FIELD ADJUSTMENT, TUNING, AND BEAM ANALYSIS OF THE HIGH-INTENSITY CERN RFQ

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Summary

A proton RFQ accelerator, with an output energy of 750 keV has been completed, tuned, and put on the test stand. This RFQ, called RFQ2, is intended to serve as the injector to the CERN Linac 2, provided the requirements for its output beam and reliability of operation are met.

The field adjustment procedure, the RF tuning, and the beam measurements are described. After less than an hour of beam tests, the RFQ2 has delivered its nominal beam intensity of 200 mA.

Introduction

The CERN RFQ programme was launched in 1981 with a view to progressively replacing the HT Cockroft-Walton generators of the CERN Linacs 1 and 2. At the beginning of 1984, the 520 keV, 80 mA RFQ1 was installed at Linac 1. Work on the RFQ2 started in 1983; by 1984 all the main parameters were fixed, but its construction began in earnest only in 1988.

The RFQ2 was designed with an ambitious goal in mind, i.e. to accelerate 200 mA of protons up to 750 keV; this necessitated fields as high as 35 MV/m, which is two and a half times the Kilpatrick limit. Such parameters required careful design, execution, assembling, and field adjustment. Indeed, the RFQ2 reached its nominal performance after less than one hour of beam tests. This is the highest current ever achieved with an RFQ as injector for a linac [1].

The activities that accompanied the construction of the RFQ2 are reported, together with the first beam measurements.

Description of the RFQ2

The structure of the RFQ2 is of the four-vane type (see Fig. 1). Its main design parameters [2], are shown in Table 1.

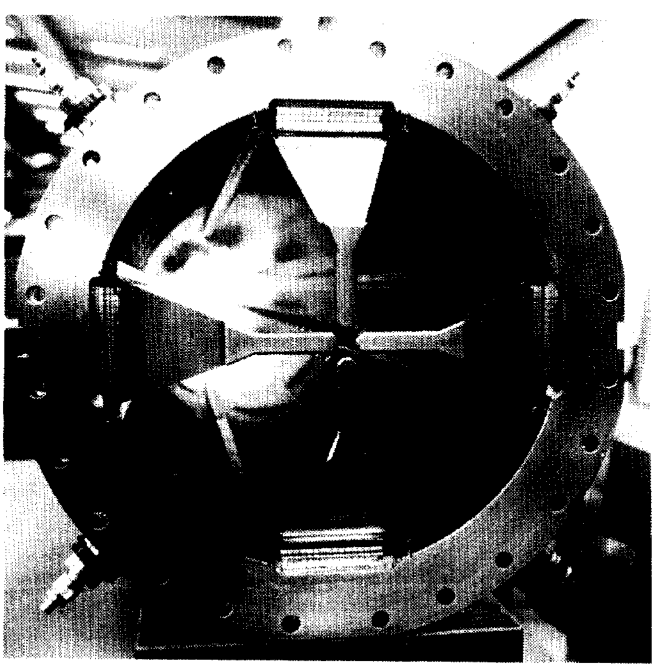

Fig. 1 RFQ2 with end covers removed

Table 1: Main RFQ2 design parameters

RF frequency	f_0	202.56 MHz
Input energy	W_{in}	90 keV
Output energy	W_{out}	750 keV
Output current	I_{out}	200 mA
Efficiency	η	~90 %
Vane voltage	V_0	178 kV
Final synchronous phase	φ_s	−35 °
Modulation factor	m_{max}	1.7
Mean aperture radius	r_0	7.87 mm
Cavity length	ℓ_{RFQ}	178.5 cm
Vane length	ℓ_v	175.2 cm
Cavity diameter	d	35.4 cm

The cavity, including the end cells, has been designed using the programs SUPERFISH and MAFIA [3]. Comparing the results of both programs with measurements on the RFQ1, reliable values have been obtained, linking the cavity dimensions and the frequency of the TE_{210} mode. A brief review of the main RFQ2 features follows.

Mechanical Features

- Tank: Cu-plated mild steel.
- Vanes: Cu-Cr alloy, with a conductivity of about 80% of that of Cu, but with a much better rigidity. The tips of the vanes have a constant transverse radius of curvature and could therefore be machined with a specially constructed cutting wheel on a computer-controlled milling machine.
- Positioning of vanes in the tank: Each vane is placed on three spacers, machined so as to position the vane precisely.
- Connection of vane to tank: To ensure a safe current flow from vane to vane via the tank, each vane is fixed to the tank by flexible Cu strips, which are electron-beam-welded to the vane on one side, and arc-welded, on the other side, to special rails, previously brazed into the steel tank. These Cu strips still allow for small repositioning of vanes, should this be necessary. In addition, the strips have been formed in such a way that they can act as bulk tuners and annul the natural tilt in the RF field caused by the vane modulation.

RF Features

The RF power is introduced into the RFQ2 by a feeder loop in one quadrant. In the opposite quadrant, a dummy tuner compensates for the asymmetry thus introduced. In the remaining quadrants two piston tuners are installed, which move synchronously in order to preserve field symmetry. Twelve calibrated measurement loops permit the shape of the RF field to be checked. A rigid 6⅛-inch line which was available as a spare part for Linac 1, is used to bring the RF power to the cavity. During transient operation, this line can safely handle the high overvoltages that are due to the high power required by the RFQ2.

Vacuum Features

Four vacuum pumps are connected to the RFQ2: one turbomolecular, 450 l/min pump; and three ion pumps of 300 l/min each. Without beam, the pressure in the tank is a few times 10^{-8} Torr; with beam, the pressure rises to about 10^{-6} Torr, owing to the high hydrogen loading.

RF Field Adjustment and Tuning

The shape of the RF field in an RFQ is computed assuming a constant voltage along the vanes and a quadrupolar symmetry of intervane voltages. In order to bring the reality into line with the design assumptions, a goal has been set to keep the overall error to $\leq \pm 1\%$.

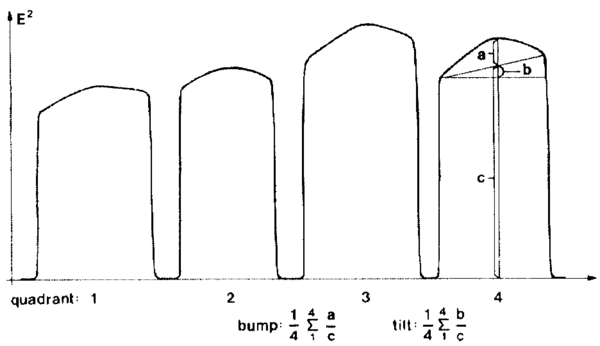

Fig. 2 Initial bead-pulling measurement on the RFQ2

The RF fields have been measured by a perturbation method developed at CERN, which makes use of ping-pong balls as the perturbing objects. This method is particularly suitable for checking vane voltages [4].

The measurements started with the cavity terminated at both ends by open cylindrical extensions of 0.5 m. One of the first field measurements is shown in Fig. 2, where asymmetries coming from mechanical errors in the positioning of the vanes add to longitudinal bumps, depending on the particular terminations of the cavity. A careful mechanical repositioning of the vanes eliminated random longitudinal field tilts, leaving only a natural tilt of 3.8% due to vane modulation. When the cylindrical extensions were tuned by various inserts, the bumps could be removed, and a cut-off frequency of 201.29 MHz was measured. This frequency is 810 kHz lower than that computed by SUPERFISH; the difference is explained by the effect of the vane modulation, which is not taken into account in the computations, and by the imprecision of the computations themselves. In fact, the traditional method of calculating the frequency of a toroid with the cross-section of an RFQ octant gives slightly higher values, depending on the diameter of the toroid.

Following these measurements, the form of the previously mentioned Cu strips was determined in order to bring the frequency to the desired value and, in addition, to annul the tilt. After the final welding of the Cu strips, a slight pivoting of the vanes, which was done by changing the vane spacers, allowed the fields in the four quadrants to be equalized. After a few iterations, the result was the measurement shown in Fig. 3.

Measurements on the closed cavity proceeded as follows: two dummy end covers, with holes for ping-pong balls, were used to study the effect of end cells, previously computed by the program MAFIA. Small rectangular tuning plates were placed in the cover, in front of the vane ends, to bring the frequency of the end cells to exactly the cut-off of the RFQ. The distance between the plates and the vanes was only about 2 mm lower than that computed by MAFIA. The plates were then brazed on the real covers and the cavity was closed. At the required frequency of 202.56 MHz, the overall field error, measured at the monitoring loops, was below ± 1%. At this point, the decision was taken not to install any transverse stabilizing scheme: the field symmetry was already good enough, and it was feared that the stabilizing cells, although very efficient in suppressing the transverse dipole modes [5, 6], could introduce longitudinal field perturbations. The natural dipole modes were 2.8 MHz and 1.7 MHz lower than the quadrupole mode. The piston tuners allow a tuning range of (− 100/ + 250) kHz around the operating frequency, to compensate for

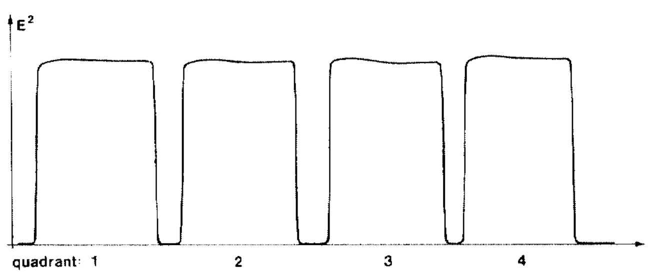

Fig. 3 RFQ2 fields after symmetrization

frequency variations during operation. (Owing to the very low average power, the cavity is not water-cooled, although provisions for doing so exist.) The measured unloaded Q-value was 9630, i.e. about 73% of the SUPERFISH Q. Most of the additional losses are due to the roughness of the tank surface and to the copper plating (the empty tank showed only 72% of the theoretical Q when measured in the TE_{111} mode and 45% in the TM_{010} mode). The power loop was adjusted to give a cavity input impedance of 64 Ω—a value calculated from the measured Q to give a proper 50 Ω matching under beam-loading condition.

Cavity Conditioning and First Beam Tests

The completed RFQ2 has been installed in its experimental area, aligned, and submitted to RF and beam tests (see Fig. 4). After about one day of conditioning, the nominal RF power level could be kept safely in the cavity. The power needed is about 440 kW for the cavity and 140 kW for the beam (the RF power generator can deliver up to 1 MW); the duty cycle is 10^{-4}. During beam tests, where operating conditions are varied, there is at present less than one missing pulse per hour.

The beam tests gave excellent results from the start: with preset parameters, 180 mA was obtained immediately, which was raised to 200 mA in less than an hour. The rapid reaching of the nominal current has been facilitated by the careful design of the matching system into the RFQ2, comprising the 90 kV accelerating column [7] and the low-aberration solenoids (designed with E. Boltezar). Figure 5 shows the first

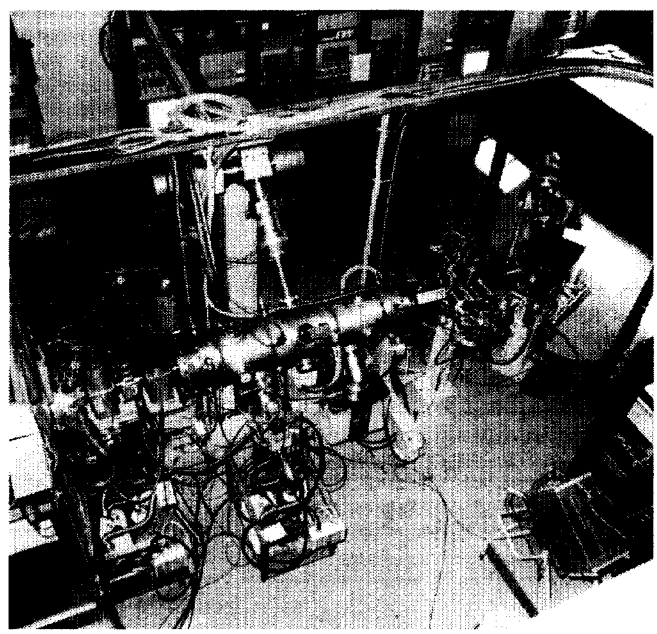

Fig. 4 RFQ2 in its experimental area

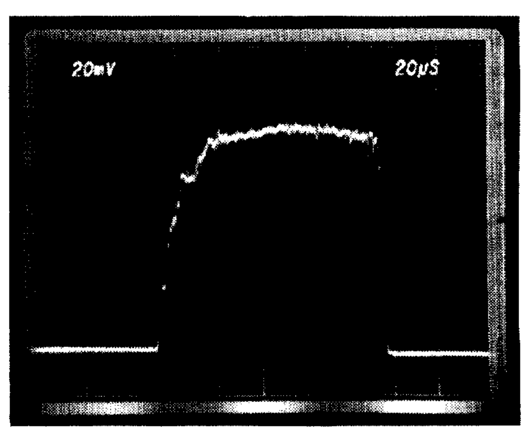

Fig. 5 RFQ2 output beam (vertical scale: 40 mA/div)

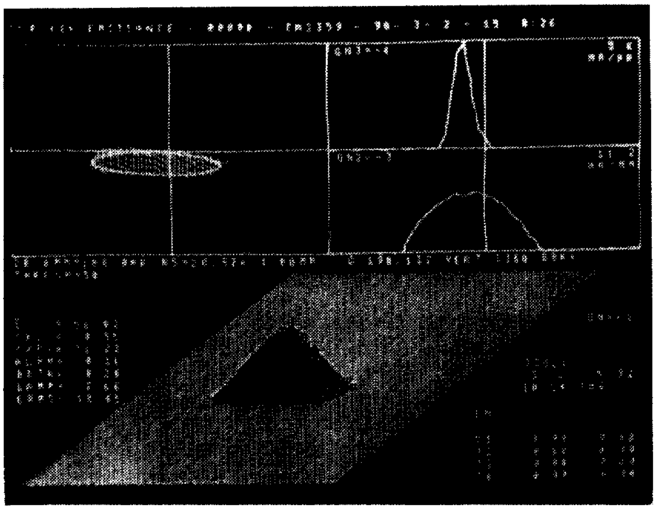

Fig. 6 RFQ2 output emittance

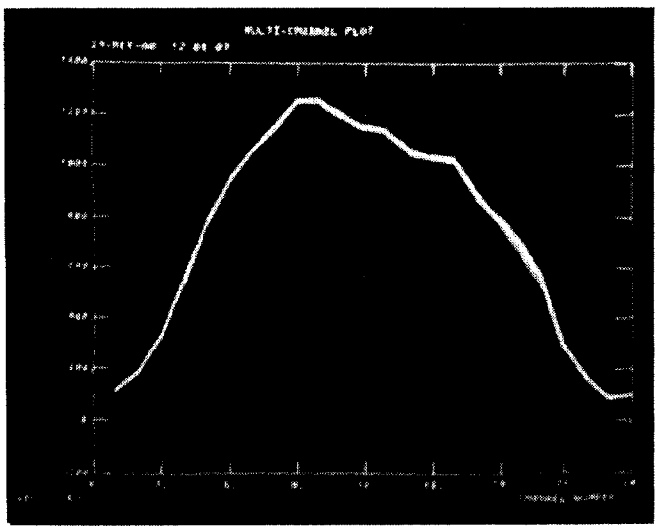

Fig. 7 Energy spread of the RFQ2 output beam (horizontal scale: 20 keV/div.)

oscillogram of the 200 mA beam; the emittance is shown in Fig. 6. Comparing the emittances measured at the input and output of the RFQ2, an emittance increase of 30% to 35% is deduced, which is reasonably low for such a high beam intensity. The output energy of the RFQ2 lies between 750 and 770 keV; the energy spread is shown in Fig. 7. Note that owing to space charge, the energy spread is increased by a factor of about 3 between the RFQ2 and the measuring device. The capture efficiency of the RFQ2 is about 90%.

Conclusions

It is reassuring that a high-intensity RFQ has operated according to computations, thus proving the correctness of our design approach.

The RFQ2 was designed and constructed entirely at CERN. It is now installed in its experimental area, where it is undergoing a series of measurements to assess its performance and reliability prior to its installation at Linac 2.

Acknowledgements

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