := \sqrt{Pin \cdot \left|Zr_n\right| \cdot 2 \cdot Zo}$$



Since the breakdown voltage and peak voltages along the line have been calculated, the Voltage Safety Factor along the line is:



To maintain a voltage safety factor of two, the input power will have to be reduced as shown below:

$$P'in := \left[\frac{\min(VSF)}{2}\right]^2 \cdot Pin \qquad P'in = 2.99 \cdot 10^5$$

## Original Voltage and Gradient Distributions

The above calculations and graphs reflect the ideal situation where the tapered section is loaded in purely resistive components. As measure with a HP8753A network analyzer, the input to the taper section is a complex number. When the formulas are modified to accept the complex numbers and the associated wavelength changes, the following voltage distributions and safety factors result.

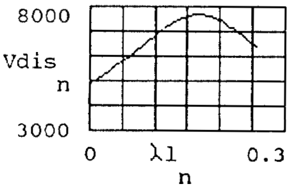
The input impedance of the tapered section as measured with the HP8753:

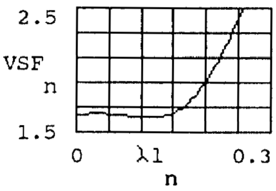
$$zr := 55.35 - 32.82j$$

Where: In polar format, zp is the magnitude of the impedance, zr, and $\lambda s$ is the calculated wavelength from an open to the loop.

$$Zp_n := |zp| \cdot e^{j \cdot \left[4 \cdot \pi \cdot \left[\lambda s - \lambda 1_n\right]\right]}$$

As shown on the graphs below, the peak voltage distributions and safety factors have been greatly modified by the loop assembly.





Maintaining the voltage safety factor of two, the input power will have to be further reduced to 2.08 x $10^5$.

## Limiting Factors

The two main contributors to the reductions in input power are the loop inductance and the ceramic insulator. To alleviate some of the effects, the loop angular displacement was increased from ~60 degrees to cover almost 180 degrees. See figure 2 for the original loop. The present loop is shown below.

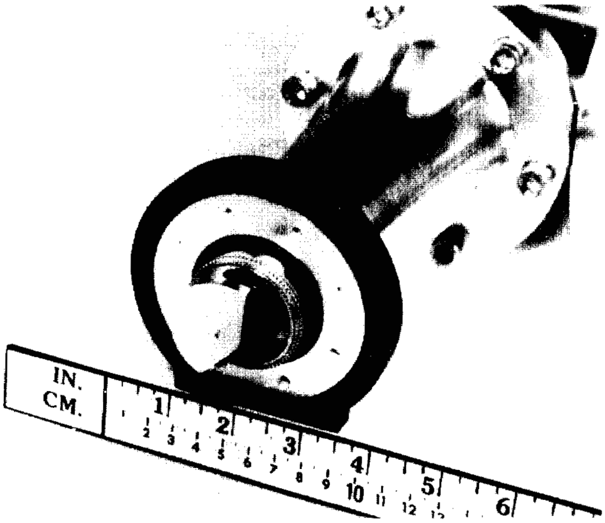


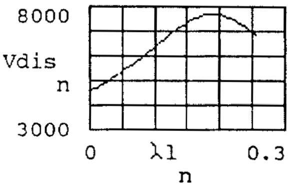
Fig. 3. The Modified Loop Assembly

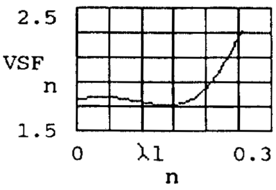
The ceramic insulator was replaced with a TEFLON insulator as the effects of shunt capacity in the line make the loop appear more inductive. The effects of these changes is shown below when the new impedances are calculated.

The input impedance of the tapered section as measured with the HP8753:

$$zr := 66.46 - 32.61j$$

As can be seen in the following graphs, while maintaining a voltage safety factor of two, there is a modest change in allowable input power. The distribution of the safety factor is desirable as it increases the safety factor at the insulator.





The calculated, maximum input power allowable, including a voltage safety factor of 2, is 2.33 x $10^5$.

## Matching Section

The matching assembly outer conductor is constructed of standard 3 1/8 inch line with a .046 inch wall thickness, however, the center conductor is not standard. As 1 5/16 inch tube was not available, we substituted with tube measuring 1 1/4 inch in diameter. The matching section impedance is then 53.13 ohms. The components required to match the above impedance to 50 ohms are shown below with the dimensions given in inches:

Shorting surface to the center of "T": 4.75
Center of the "T" to tapered section input flange: 2.16

The unit pieces are hard soldered and silver plated. Outer conductor connection to the tapered section is accomplished by a 3-1/8 inch bolt circle while the center conductor bolt is accessed on the inside of the conductor, near the taper. The RF input port, the third connection to the "T" is a standard 3 1/8 inch EIA flange. Low power SWR was measured with the HP8753A at < 1.2:1.

## High Power Tests

High power testing of the RFQ was completed by ACCSYS TECHNOLOGIES, Pleasanton, CA, in the fall of 1988. The RF drive source chain consisted of the amplifier, a series sliding line, a directional coupler, and the input to the matching section. Directional coupler measurements, at high power, indicated an SWR in excess of 1.2:1. The increase was attributed to the combination of the loop SWR and the directional coupler directivity. Although not designed for this service, the drive loop was successfully rotated several times, at low power, under vacuum, to minimize the change in the directional coupler reflected power output as the sliding line was moved over a 1/2 wavelength.

The input power was restricted to 160 kilowatts, during flat-top, in closed loop operation. During the early stages of testing, dry nitrogen was supplied to the drive line assembly and removed at later stages, when the baked-in procedure of the RFQ was deemed a success.

During operation, no adverse effects from the TEFLON were detected. The inspection performed after the high power test was also encouraging as there were no signs of sparking or burning at the insulators, or in the drive line assembly.

## Conclusion

The 1/4 wave transformer as tested appears to be a viable alternative to multi-port drive systems where modest increases beyond the rated power levels are required.

## Acknowledgements

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## References

[1] J. Staples, S. Abbott, R. Caylor, R. Gough, D. Howard, R. MacGill, "A compact proton RFQ injector for the Bevalac," conference paper, LBL No. 25367.

[2] S. Abbott, R. Caylor, R. Gough, D. Howard, R. MacGill, J. Staples, "Design of an integrally formed RFQ," conference paper, LBL No. 25890.