RFQ1 DESIGN PARAMETERS

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Summary

The CRNL RFQ1 accelerator is being built to study the physics and engineering of launching a moderate energy, high current cw proton beam with good quality and reliability. A design review was held in June 1983 in which design parameters were presented. Since that time the CRNL RFQ "sparker" experiment has shown that cw fields above twice the Kilpatrick limit are possible, making the previous RFQ1 design too conservative. A review of the basic design showed some advantages in using a higher field. This paper discusses the design modifications and comments on the progress of the overall RFQ1 program.

Introduction

The CRNL RFQ1 accelerator program was initiated in 1981 as a first step in the ZEBRA[1] development program, which would make use of existing facilities where possible. The design work reviewed in June 1983 has been modified to take advantage of our recent experience with a high power unmodulated cw RFQ.

Aims

RFQ1 is to be CRNL's first full power cw RFQ to accelerate beam. It was initiated as a first step in the ZEBRA program to gain operating experience and to determine acceptable design and construction techniques prior to the construction of the ZEBRA RFQ.

Aims of the experiment are:

(a) To study consequences of long term cw operation, including erosion and sputtering of the vanes, and degradation of the rf joints.

(b) To study the beam current limit and compare predictions of particle beam dynamics codes with observed results.

(c) To develop diagnostic tools.

(d) To verify mechanical design concepts (especially those related to cw operation).

The ZEBRA program itself has been delayed[2], primarily because the need for accelerator breeding is now further in the future. However, our long term interest in high current cw proton linacs remains and the RFQ1 program is relatively unaffected.

RFQ1 Design Review

A RFQ1 design review[3], with participation from the United States, Germany and Japan, was held at Chalk River in June 1983. All aspects, from conceptual design to mechanical details, were reviewed. Suggestions in numerous areas are being implemented - in particular on the mechanical design. At the time of the review, RFQ1-A[4] was the reference design, but recent experiments have shown that design changes should be made.

Choice of Design Field

The CRNL "sparker" RFQ first operated in November 1983[5]. It has shown that cw operation with peak electric fields twice the Kilpatrick limit (2.0 * Kp) is possible. Although this field level is routinely used in pulsed RFQ's it was not known whether it could be maintained in a cw one. RFQ1-A, which was based on design fields of 1.25 * Kp, with operation possible at reduced current at 1.0 * Kp, was felt to be too conservative, and a new design (RFQ1-B) based on design fields of 1.5 * Kp has been prepared. The new design is shorter and requires less rf power. The biggest advantage of this change is that the existing rf power supply should now be adequate to produce 2.0 * Kp fields in RFQ1-B whereas it would have required extensive modifications to produce them in RFQ1-A. A further increase of design field could lead to an even shorter, lower power design, but the savings would be small and maximum flexibility is retained by opting for the design described below.

Design Modifications from RFQ1-A to RFQ1-B

Several design values for RFQ1-B are given in Table 1. Several features have been modified from the RFQ1-A design because of the increase of the maximum design gradient. The vane length is reduced from 2.32 m to 1.48 meters, and the structure power reduced from 242 kW to 118 kW. The vane base has been changed because the requirement for its transverse movement was abandoned.

Table 1

RFQ1-B Specifications

Frequency	269 MHz
Input Energy	50 keV
Output Energy	600 keV
Peak Electric Field	
(operating)	24.9 MV/m (1.5 * Kp)
(test limit)	33.1 MV/m (2.0 * Kp)
Vane Length	1.48 m
Vane Voltage	78 kV
Number of cells	181
Average Bore Radius	0.413 cm
Minimum Radius	0.309 cm
Structure Power (1.25 * SUPERFISH value)	
design (1.5 * Kp)	118 kW
test limit (2.0 * Kp)	210 kW
Beam Power	41 kW
Vacuum	< 10^{-3} Pa

The RFQ vanes must be supported in a manner which allows some degree of adjustment in spite of the intense surface heating associated with cw operation. For RFQ1-A the scheme shown in Fig. 1 was proposed. Details were never frozen but the main points were:

1. The outer wall was a cylinder with holes through which vane supports passed.

2. A vane base was inserted and fastened to the outer wall.

3. A flexible element (omega seal) similar to a single convolution of a bellows joined the base to the vane.

4. The four vanes were inserted with the coupling straps in place.

The omega seal would have allowed a small amount of transverse adjustment but could not be cooled satisfactorily, and there were concerns about the reliability of the vane base to tank wall joint.

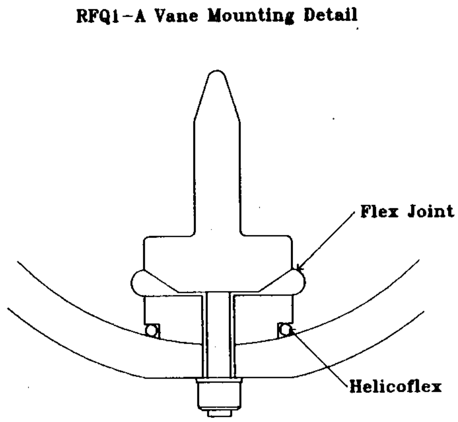

Fig. 1 RFQ1-A vane mounting detail.

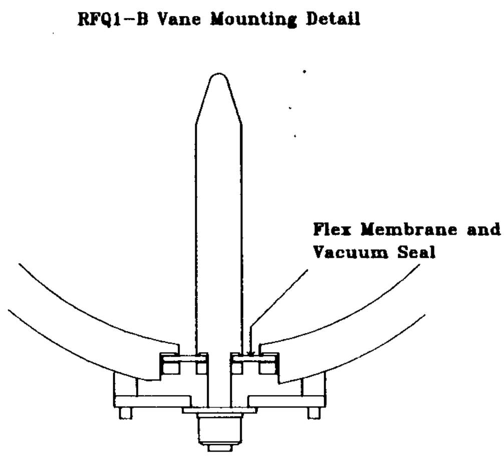

Fig. 2 RFQ1-B vane mounting detail.

An alternative vane mount shown in Fig. 2 has been proposed for RFQ1-B. The flexible member of the vane support system now uses a copper membrane incorporated into a knife edge vacuum seal. Preliminary tests of this concept are satisfactory. The seal remained vacuum tight after 30 cycles of a radial adjustment of ± 0.5 mm and 50 cycles of transverse rotation of the tip by ± 1.0 mm.

For RFQ1-B the outer wall has full length slots through which the vanes can be inserted. Vanes, gaskets, and all clamping devices are mounted from the outside and the vacuum seal is part of the flexible element. Three pairs of coupling straps or rings are installed through ports after installation and preliminary alignment of the vanes.

End tuner stubs which are used for field flattening are machined to size and are not adjustable. Two bulk tuners located in opposite quadrants are used for frequency adjustment. The other quadrants contain rf drive ports although only one drive loop will be used initially.

Vane Tip Shape

The vanes, shown in cross section in Fig. 1 and 2, are topped by a circular arc. The vane tip height is determined by the modulation required by the particle dynamics. The tip cross section is chosen to reduce the field enhancement factor and limit the higher order harmonic terms of the potential[6,7]. For small modulation a satisfactory shape is obtained by maintaining the center of curvature at a fixed distance from the beam axis. At larger modulations this can lead to excessive field enhancement. For RFQ1-B the arcs were drawn with a fixed center 0.761 cm from the beam axis for cells 1 to 165 and in subsequent cells the radius of curvature was restricted to maximum and minimum values which varied linearly from 0.282 and 0.410 cm at cell 165 to 0.300 and 0.390 cm at cell 181 (the final cell). With these restrictions the enhancement factor is 1.36 or lower.

Harmonic Content

The expansion terms of the potential near the beam axis are given in Table 2. In the equation accompanying Table 2, A_{01} and A_{10} are the fundamental terms of the RFQ. A_{03}, the duodecapole term, is a non-linear focusing term and may be helpful in confining the beam as in the example below. A_{12} is the first r-z coupling term and in most designs is the most harmful harmonic component. The vane tip design procedure described above keeps A_{12} small. The higher order terms A_{21}, A_{23}, A_{30}, A_{32} are of decreasing importance. Transmission of a 90 mA beam using harmonic terms as specified is as follows:

All terms	81%
$A_{03} = 0$	76%
$A_{12} = 0$	81%
Only A_{01} A_{10} A_{03} $A_{12} \neq 0$	83%
Only A_{01} $A_{10} \neq 0$	80%

Beam Transmission Curves

The transmission of RFQ1 when operating at design fields (1.5 * Kp) and at alternative fields (1.25, 1.75, and 2.0 * Kp) is shown in Fig. 3. At the design field it will deliver 75 mA with an input of 95 mA and a transmission efficiency of 79%. Of the 20 mA lost 5 mA are transmitted without being accelerated and 15 mA are lost to the vane structure primarily in cells 115 to 170. If it is operated at 1.75 * Kp it will deliver 75 mA with an input of 85 mA (88%).

These transmissions were calculated with a particle dynamics code which includes the harmonic terms of Table 2 and a simplified space charge calculation.

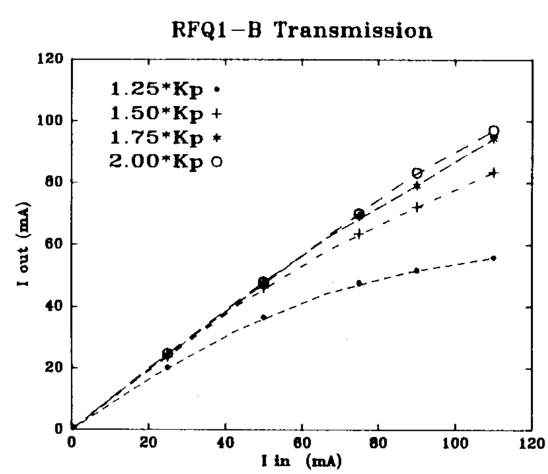

Fig. 3 RFQ1 transmission.

Table 2

Harmonic Content

Cell	A_{01}	A_{10}	A_{03}	A_{12}	A_{21}	A_{23}	A_{30}	A_{32}
0	0.01477	0.000000	0.03826	0.	0.	0.	0.	0.
10	0.44502	0.000094	1.15298	0.00083	-0.000001	-0.000009	0.	0.
20	0.44501	0.000282	1.15295	0.00249	-0.000002	-0.000028	0.	0.
30	0.44501	0.000469	1.15295	0.00415	-0.000001	-0.000025	0.	0.
40	0.44465	0.000648	1.14245	0.00575	0.000000	0.000023	0.	0.
50	0.44465	0.000836	1.14207	0.00758	0.000001	-0.000017	0.	0.
60	0.44465	0.001022	1.14149	0.00939	0.000002	-0.000012	0.	0.
70	0.44531	0.001217	1.13887	0.01153	0.000003	0.000029	0.	0.
80	0.44609	0.001430	1.13573	0.01385	0.000005	-0.000048	0.	0.
90	0.44606	0.001627	1.13734	0.01656	0.000006	-0.000010	0.	0.
100	0.44603	0.001858	1.13889	0.01970	0.000009	0.000034	0.	0.
110	0.44603	0.002121	1.13889	0.02433	0.000011	-0.000018	0.	0.
120	0.44602	0.002438	1.12893	0.02983	0.000014	-0.000081	0.	0.
130	0.44612	0.002977	1.11910	0.03984	0.000021	-0.000659	0.	0.
140	0.44626	0.003839	1.10563	0.05568	0.000031	-0.001585	0.	0.
150	0.44635	0.005447	1.11564	0.07670	0.000031	-0.026842	0.	-0.000030
160	0.44485	0.008810	0.95010	0.12085	0.000035	-0.079631	0.000001	-0.000091
170	0.44687	0.015063	0.65613	0.28111	0.000149	-0.814032	-0.000047	0.000101
180	0.44411	0.015769	0.67633	0.51080	0.000173	-2.861310	-0.000075	0.000702
181	0.44369	0.015816	0.67999	0.56350	0.000194	-3.225230	-0.000078	0.000816

$$
\begin{aligned}
U(r,\theta,z) = {} & A_{01} R^2 \cos(2\theta) \\
& + A_{10} I_0(kR) \cos(kz) \\
& + A_{03} R^6 \cos(6\theta) \\
& + A_{12} I_4(kR) \cos(4\theta) \cos(kz) \\
& + A_{21} I_2(2kR) \cos(2\theta) \cos(2kz) \\
& + A_{23} I_6(2kR) \cos(6\theta) \cos(2kz) \\
& + A_{30} I_0(3kR) \cos(3kz) \\
& + A_{32} I_4(3kR) \cos(4\theta) \cos(3kz)
\end{aligned}
$$

Test Piece Profile

A portion of the vane tip 28 cm long was machined from carbon steel on a numerically controlled 3D milling machine using a 2.54 cm (1.0") diameter H.S.S. ball nosed slot drill which made transverse passes with a spacing of 0.5 mm. A scan of the tip using a Canadian designed profilometer is shown in Fig. 4 displaced for clarity below the design profile. The measured and design profiles match very well from 0 to 160 mm but beyond that point the measured profile begins to sag and by the end of the vane is low by 0.1 mm. It is believed that this was caused by an alignment problem on the milling machine. Note that the profilometer is a very powerful tool for checking the accuracy of the machining.

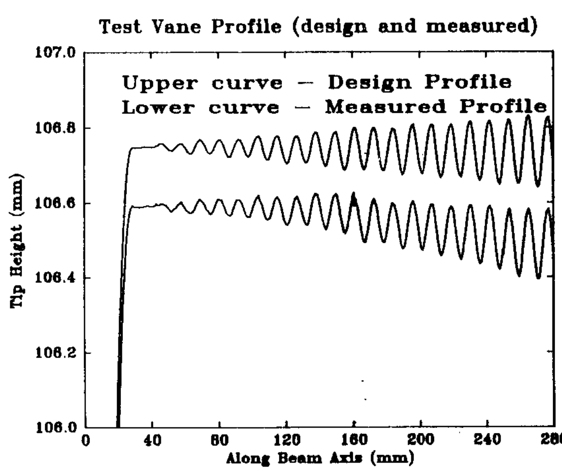

Fig. 4 Test vane profile.

Construction Schedule

The construction schedule which calls for initial operation by September 1986 is as follows:

1984 September	Decide on final mechanical design of RFQ
1985 March	Injector installed and tests begin
1986 May	Begin high power testing
1986 September	Initial beam acceleration

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