RF AND CONSTRUCTIONAL ISSUES IN THE RFQ
FOR THE CERN LASER ION SOURCE

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Abstract

An expandable RFQ has been designed and built. Its length can be modified in steps to match the different phases of the Laser Ion Source (LIS) study. This paper describes the basic design approach, the field simulations using MAFIA, the establishment of a lumped-element equivalent circuit using PSPICE, model measurements, RF cold measurements and the strategy to trim longitudinal field flatness. Results of RF power tests are also given.

Introduction

This RFQ serves the double purpose as a test item for the ion beam from the experimental laser ion source as well as a reserve item for the operating RFQ in Linac3 that has been designed and built by the laboratory of INFN Legnaro/Italy. This determines the outer dimensions flange-to-flange and also the basic electrode support structure tilted 45 degrees from vertical since a set of "Legnaro" spare electrodes should be usable in the new RFQ.

Mechanical Engineering and Vacuum

Basic Principles. The RFQ (see Fig. 1) is conceived such that it can be lengthened by adding an extension to its extremity. The total length can vary between 2.5 and 3.5 m.
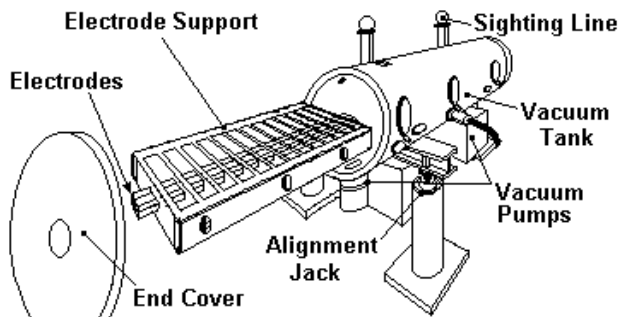

Fig. 1. General assembly of the RFQ.

The vacuum tank and the electrode support are independent elements.

The assembly and adjustment of the electrodes on their support are made outside the tank, with the support fixed in three places on a surface table in the same configuration as that foreseen in the tank. The electrodes are then put in place with respect to their references, fixed on the surface table (alignment tolerance $\pm$ 0.03 mm/2500 mm).

The sighting line, offset from the beam, is fixed with respect to the entry and exit centre line of the electrodes. This is transferred as a reference to the exterior by two targets and a transverse level. Three alignment jacks allow positioning of the completed assembly.

Vacuum tank. The vacuum tank is made from a mild steel "thick cylinder", allowing the machining from solid of the flat sealing surfaces for the metal toroidal joints.

The tank is electrolytically copper plated. This operation is facilitated by use of one material only for the tank, along with its simple geometry.

Electrode Support. The electrode support comprising 13 cells is made of mild steel. Its module of elasticity is well known and its thermal conductivity is relatively good. The assembly takes the form of a ladder, where the rungs serve as supports for the electrodes.

All machining is done before the final assembly is completed by MIG welding. This type of welding limits deformation to the order of 0.5 mm/2500 mm. The welds are vacuum tested to guarantee good copper plating. The finished support is stabilised by thermal treatment.

The copper plating of the support is performed in several steps. A first copper layer of 10 µm is applied globally followed by tinning of the faces that will receive the cooling circuit. The cooling circuit is then soft soldered to the ladder. A second copper plating of 50 µm (certain precision surfaces being protected) is then applied.

Water cooling reduces the forces induced in operation between the electrode and its supports due to differential thermal expansion.

The ladder assembly is fixed inside the tank on 3 points reproducing the support conditions that have served outside for adjusting the electrodes.

Electrodes. The electrodes are drawn from square copper bars OFE 4/4 (hard) The transverse profile is obtained by planing, the longitudinal modulation by a C.N.C. machine and profiled milling cutters.

The electrodes are fixed to the support with intermediate copper shims (to guarantee good heat transfer) and stainless steel keys. One central dowel pin per electrode assures the longitudinal position. This system allows one to absorb up to $\pm$ 2 mm of positioning tolerance.

The contact between electrodes and their support is achieved with the aid of commercial RF finger contacts attached to a flexible copper element permitting the absorption of possible deformations. They do not interfere

with the positioning of the electrodes and are fixed both sides with partially copper plated stainless steel screws.

The contact between the ladder and the tank is made using commercial RF contacts mounted on a retractable assembly permitting the introduction (in a vertical position) of the ladder with its assembled electrodes, into the tank.

Vacuum. The nominal pressure of the system is 10^{-7} torr. The RFQ is equipped with a 240 l/s turbo molecular pump for the pre pumping and two 400 l/s ion pumps.

All the joints in direct contact with the vacuum tank are aluminium coated toroidal joints. $6 * 10^{8}$ torr have been reached with particle source disconnected.

Electromagnetic Field Computations

Finite element representation of the resonators. The cylindrical RFQ tank consists of 13 cells. A single cell of 2 * 96.1 mm length = 2500mm/13 has been modelled with program MAFIA (Fig. 2) for the geometry of existing RFQ electrodes (compatibility). The radius has been varied until the frequency of 101.28 MHz was obtained for r=281mm.
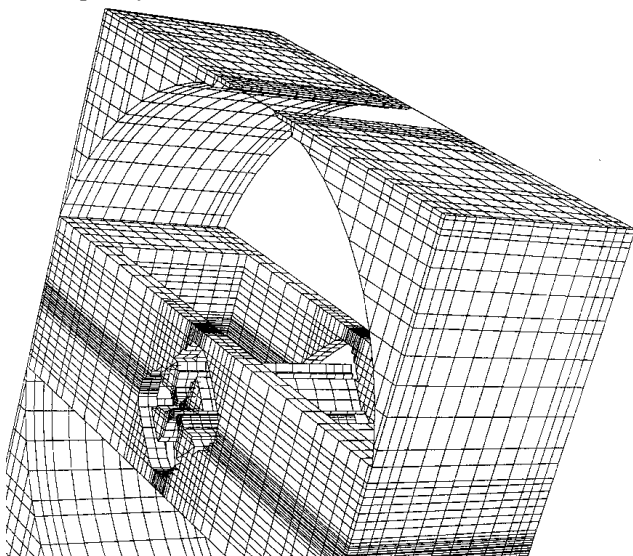

Fig. 2.   Single RFQ-cell geometry representation.

One can see how the 4 quadrupole electrodes or "vanes" which focus the beam are supported by stems with holes. These are the rungs of the ladder mentioned earlier. The 4 vanes pass through all holes but only 2 are fixed to the upstream stem and 2 to the downstream stem producing a 72kV quadrupole field. Subsequent holes are turned $\pm 45^{0}$ in order to make their inductances equal. This destroys all symmetries in x, y and z and increases computing time because the full cell of 61*55*14= 46970 mesh points has to be computed. Assemblies of 13 cells have been modelled. MAFIA's choice of elements is limited: "bricks" (rectangular parallelepipeds) and only on boundaries, "prisms" (diagonally halved bricks). Moreover all bricks are aligned in x,y,z-

planes. Since one needs small spacing for the vanes (3.5mm distance from axis) the latter limitation leads also to very thin, long bricks on the periphery where less resolution is needed. One easily exceeds the safe 1:10 limit ratio of rectangle sides. This is why modelling of heavy ion RFQ's with their large, low- frequency cavities and closely spaced vanes is difficult with this program.

As the electrode capacity (and frequency) is sensitive to meshing it has been computed independently with finer meshes in MAFIA' s static solver, MAGNET and POISSON. Then the coarser RFQ- meshes have been readjusted to yield the same precise capacity values.

Higher modes have been predicted at 268 and 272 MHz.

Many coupled cells and end effects After establishment of the geometry of the fundamental cell for an infinitely long RFQ, finite element models with 1 - 13 coupled cells and closed end covers have been computed. Figure 3 illustrates that 1 cell with end covers resonates at a higher frequency than 2, 3, 6, 13 ... ∞ cells and f [MHz] is higher for odd n than even n (explainable by field plots).
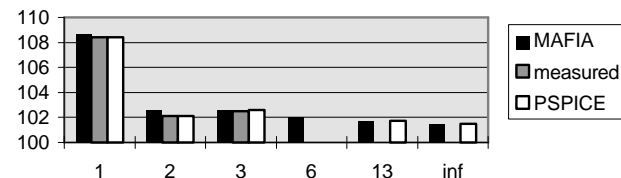

Fig. 3.   Frequencies of RFQ models with n cells.

These computations have been confirmed by measurements on a model and equivalent- circuit analysis with PSPICE.

The program predicted vane voltage variations between centre and ends of a cell, particularly in end cells:
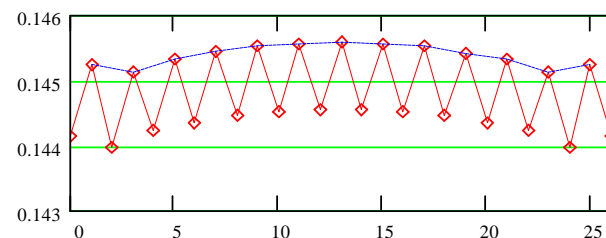

Fig. 4.   Voltage variations along 13-cell RFQ.

Figure 4 shows also that overall variations along a 13-cell RFQ (which were large initially) can be made as small as variations within cells by slight geometry changes near the end covers which match this slow wave structure.

RF aspects

3-cell model. A short full-scale model equipped with unmodulated vanes was constructed. The possibility to implement a 1, 2 or 3 cell configuration allowed to study different combinations of a regular cell and end cells, and to separate the impact of different perturbations.

Errors due to electrode misalignment had to be taken into account. Theoretical studies had shown that the *sum* of the four interelectrode distances determines to first order the total vane capacitance hence the resonant frequency. This dependence was experimentally verified and then used to correct the raw frequency measurements. The measured parameters for 1, 2 and 3 cells laid the basis for a PSPICE equivalent circuit model of the full RFQ.

A rapid way of measuring r/Q was found in passing. It consists of measuring the change in admittance ΔY of a vane as a function of frequency offset Δf by direct connection of a network analyser: $r/Q = (\Delta f/\Delta Y)*(2/f_{res})$. This method is only valid for short geometries where feeding a single point does not perturb the field pattern.

PSPICE simulation. Figure 5 shows the equivalent circuit for inner and end cells. The vane pairs are represented by the usual LC low-pass ladder whose parameters CV_2 and LV_2 can be derived from the known electrode capacitance. The surrounding tank structure and the electrode supports for end and inner cells are modelled by the inductances LCAV, LEXT and LSTEM, the window and end cell stray capacitances by CWIN and CSTEM respectively.
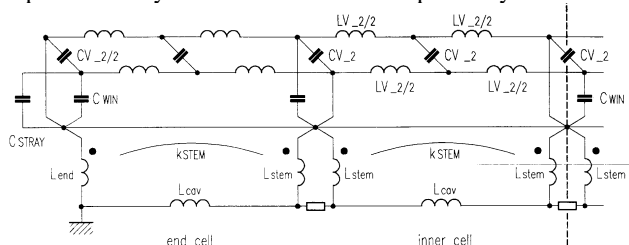

Fig. 5. PSPICE equivalent circuit.

All circuit parameters are fitted on the basis of the model measurements. An essential ingredient is the coupling factor k_{STEM} between the two supports in a cell to take the magnetic field perturbations in the asymmetric end cells into account.

Low power RF measurements. The RF properties of the RFQ were measured in different phases of completion. The Q-factor Q= 4230 of the fully equipped RFQ is only about 35.6% of the theoretical value; this can be attributed to less than perfect copper plating and ill-directed surface roughness due to machining perpendicular to the RF current path.

The vane voltage developed for a given RF power level was measured by a calibrated capacitive pickup to determine directly the r/Q parameter. Its value of r/Q=3.64 Ohm corresponds very well to theoretical predictions. The diagnostic probes were adjusted and calibrated accordingly.

The longitudinal field pattern was measured by a bead pulled longitudinally through the RFQ and supported by the electrodes themselves. The initial pattern was strongly tilted (18.6%) as well as concave (13%) in addition to the unavoidable variation within a cell (1%).

Field correction strategy. Provisions had been made to mount either "flaps" between the stems and electrodes or to add "plates" on the girder. The former allow to *decrease*, the latter to *increase* the local cell resonant frequency.

The PSPICE model proved to be a very convenient and rapid means to simulate arbitrary capacitive or inductive perturbations. It was not possible to establish a 13*13 Jacobian matrix to relate field errors linearly to cell perturbations because of the simultaneous frequency changes involved. However, qualitative rules for the effects of perturbations on field pattern were found :

-in uniform structures the *difference* in end cell loading determines the tilt. Capacitive loading increases the field at the respective end, in the present case by 3.71 %/pF.

-in uniform structures the *sum* of end cell loading determines the field curvature and the resonance frequency. Capacitive loading leads to a concave, inductive loading to a convex pattern. The respective factors are here 0.9 %/pF for the bump and 120 kHz/pF for the frequency.

-arbitrarily perturbed structures can be corrected by first fitting the field pattern to a polynomial of degree 2, then placing corrective elements iteratively at spots of maximum deviation to get the equivalent of a uniform structure. Remaining bump and tilt are finally removed as above.

Here the field pattern was corrected to 2.5% bump and zero tilt by placing 16mm plates in the upstream and 4mm plates at the downstream end cells. The resonant frequency was too high since the influence of bulkier RF contacts had been underestimated. PSPICE runs show that the frequency can be brought to nominal with less than 0.6 % field distortion by placing four sets of "flaps" in stems 2/3, 4/5, 9/10 and 11/12. Since the RFQ frequency is not important in this application that correction was postponed .

High power test. Nominal field level of 72.1 kV (~ 1.9 Kilpatrick) was reached after one weekend of conditioning. The RFQ finally held 115 % field with virtually no break-downs at a vacuum of $2.5 *10^{-6}$ torr (less than ideal due to the connected ion source). Operation at 7% and 28% field levels for proton and helium beam tests was perfectly possible in closed-loop operation where the multipactor level was broke through at the beginning of each pulse. The beam tests proper are reported elsewhere [1].

Acknowledgements

References

[1] A.M.Lombardi and E.Tanke, "Design and Test of an RFQ to Accelerate a Lead Ion Beam from a Laser Ion Source", this conference.