WP/tp

PS/RF/Note 83-4
18.5.1983

TUNING OF THE RFQ

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GENERAL

The aim of the tuning is the adjustment of the fields in the four "cylinders" (i.e. the intervane space between adjacent "electrodes"). The goal was somewhat arbitrarily fixed to limit the over-all field error to less than ± 2.5 %, comprising the azimuthal unsymmetry as well as the longitudinal tilt. In addition, the operational frequency of the RFQ shall be adjustable to the nominal frequency of the CERN Linac 1 working at 202.570 ± 0.02 MHz.

The structure of the device is described in detail in [1]. It is recalled that there is a total of 8 piston tuners (2 per cylinder), these being the only elements that can be adjusted under operation. The 4 vanes, 8 end-cell tuners, 10 diagnostic loops and the single high-power loop are by contrast definitively positioned during the tuning procedure, which can be broken down into several independent steps:

1 - Vane adjustement for correct frequency

2 - Equalization of cylinders

3 - Calibration of the probes

4 - Tuning of the end sections

5 - Adjustment of the feeder loop

6 - Final trimming by means of the piston tuners

(7 - Concluding remarks).

Each step is described in a separate paragraph.

1. VANE ADJUSTMENT FOR CORRECT FREQUENCY

The resonant frequency of the RFQ can be predicted by computer programs like LALA or SUPERFISH for flat vanes. The total uncertainty is a few percent, taking into account the influence of finite mesh size and the vane modulation as well as the manufacturing tolerances (machining and copper plating). This error is too large to be compensated for by the piston tuners. In our case the adjustment of vane penetration was preferred for simplicity; symmetric variations of the order of 0.1 mm seem permissible from a beam dynamics point of view.

After careful mechanical adjustment of the vanes to the nominal positions as defined by the machined reference slot, the RFQ is terminated in two open tubes, Fig. 1a, and the over-all resonance frequency measured. It is a weighed average of the individual resonant frequencies of the cylinders and the end regions; a field measurement is needed to separate them. The fact is used that the curvature of the longitudinal field distribution is a sensitive indicator of the structures cut off-frequency relative to the excitation frequency.

Annex 1 gives details of the measurement set-up. By manipulation of the end cells, the over-all assembly is resonated at different frequencies: insertion of U-shaped, folded strips of Teflon-foil lowers it, partial closure of the vane cut out increases it. Fields are plotted and the curvature is evaluated. Shown in Fig. 2a is the structure resonated at about the cut off-frequency, hence with almost linear (however tilted) fields. Partial closure of the end cuts (Fig. 2b) increases the over-all resonance frequency by ∿ 1.1 MHz, but leads to a noticeable hump of ∿ 4.5 %. This illustrates the necessity to tune the structure within approximately ± 500 kHz of the operating frequency, to avoid excessive humps or bumps. Reducing the vane penetration (by cutting all supporting washers uniformly by 50 μ) shifted the frequency into the required range and above. Fig. 3 gives the corresponding field plots for two piston tuner positions with unmodified end cells. As the piston tuners act in a lumped rather than distributed way, they cause local perturbations. Note the increased ripple for full tuner penetration; the presence of additional perturbing volumes in the middle of the definitive structure (power loop and its dummies) improves this situation.

2. EQUALIZATION OF CYLINDERS

Field plots like Fig. 3 are typical of an untrimmed RFQ, since even high-precision mechanical alignment has inadequate resolution to equalize the effective intervane regions. Although it is in principle possible to compensate these positioning errors directly by the tuners, it is preferable to proceed first to a mechanical equalization using electrical criteria.

The approach used in the CERN-RFQ is illustrated in Fig. 1b. A pair of short-circuiting plates is inserted at the high- and low-energy end of a cylinder, reducing its flux to negligible levels. The flux in the remaining cylinders is ideally distributed like + 0.5, - 1, + 0.5, corresponding to weighing factors for frequencies and Q-values $/0,5/^2$, $/1/^2$, $/0.5/^2$. The influence of the cylinder opposing the short is thus 4 times as high as of its neighbours; this fact leads to a powerful diagnostic tool. The simplest strategy is to neglect the influence of the 2 peripheral cylinders and to attribute measured over-all values of f and Q entirely to the central cylinder. Fig. 4 is a copy of a form used during the alignment, based on this simplified assumption. The four cylinders are in turn short-circuited and the over-all resonant frequency is recorded ("cylinder 4" is highest, "cylinder 2" is lowest; difference as high as 426 kHz). Assuming a linear dependence of the frequencies vs. a single intervane distance, a simple matrix transform leads to the projected positioning errors R,S,T,U using an experimentally found calibration factor of 0.065 [µ/kHz] referred to the positioning washers. R is arbitrarily chosen as reference point with error ∅ by definition. The process converges quickly, one round of adjustment reduces the frequency deviation by a factor of 2 to 3.

After two rounds of corrections, the measured frequencies were within 50 kHz. This remaining error was then compensated by the bulk tuners, using a similar iteration process to reduce the measured frequency spread to 10 kHz. Back in the quadrupole mode, whose frequency is about 2 MHz higher, the average fields in the cylinders (excluding tilts) were uniform within the reproducability limit of ∿ 1 %. Equalizing the cylinders using the relative field levels as criterion is possible too. Note that the field pattern of Fig. 3 does not exactly match the frequency pattern of Fig. 4. The frequency-method used is preferred as the input information is easily obtained with high precision; it permits at the same time the evaluation of the individual Q-factors and hence tracing of bad contacts.

3. CALIBRATION OF THE PROBES

It is very convenient to sample the electric intervane field of an RFQ with open ends by the table-tennis-ball method; difficulties arise, however, to move and withdraw the beads once the end plates are mounted. During a first phase, the problem was solved by leaving the four balls in the structure, attached to their threads run through the beam holes, but drawn to the outer wall by means of a sort of crochet needle if not in use. The extra effort is however not really justified and all later measurements with closed ends relied on the two probes provided near the ends of each cylinder. These probes are calibrated, by adjustment of their penetration and orientation, such that relative levels correspond within 1 $^0/_{00}$ to the local electric intervane field obtained by a run of the dielectric bead.

The absolute attenuation of the probes with respect to the feeder was measured on the finished RFQ; it is 40 dB nominal and reflects of course the errors of the field pattern.

Calibration fo the probes with respect to the intervane voltage was performed using the R/Q-value predicted by SUPERFISH together with the measured Q-factor; its value was well confirmed by beam transmission measurements.

4. TUNING OF THE END SECTIONS

Dummy end plates (which can be perforated at will) were mounted on the ends of the RFQ, at exactly the same distances as the definitive, vacuum-tight end covers. Eight threaded stubs were located in front of the vane tips to permit continuous adjustment of the end capacitance.

(a) A short-circuit (Fig. 1c) is introduced at each end via the beam hole, such that only a single vane with its adjacent two cylinders is active. The frequency of this (dipole) mode is consecutively set to the same valve for each vane by adjustment of the two pertinent end capacitances.

(b) Short-circuits are eliminated and fields are measured at the Quad-mode ($\sim$ 0.8 MHz lower); tilts are evaluated.

(c) Short-circuits are put back to isolate a tilted vane. At the end with high field the capacitance is lowered (thus the resonance frequency increased, about $\sim$ 50 kHz per percent tilt in our case). The original dipole frequency is restored by increase of the capacitance of the opposite end.

This process is iterated, with readjustment of the dipole-frequency should the resulting Quad-frequency be too far from the cut off frequency found in step 2.

After two hours of iteration a b c b the structure is tuned within a few percent, provided the range of adjustment of the stubs is adequate. It was found that the low-energy end needed much more capacitance to overcome the tilt; this may be a general trend rather than a trivial adjustment error, since the increasing vane modulation towards the high-energy end is expected to raise the capacitance (more C added at low vane distance than lost at high distance). Coaxial trimmers* with direct contact to the vanes were therefore installed in the stubs at the low-energy end to ease the adjustment.

The capacitance pattern thus found is then transferred one by one to high-power capacitors with very limited adjustment range. They are mounted on a circular plate which in turn is attached inside the end cover (Fig. 1d); the gap to the vane ends is everywhere larger than 70 % of the intervane

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(*) JFD model MM010, 10 turns/10 pF.

distance to avoid breakdown problems. Lateral flaps had to be added on the low-energy end. Three out of the eight vane-end cutouts were slightly reduced by screwed-on plates to bring the corresponding end capacitances into the adjustment range.

5. ADJUSTMENT OF THE FEEDER LOOP

So far all measurements are carried out via the small diagnostic probes; the openings for the power loop in each cylinder is closed by an equivalent perturbing volume called "dummy loop". Four openings have been provided to permit the implementation of a 4-loop scheme in case the high-power tests with a single feeder would fail.

The high-power loop is inserted into one cylinder and adjusted by rotation to achieve match. Loop size was found to be too large and the perturbation of the corresponding cylinder smaller than the perturbation by the adjacent compensating dummy loops. Both effects are explained by a larger than expected penetration of the fields into the 3 1/8" coaxial part of the feeder loop; they were cured by closing a large fraction of the loop area by a block of copper.

Feeding the RFQ via the modified single feeder changed the previously established field pattern by about 2 %.

6. FINAL TRIMMING BY PISTON TUNERS

Remaining minor errors after final assembly and pumping are corrected by adjustment of the piston tuners. A problem is the interaction of the cylinders: if F_N and T_N represent field and tilt in the N-th cylinder, $F_1 - F_2 + F_3 - F_4 = \emptyset$ and $T_1 - T_2 + T_3 - T_4 = \emptyset$ hold as first approximation due to the conservation of the magnetic flux.

For instance, augmented penetration of both tuners (+ 1mm) in cylinder 1 leads to higher field in cylinder 1 ($\frac{\Delta F_1}{F_1} \sim 1.5$ %); the opposite cylinder is decreased ($\frac{\Delta F_3}{F_3} \sim 1.5$ %), whereas adjacent cylinders remain almost unchanged ($\left|\frac{\Delta F_2}{F_2}\right| \sim \left|\frac{\Delta F_4}{F_4}\right| < 0.1$ %). The over-all resonance frequency was increased by 13 kHz or 0.0064 %. Similarly, the tilt may be manipulated by differential action on the tuners of a cylinder; relatively wide excursions are however necessary in this case.

It is planned to replace the present final intuitive trimming by a straightforward approach, based on a linear model to find the required tuner excursions directly.

For the first high power tests, the RFQ resonant frequency was left as given by the initial piston tuner positions; the frequency of the master oscillator which powers the RF-chain was modified accordingly. A total variation of $\sim$ 50 kHz as a function of ambient conditions and internal RF dissipation is observed. The frequency increases after switching-on the RF, reaches a peak and decreases towards a steady-state limit as expected for uniform thermal expansion.

Only at a later stage, with stepping motor electronics installed, the RFQ will be kept at constant frequency by servo-controlled tuners.

7. CONCLUDING REMARKS

The RFQ tuned by this method was up to the nominal field after a few hours of conditionning, and accepted reliably the full available amplifier power* within less than a day; the measured unloaded Q-factor was only $\sim$ 50 % of the value predicted by SUPERFISH. Both effects may be connected with a gold-flash which had been applied as surface-finish to the vanes.

By far the most tedious part of the tuning was the implementation of the Hi-power end capacitors; their limited range of adjustment will be increased by a modified design with a large rectangular movable plate. As a complementary action, it is planned to reduce the spread in the required capacitances

(*) 3 dB above nominal; pulse length 200 μsec., duty factor 1/5000. The corresponding field strength including the 2-dimensional field enhancement factor (but neglecting 3-D modulations) is $\sim$ 30.0 [MV/m], i.e. about 2.13 times the Kilpatrick limit for the same distance (14.1 MV/m).

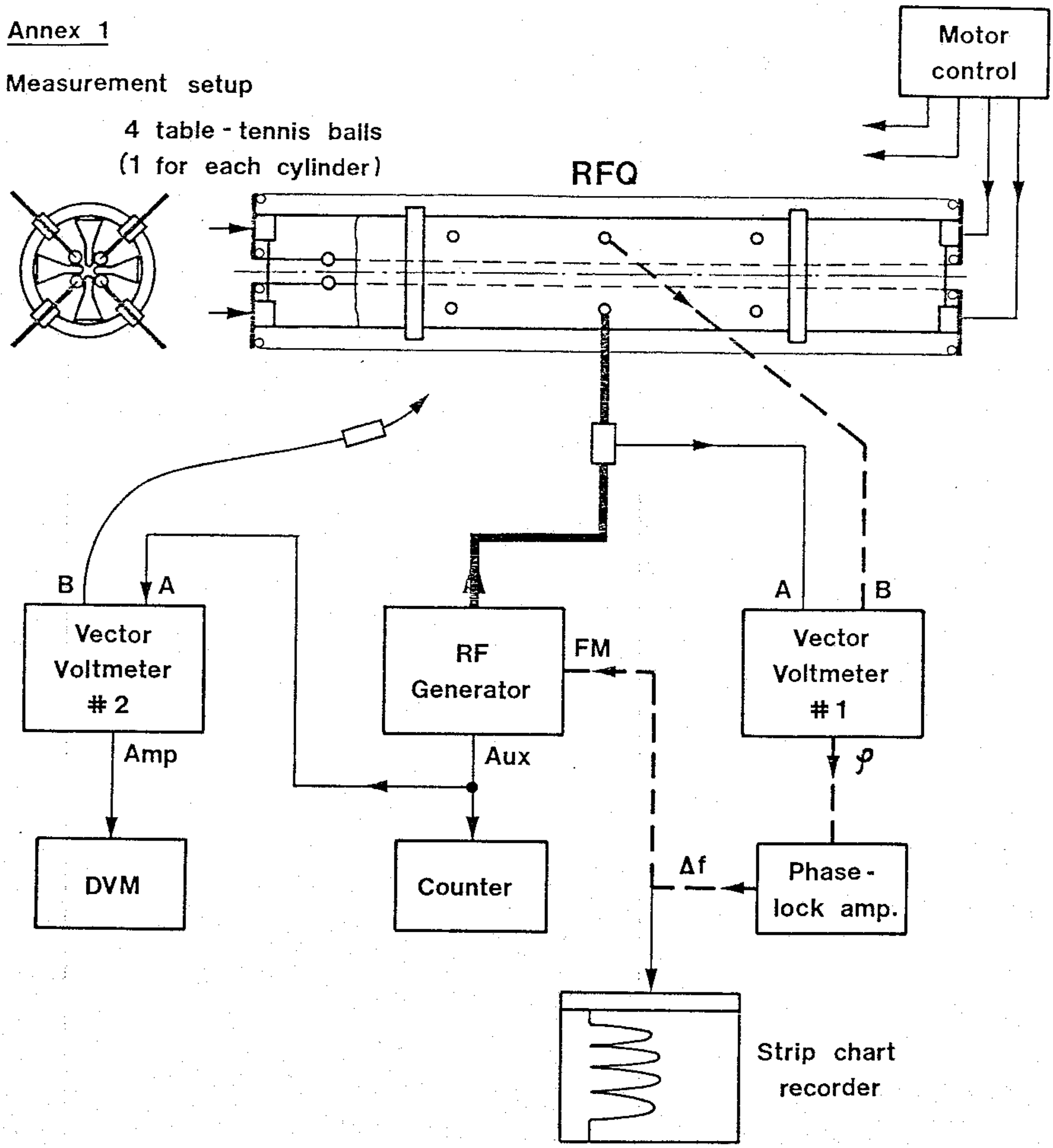
by extended vane positioning: in addition to step 2 which equalizes the cylinders frequencies by transversal trimming, the cylinders tilts shall be made uniform by radial adjustment.

Reference: [1] K.R. Crandall et al., E. Boltezar et al.
"Experimental RFQ..."
CERN PS/LR/81-29 or
Santa Fe Conference 1981

Distribution: open

Annex 1

Measurement setup



- 4 standard table-tennis balls act as dielectric perturbators. Motor control allows to put one ball at a time into the active region. Balls are guided by the vanes for precise alignment
- Vector voltmeter # 1 is essentially used as phase detector for the phase-lock circuit
- Phase-lock amplifier has touch-buttons for precise phase offsets of + 45°; - 45° (evaluation of bandwidth) and + 5.7° (reference trace at beginning of each plot, see figs. 2, 3)
- Vector voltmeter # 2 together with the digital voltmeter allows sensing of the probes output with a resolution of 1 ‰

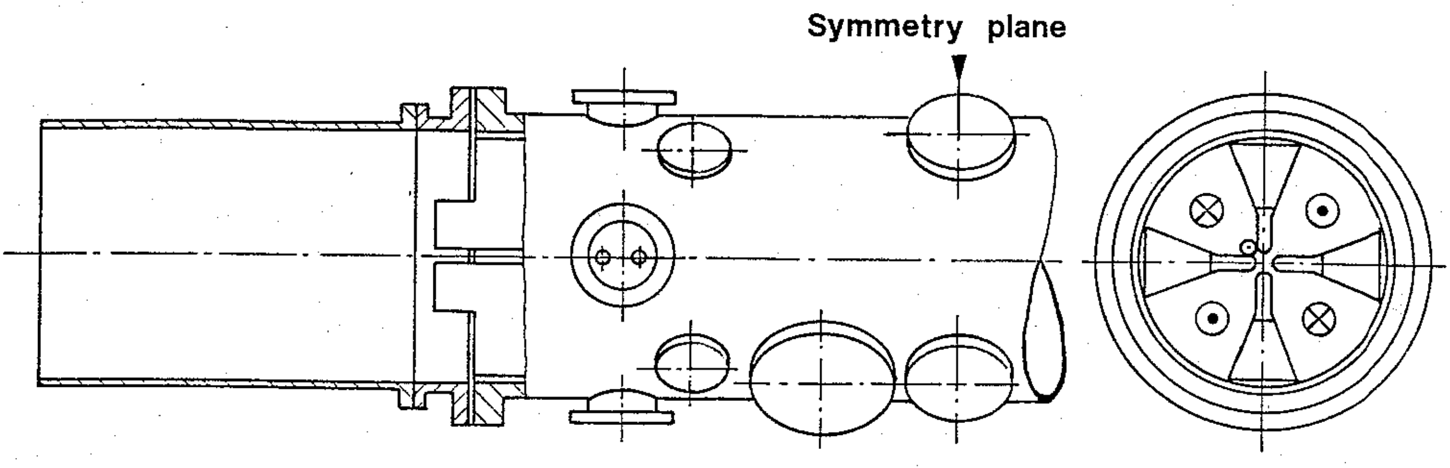


Fig. 1a: RFQ with end tubes for bead-pull measurements (table-tennis ball)

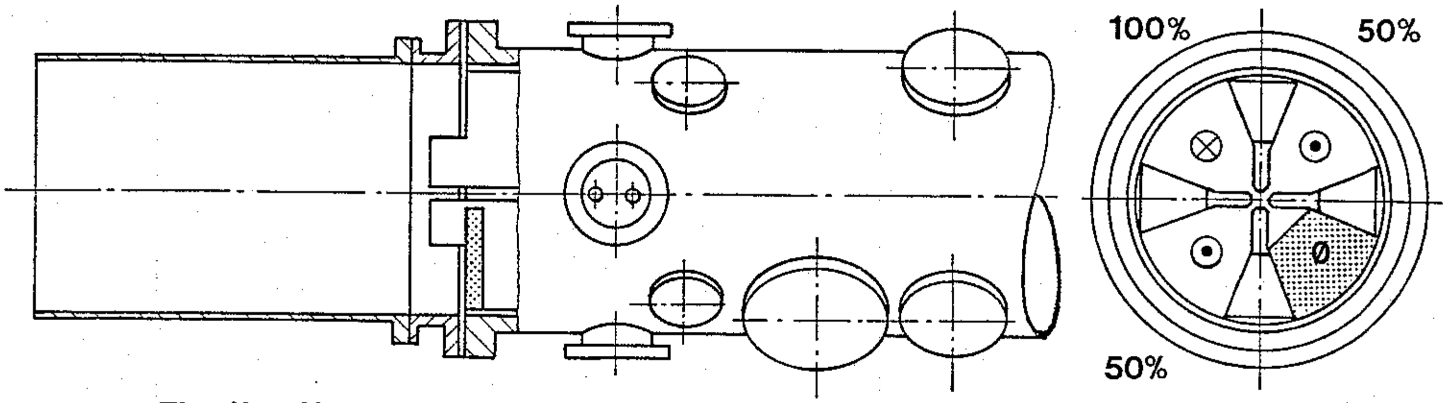


Fig. 1b: Shorting of a cylinder

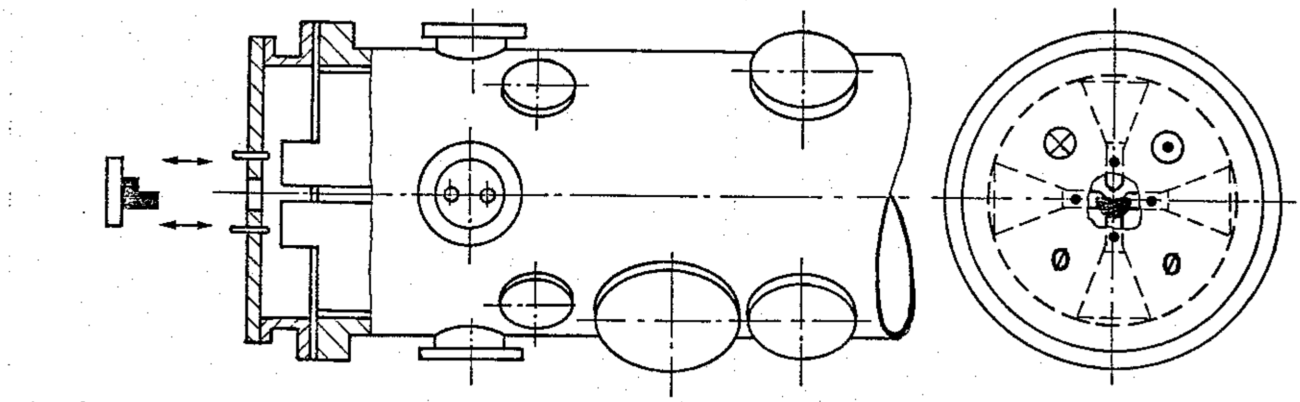


Fig. 1c: Shorting of 3 vanes

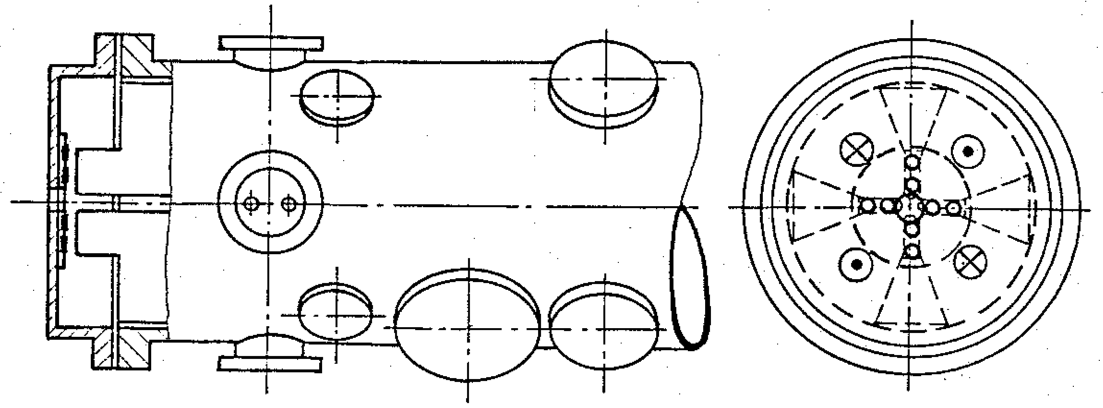


Fig. 1d: Definitive RFQ with Hi-power end plate

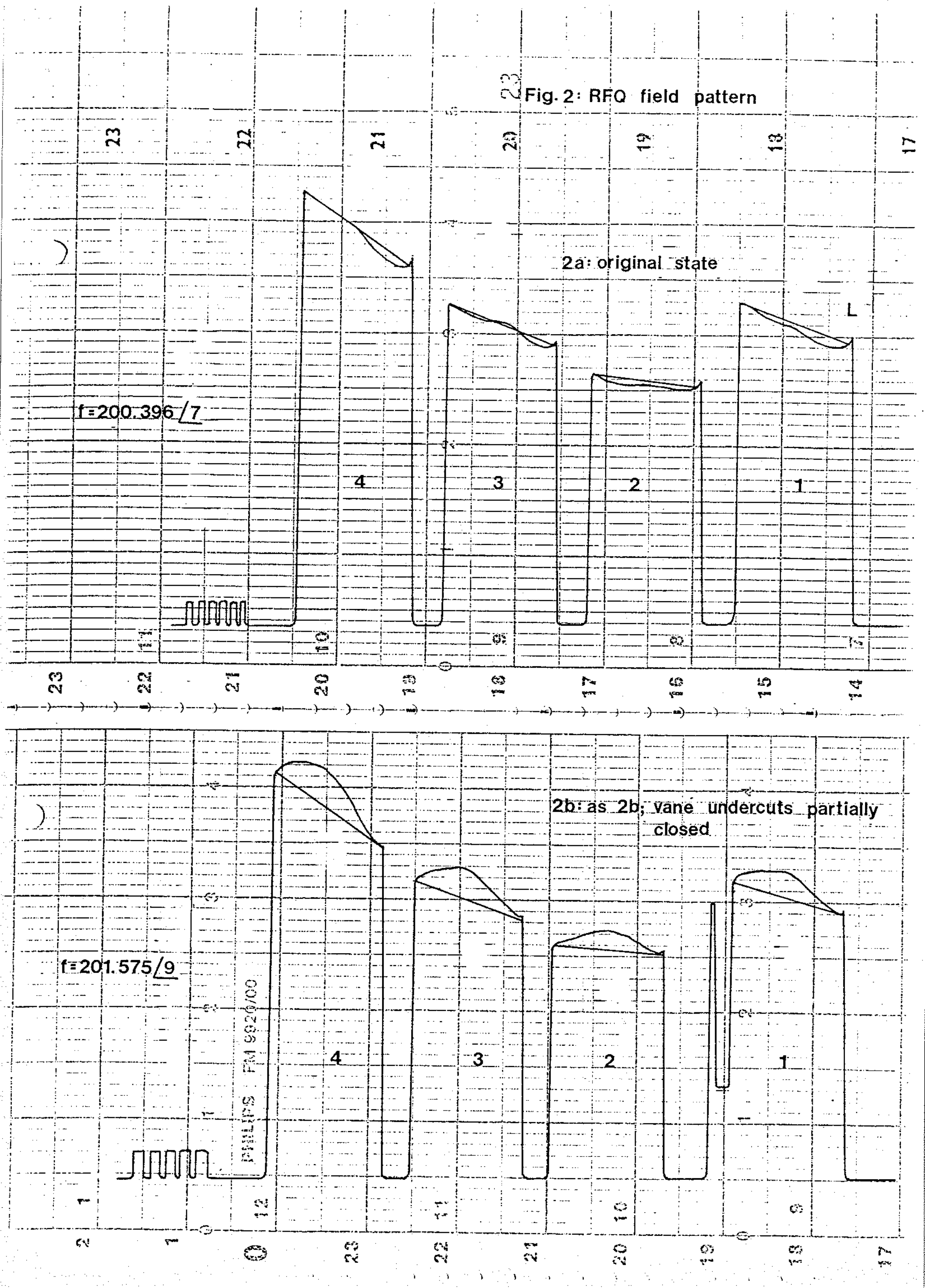


Fig. 2: RFQ field pattern

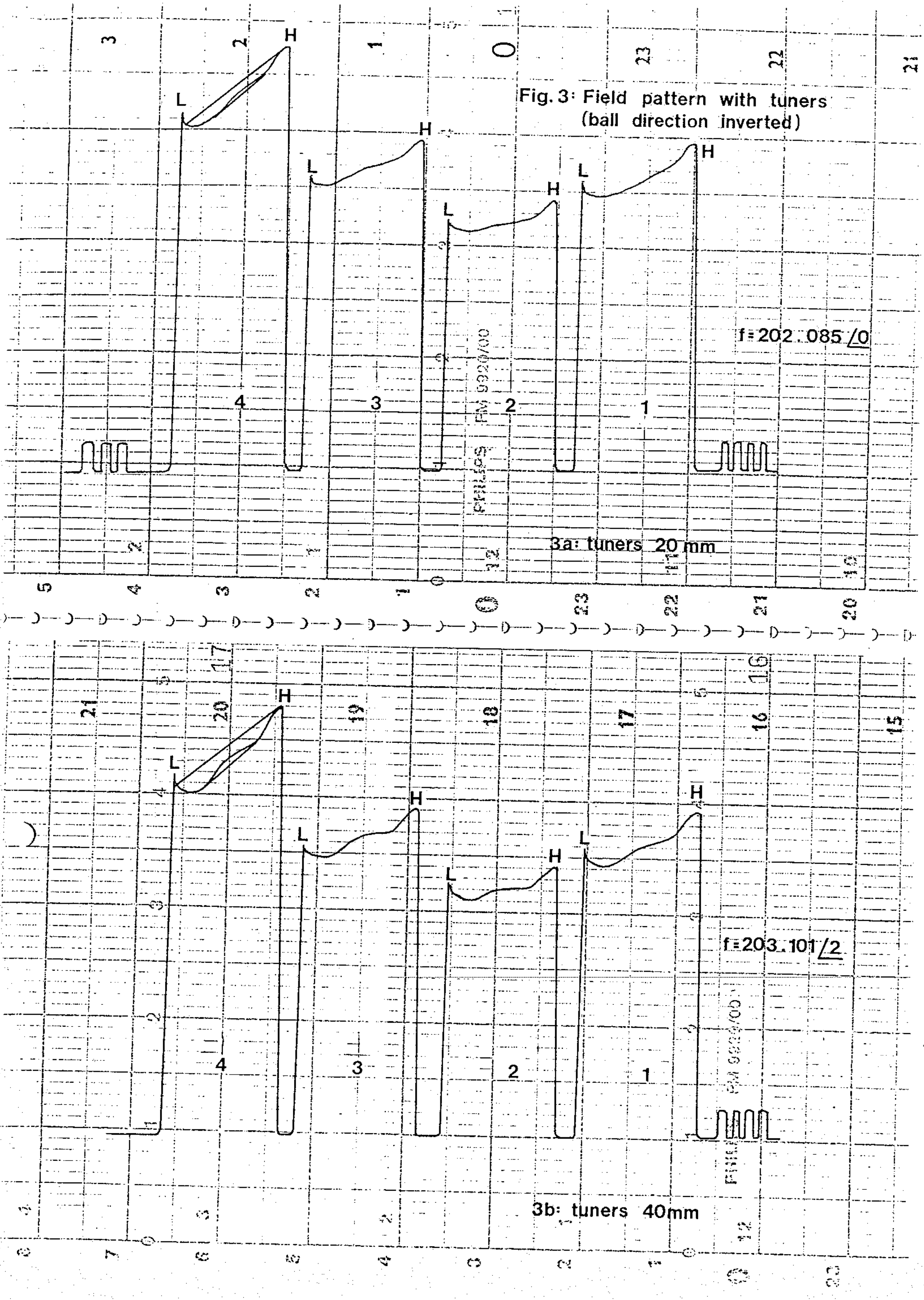
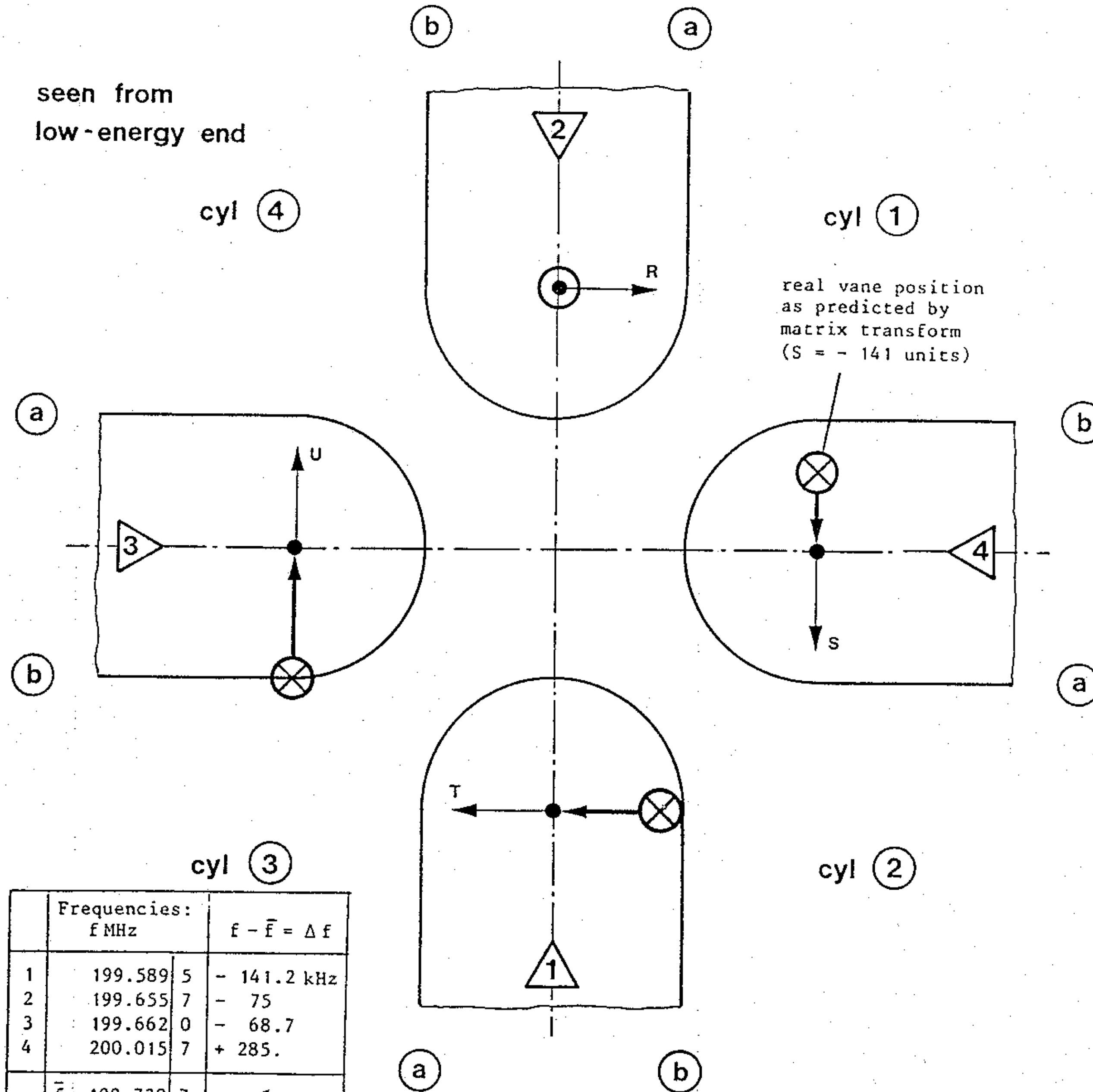


Fig. 3: Field pattern with tuners (ball direction inverted)



	Frequencies: f MHz		f − $\bar{f}$ = Δ f
1	199.589	5	− 141.2 kHz
2	199.655	7	− 75
3	199.662	0	− 68.7
4	200.015	7	+ 285.
	$\bar{f}$ = 199.730	7	∅

Statistics:
- $\delta = 0.166\,96$ RMS-deviation
- $\hat{\hat{1}} =$ 426 kHz maximum difference

$$\begin{bmatrix} -141 \\ -75 \\ -69 \\ +285 \end{bmatrix} \Delta f$$

$$\begin{bmatrix} -1 & -1 & -1 & 1 \\ \emptyset & -1 & -1 & -1 \\ \emptyset & \emptyset & -1 & -1 \\ 1 & 1 & 1 & \emptyset \end{bmatrix} \begin{bmatrix} \emptyset \\ -141 \\ -216 \\ -285 \end{bmatrix} \begin{matrix} \leftarrow R & \emptyset \\ \leftarrow S & 9.3\ \mu \\ \leftarrow T & 14.3\ \mu \\ \leftarrow U & 18.8\ \mu \end{matrix}$$

mechanical correction needed

check

$$\begin{bmatrix} -1 & 1 & \emptyset & \emptyset \\ \emptyset & -1 & 1 & \emptyset \\ \emptyset & \emptyset & -1 & 1 \\ 1 & \emptyset & \emptyset & -1 \end{bmatrix} \begin{bmatrix} -141 \\ -75 \\ -69 \\ 285 \end{bmatrix} \Delta f$$

Configuration : Definitive, rewelded vane
(1) configuration from shop

Fig. 4: Example of a form for equalization of cylinders