ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
им. Г.И. Будкера СО РАН

N. Gavrilov, I. Kuptsov, G. Kurkin,
L. Mironenko, V. Petrov,
I. Sedlyarov, V. Veshcherevich

RF CAVITY FOR THE NOVOSIBIRSK RACE-TRACK MICROTRON-RECUPERATOR

BUDKERINP 94-92

НОВОСИБИРСК

RF CAVITY FOR THE NOVOSIBIRSK RACE-TRACK MICROTRON-RECUPERATOR

N. Gavrilov, I. Kuptsov, G. Kurkin, L. Mironenko,
V. Petrov, I. Sedlyarov, V. Veshcherevich

ABSTRACT

Geometry, engineering design and characteristics of a 181 MHz RF cavity are described. The cavity has copper clad stainless steel walls and has a Q of 42,000 and a shunt impedance of 8.5 MOhm. The cavities of that type are parts of an RF system of a CW race-track microtron-recuperator (RTMR). More than 20 RF cavities will be built and installed into a RTMR for FEL program at Novosibirsk. Two cavities have been successfully tested up to an accelerating voltage of 1.2 MV which is 20 % over the design value. One of them has a slightly modified geometry and a frequency of 178 MHz. It has been built by a special order of Duke University for the Duke's storage ring.

ВЧ РЕЗОНАТОР ДЛЯ РАЗРЕЗНОГО МИКРОТРОНА-РЕКУПЕРАТОРА В НОВОСИБИРСКЕ

В. Г. Вещеревич, Н. Г. Гаврилов, И. В. Купцов, Г. Я. Куркин,
Л. А. Мироненко, В. М. Петров, И. К. Седляров

АННОТАЦИЯ

В работе описаны форма, конструкция и параметры ВЧ резонатора на частоту 181 МГц. Корпус резонатора изготовлен из биметалла. Резонатор имеет добротность 42 000 и шунтовое сопротивление 8,5 МОм. Резонаторы такого типа входят в состав ВЧ системы разрезного микротрона-рекуператора непрерывного действия (РМРНД). Более 20 таких резонаторов будет изготовлено для РМРНД, сооружаемого в Новосибирске для работы с лазером на свободных электронах. Два резонатора успешно испытаны на ускоряющих напряжениях до 1,2 МВ, что на 20 % превышает проектное значение. Один из этих резонаторов имел немного измененную геометрию и частоту 178 МГц. Он был изготовлен по специальному заказу Дюкского университета (США) для Дюкского накопительного кольца.

INTRODUCTION

A 60 MeV, 1 A CW race-track microtron-recuperator (RTMR) is to be built at Novosibirsk for a free electron laser project [1]. An RF system [2] is one of the key parts of this machine. Due to the beam-cavity interaction during an acceleration cycle a part of electromagnetic energy, stored in RF cavities, is transformed into kinetic energy of the electron beam. During a recuperation cycle the kinetic beam energy is transformed into the electromagnetic energy of the cavities. Therefore, the average beam loading of the RF cavities is small despite a high value of beam current.

The accelerator RF system will operate at the frequency of 181 MHz. The main reason of this choice is the availability of high power RF tubes in Russia: there are no high power CW tetrodes or klystrons at frequencies beyond 200 MHz. 25 single cell RF cavities will be built and installed into the machine. Fig. 1 shows a general scheme of the RF system of RTMR.

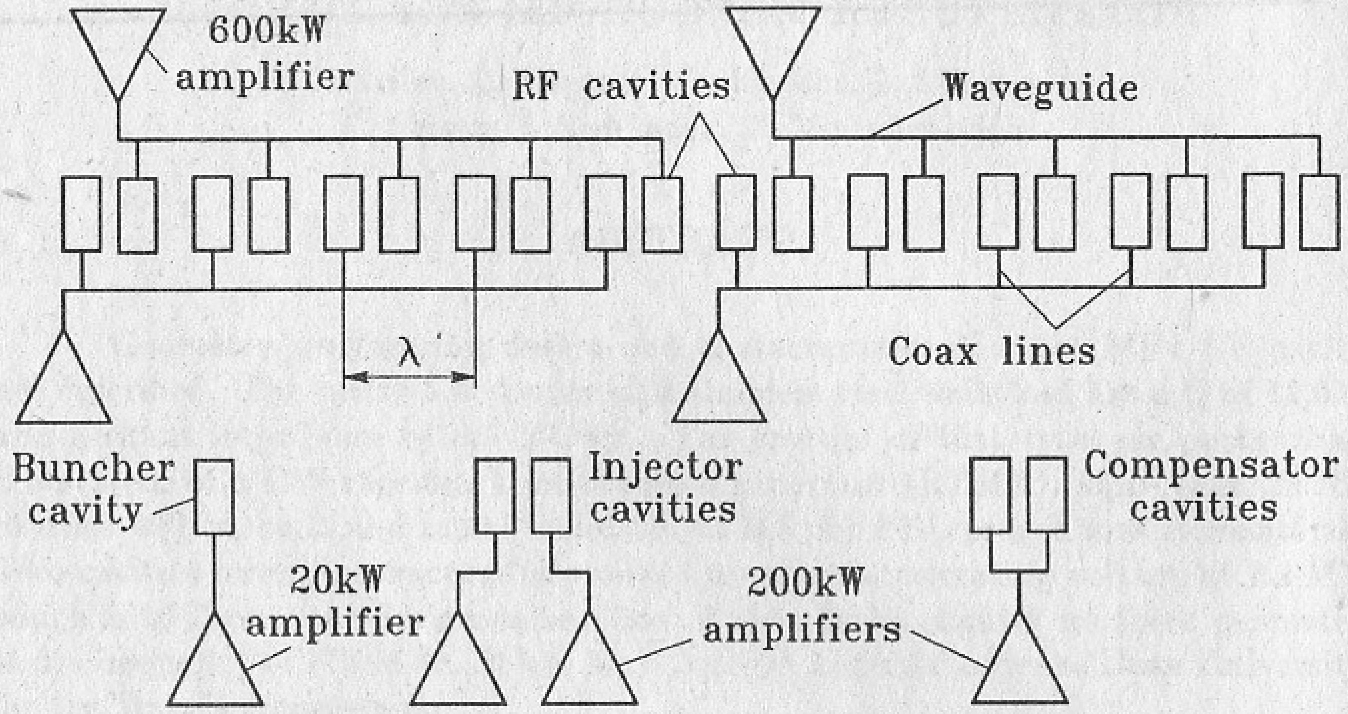


Figure 1: *Scheme of RF system for microtron-recuperator.*

RF Cavity Design

The total number of RF cavities in the machine is rather big. Therefore, we decided to simplify the cavity design in order to decrease the fabrication time and construction costs. Geometry of an RF cavity is shown in Fig. 2. The side walls have conical shape. It is good for mechanical rigidity and cavity electrical characteristics. But there are no nose cones. The cavity length is less than an optimal one. The reason for this is the general machine design. Elements of magnet system (focusing solenoids) are to be placed after every other RF cavity. The fundamental cavity mode is of E_{010}-like type. It has longitudinal electric field with angular symmetry. Cavity characteristics are summarized in Table 1. Figure 3 presents computed plots of electrical field lines and field distributions along the beam axis for the fundamental and some higher order modes of the cavity. The plots were produced by the SUPERLANS computer code [3].

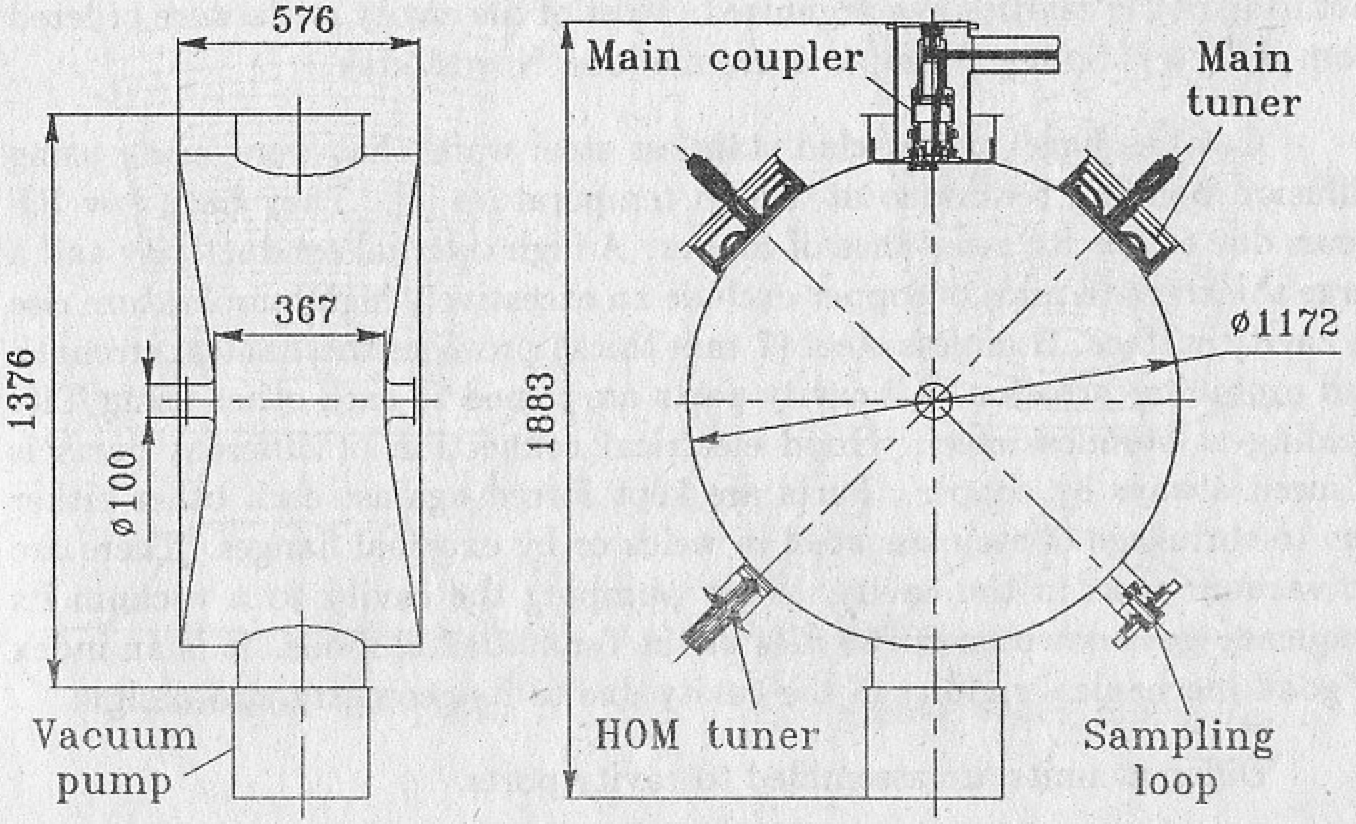


Figure 2: *Sketch of the RF cavity.*

Table 1: Parameters of the cavity

Accelerating voltage (V) —	0–1000 kV
Q value —	40,000
R/Q value (*) —	215 Ohm
Shunt impedance (*) —	8.5 MOhm
Resonance frequency —	180.5 MHz
Tuning range of cavity frequency —	320 kHz
Tuning rate —	5 kHz/s
Wall loss at $V = 1000$ kV —	120 kW
Maximal power flux at $V = 1000$ kV —	3.5 W/cm^2

(*) Shunt impedance R is defined as $R = V^2/P$,
$V^2 = (\int E_z cos(kz)dz)^2 + (\int E_z sin(kz)dz)^2$

The design of the cavity was made at BINP. A semi-industrial manufacturing of the cavities was organized. Most of the cavity parts were ordered from industry. Some of the parts are made at Novosibirsk.

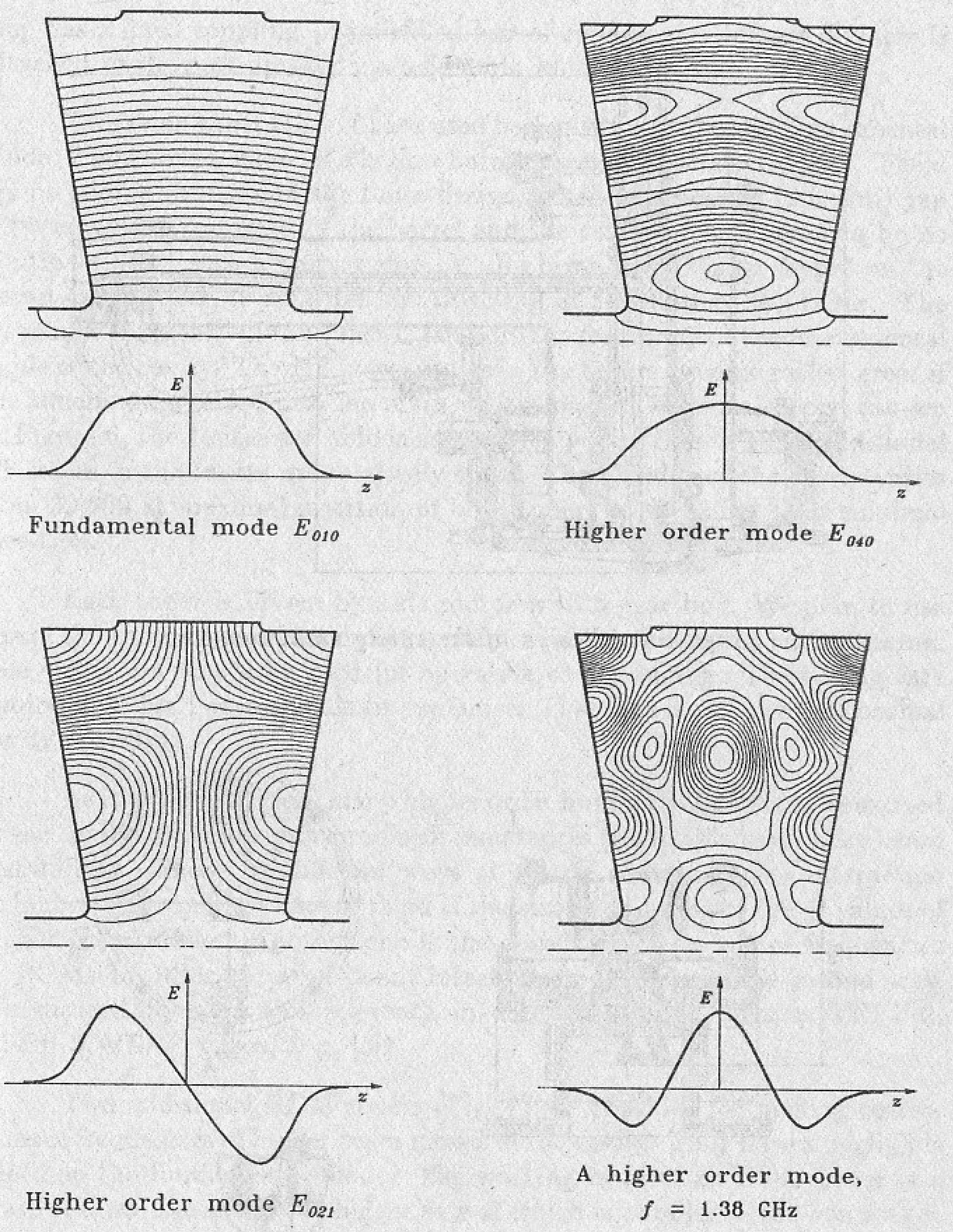
Cavities have copper clad stainless steel walls that were made using diffusion bonding technique at a high temperature [4]. They have low RF losses due to low RF resistance of copper. A high thermal conductivity and a large thickness (8 mm) of copper exclude an excessively high temperature rise at cavity surface. Stainless steel (7 mm thick) provides mechanical strength and prohibits corrosion. All cavity parts are joined to each other using TIG welding at stainless steel. Good electrical connection of different parts is ensured always by copper. Parts are kept forced against each other either due to shrinkage of stainless steel in welds or by external flanges. There are no vacuum seals in the cavity. After pumping the cavity to a vacuum its frequency goes down on 60–80 kHz at the fundamental mode. It is an index of good mechanical rigidity of the cavity due to its geometry and design.

Different units are assembled to cavity ports.

One of them is a main coupler (Fig. 4). It has a coaxial design. A cylindrical alumina ceramic RF window is incorporated in it. Coaxial input line has a wave impedance of 75 Ohm, the diameters of its outer and inner conductors are 160 mm and 45 mm respectively. The coupling loop has a triangular cross-section for eliminating multipacting in it. It was shown long ago [5] that multipacting cannot occur between skew electrodes. We successfully use this approach in different RF cavities for years. The coupler may be rotated around its axis for adjusting the right coupling value. This procedure should be done before final welding of the main coupler to the cavity.

The side leadaway pipeline shown in the Fig. 4 is used for feeding the cooling water into the central conductor of the coaxial line. It looks like a coaxial quarter-wave stub and can be considered as a metal insulator in the main line.

Another unit is a pick-up loop (Fig. 5). It provides electrical signals the amplitude and phase of which are proportional to amplitude and phase of the cavity voltage. They are used in the RF control system. In the same way as the main loop, the sampling loop has a delta-like shape. The pick-up



Fundamental mode E_{010}

Higher order mode E_{040}

Higher order mode E_{021}

A higher order mode, f = 1.38 GHz

Figure 3: *Electrical field patterns and field distributions along the beam axis for some cavity modes.*

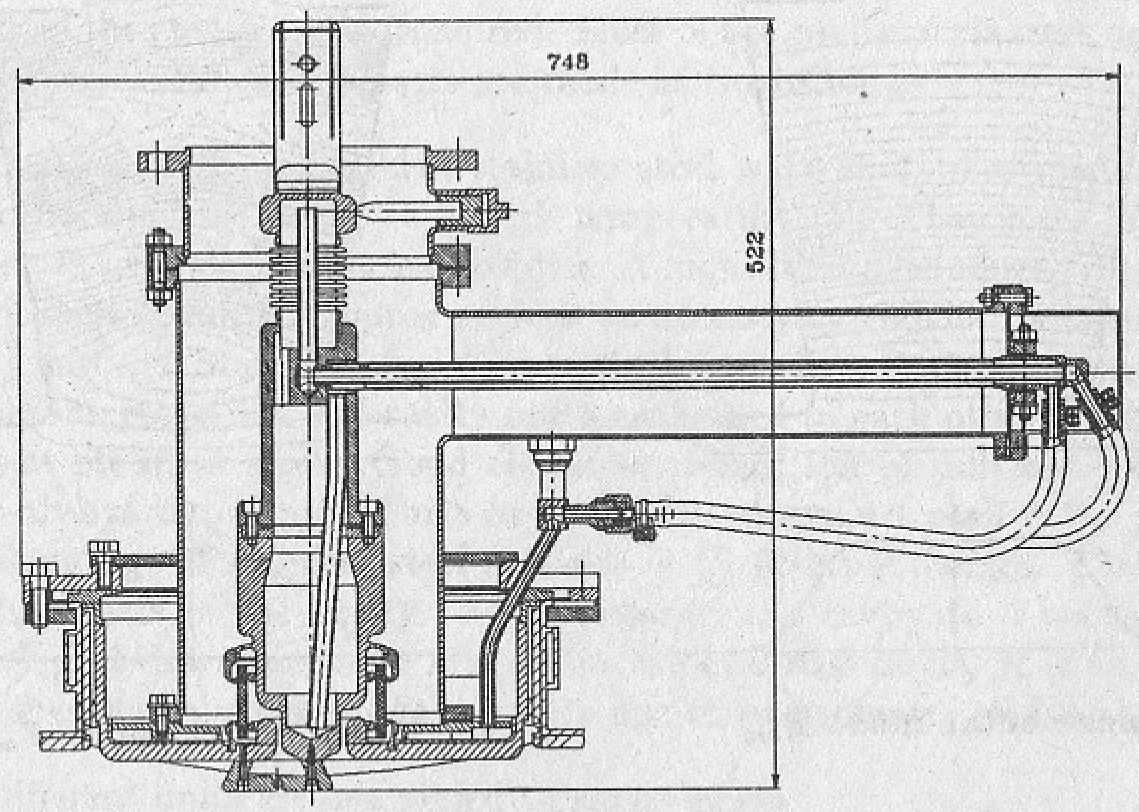


Figure 4: *Design of the cavity main coupler.*

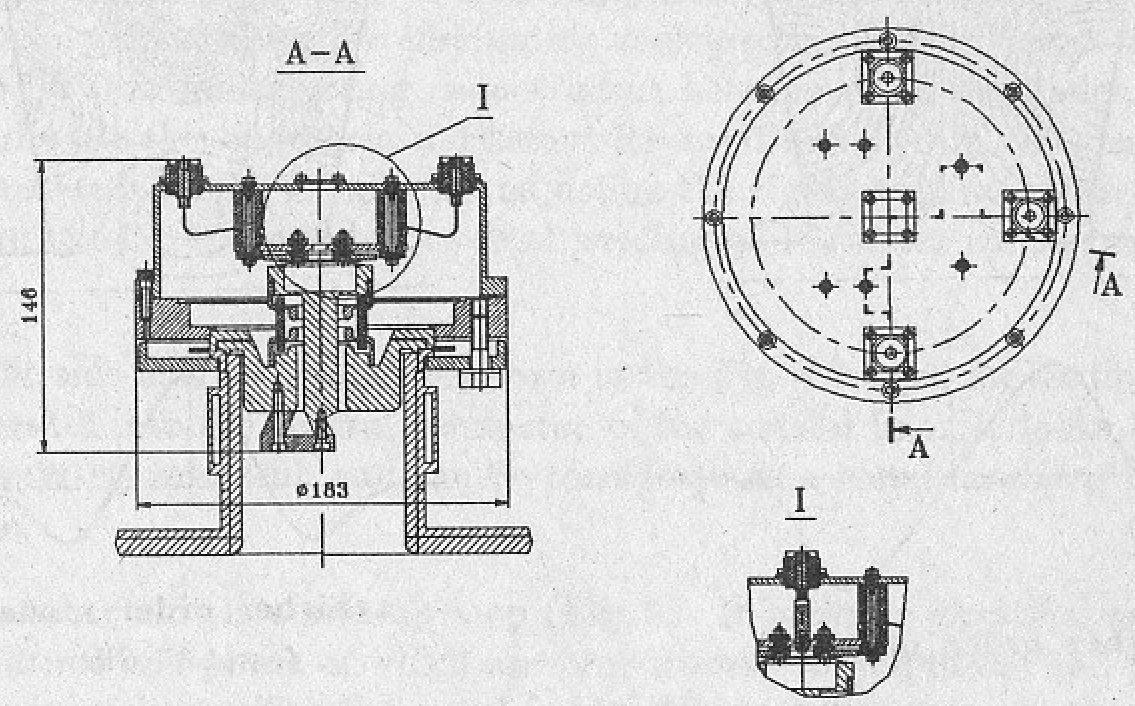


Figure 5: *Design of the cavity pick-up loop.*

loop has a fixed coupling. An airfilled box of capacitance voltage dividers is attached to the pick-up loop via a ceramic window.

Two main tuners (Fig. 6) are used basically for tuning the fundamental mode. They have a shape of a hollow barrel inserted into a cavity port. There are no sliding contacts in the tuner design. There is a narrow (2.5 mm) gap between cylindrical walls of the barrel and the cavity port. There can be no multipacting in such a narrow slot. A thin layer of TiN is sputtered on the barrel face surface to suppress multipacting at this part of the tuner. The resonance frequency of the tuner is far from the frequency of the fundamental mode of the cavity. The RF power losses in the tuners become rather great if the tuners are inserted into the main cavity space. Therefore, as one can see in Figure 6, the tuners are hidden into cavity ports. Due to that, additional RF losses in the tuners are relatively small. The Q value of the cavity varies from 39,000 at maximal insertion of both tuners to 41,000 at their minimal insertion.

Each tuner is driven by a dc motor with a gear box. We plan to use one of the tuners for correction of mechanical errors and initial cavity tuning. The other one should be used for operative cavity tuning. The tuning rate quoted in Table 1 corresponds to one tuner. That rate is sufficient for normal cavity operation.

As it was mentioned, many higher order modes (HOMs) may be excited in the cavity. At some unfavorable circumstances the HOMs may cause beam instabilities. There are different ways of control of beam-cavity interaction at higher order modes. One of them is the strong damping of the Q values of higher order modes. Another one is the correction of resonance frequencies of HOMs in order to avoid beam instabilities. We chose the second way. We successfully used this approach in different storage rings as VEPP-2, VEPP-3, VEPP-4 (see, e. g. [6]).

Two additional HOM tuners (Fig. 7) are provided for making corrections of frequencies of higher order modes of the cavity. They have a negligible effect on the fundamental mode. The working head of an HOM tuner is a plate of a ∞-like shape the bigger axis of which is parallel to the beam axis.

There is an auxiliary port at the cavity shell which is used for a vacuum gauge and for rough pumping of the cavity. Besides, on the first cavities a

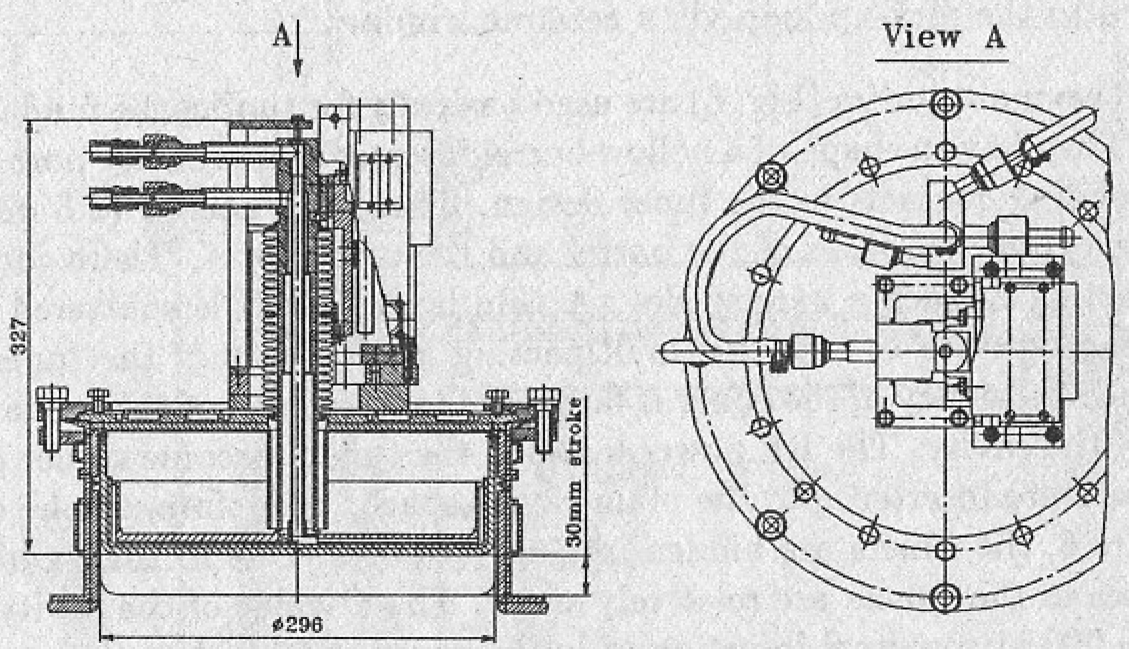


Figure 6: *Design of the main cavity tuner.*

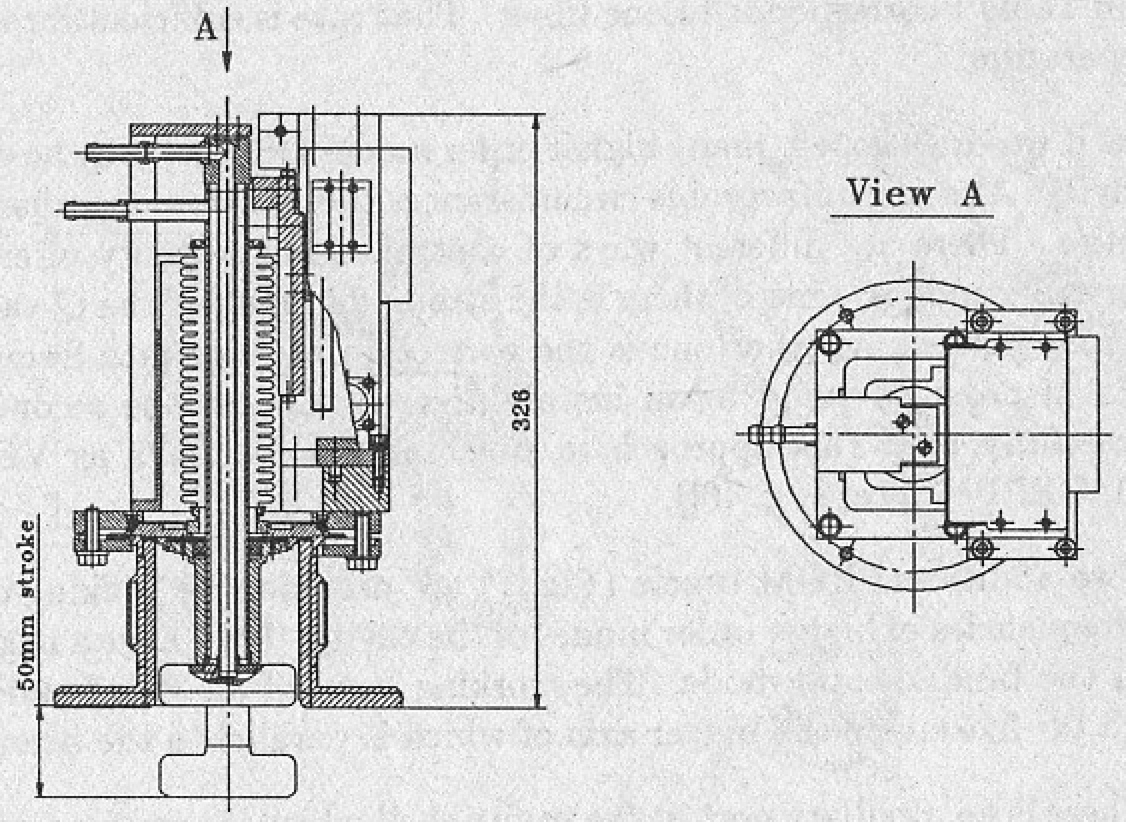


Figure 7: *Design of the cavity HOM tuner.*

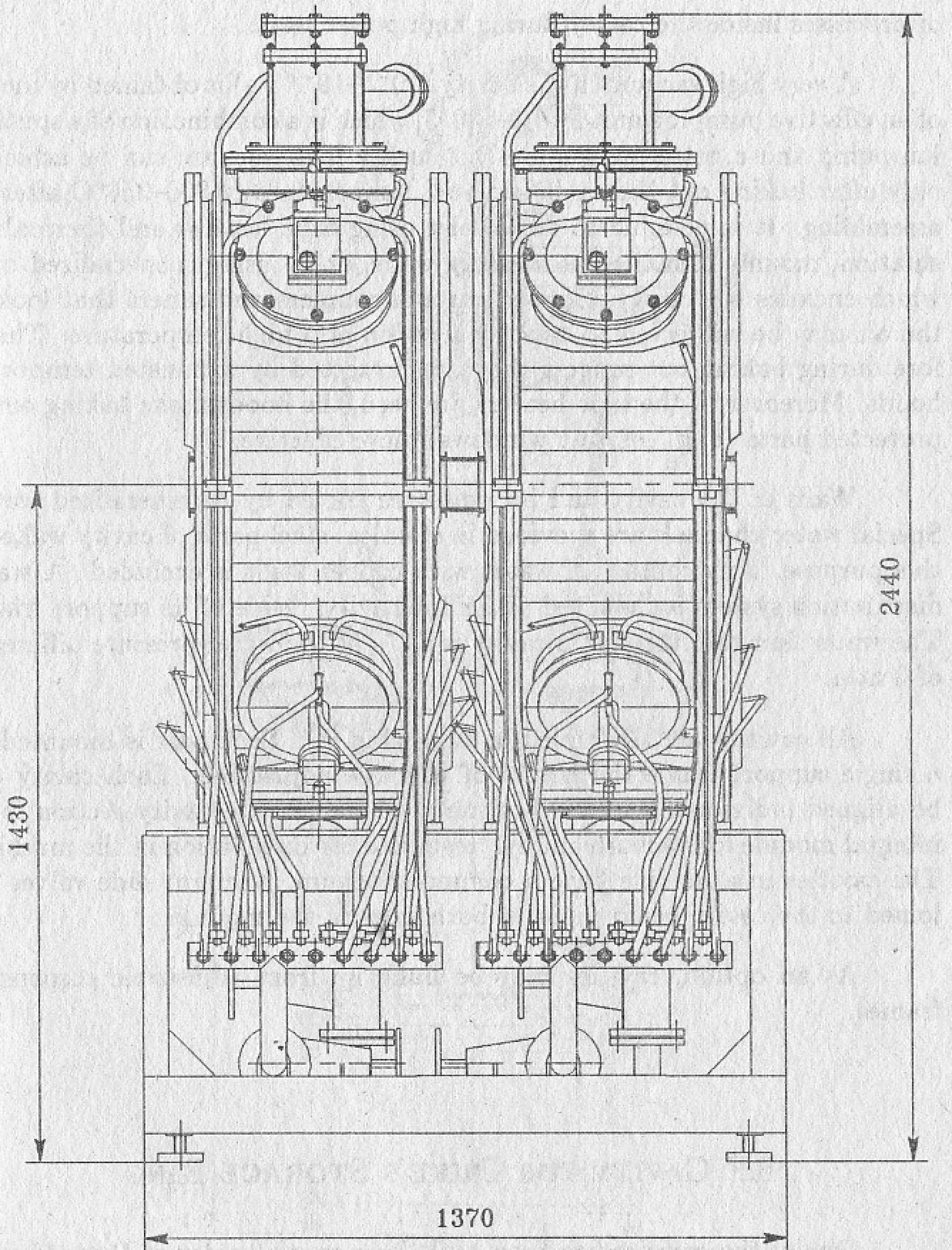


Figure 8: *A two-cavity module.*

glass window was also mounted to this port. It was used for visual observation of processes inside the cavity during high power tests.

A very high vacuum in the cavity (10^{-7}–10^{-8} Pa) is obtained by means of an effective pumping unit PVIG-630 [7] which is a combination of a sputter-ion pump and a gettering pump. But such a high vacuum can be achieved only after baking out the cavity up to a temperature of 300–350°C after its assembling. It is possible to do this by using tape heaters and thermal insulation, mounted on the outer cavity walls, or by using a specialized oven which encloses the cavity. Copper parts of couplers and tuners that look to the air may be subjected to strong oxidation at a high temperature. Therefore during baking out process they are protected by exhausted temporary hoods. Moreover, if the tape heaters are used, the hoods make baking out of protected parts (e. g. ceramic windows) more effective.

Walls of the cavity and its units are cooled by demineralized water. Special water channels are provided in stainless steel parts of cavity walls for this purpose. Any contact of water with copper walls is excluded. A water distribution system is mounted under the cavity, inside of its support frame. The water flow rate through a cavity is 7 l/s at the water pressure difference of 3 atm.

All cavities are assembled in pairs (Fig. 8). Each pair is mounted on a single support frame the height of which is adjustable. Each cavity can be aligned individually in the horizontal plane. A two-cavity section is an integral module for vacuum and RF tests and for installation in the machine. The cavities in a module have a common vacuum. Vacuum slide valves are joined to the cavity beam pipes at both sides of the module.

As an option, cavities may be hung up from adjustable suspension frames.

RF CAVITY FOR DUKE'S STORAGE RING

One of the cavities has been built by a special order of Duke University (Durham, NC, USA). It has been delivered to FEL Laboratory of Duke University and installed into the Duke's 1 GeV storage ring [8] which will be used for FEL experiments.

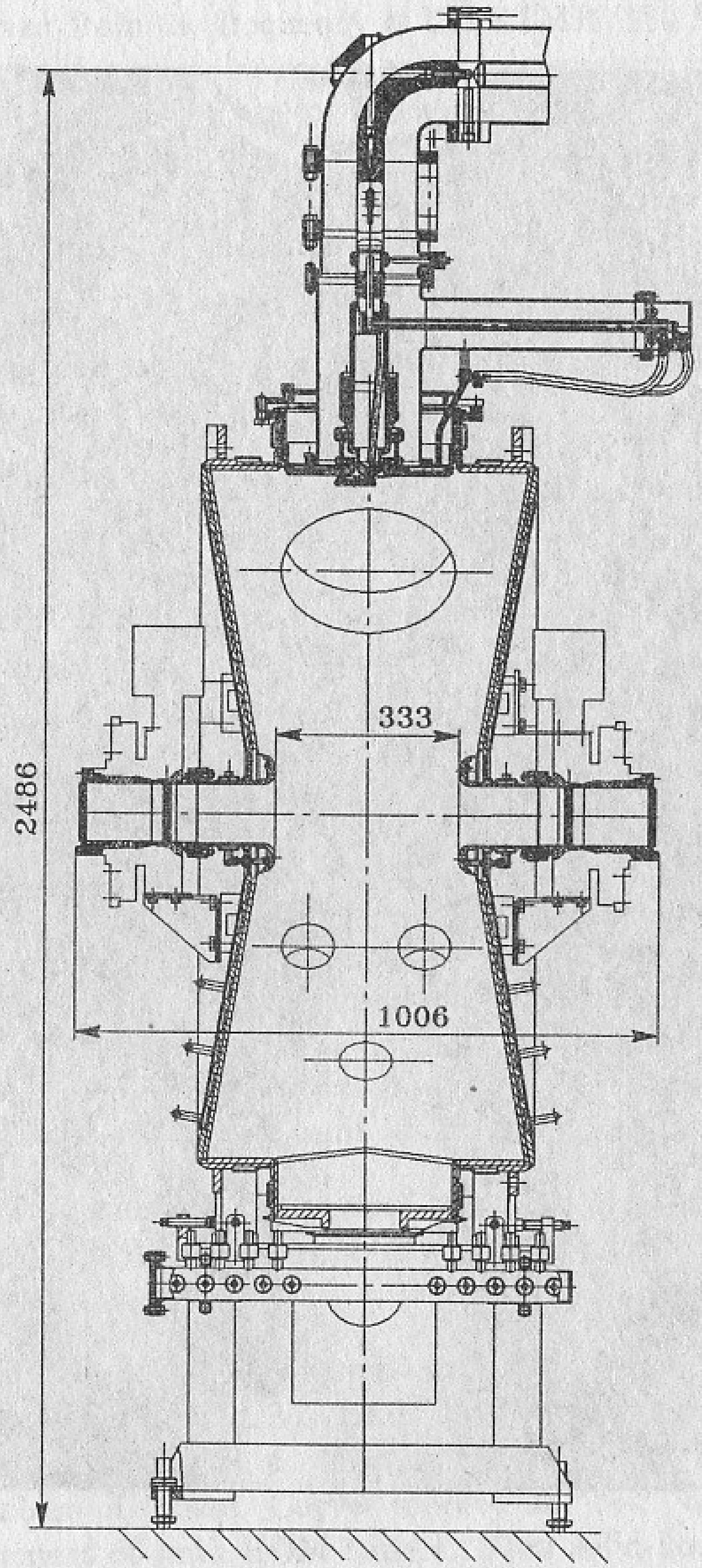


Figure 9: *Duke cavity: a sectional view.*

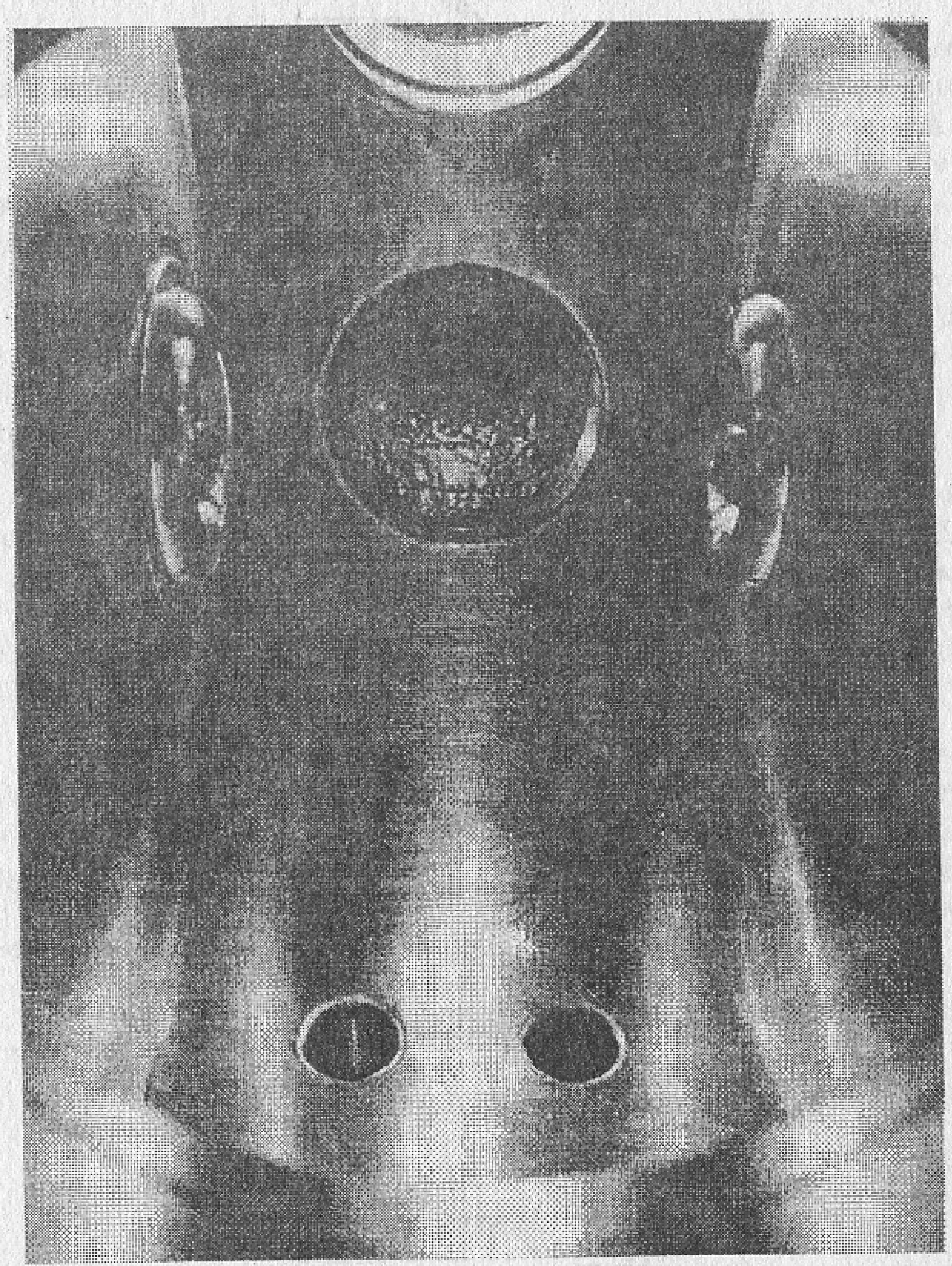


Figure 10: *Duke cavity: an inside view; cavity units are not mounted to the ports.*

The frequency of the RF system of the Duke's storage ring (178.5 MHz) is a little different from the frequency of the RTMR (180.5 MHz). Therefore the geometry of this particular cavity was to be slightly modified to accommodate its frequency to the one of Duke's requirements. It was difficult to change the cavity diameter, its length or the cone angle of the side walls. The best solution was to make small additional nose cones for decreasing the frequency of the fundamental mode of the cavity (Fig. 9). Figure 10 shows the inside picture of the cavity with nose cones.

Due to changes of geometry, some parameters of the cavity are slightly different from the ones of regular RTMR cavities. It has $R/Q = 227$ Ohm, $Q = 42{,}000$ (it varies from 41,000 to 43,000 in tuning range of 370 kHz), $R = 9.5$ MOhm. The cavity Q is a little higher also due to better surface finishing of this particular cavity.

RF measurements, vacuum and RF high power tests were done after the fabrication of the Duke cavity.

LOW LEVEL RF MEASUREMENTS OF DUKE CAVITY

During low level RF tests the right coupling value of the main coupler was adjusted, the coupling coefficient of the sampling loop was determined, characteristics of the fundamental and higher order modes were measured including the influence of all four tuners on resonance frequencies of all modes. An automated set-up has been built for low level RF measurements.

Figure 11 presents experimental frequencies and impedances of the fundamental mode and the higher order modes that have longitudinal electrical field on the beam axis.

The influence of the tuner positions on the frequencies of some higher order modes is shown in Fig. 12. HOM tuners have numbers 1 and 2, main tuners have numbers 3 and 4. The numbers of curves correspond to the sequence numbers of tuners. Curves marked as "1+2" correspond to simultaneous movement of both HOM tuners. Thin solid horizontal lines at the plots correspond to harmonics of the revolution frequency of the Duke's storage ring. One can see that different tuners produce changes of resonance frequencies that differ in signs and absolute values.

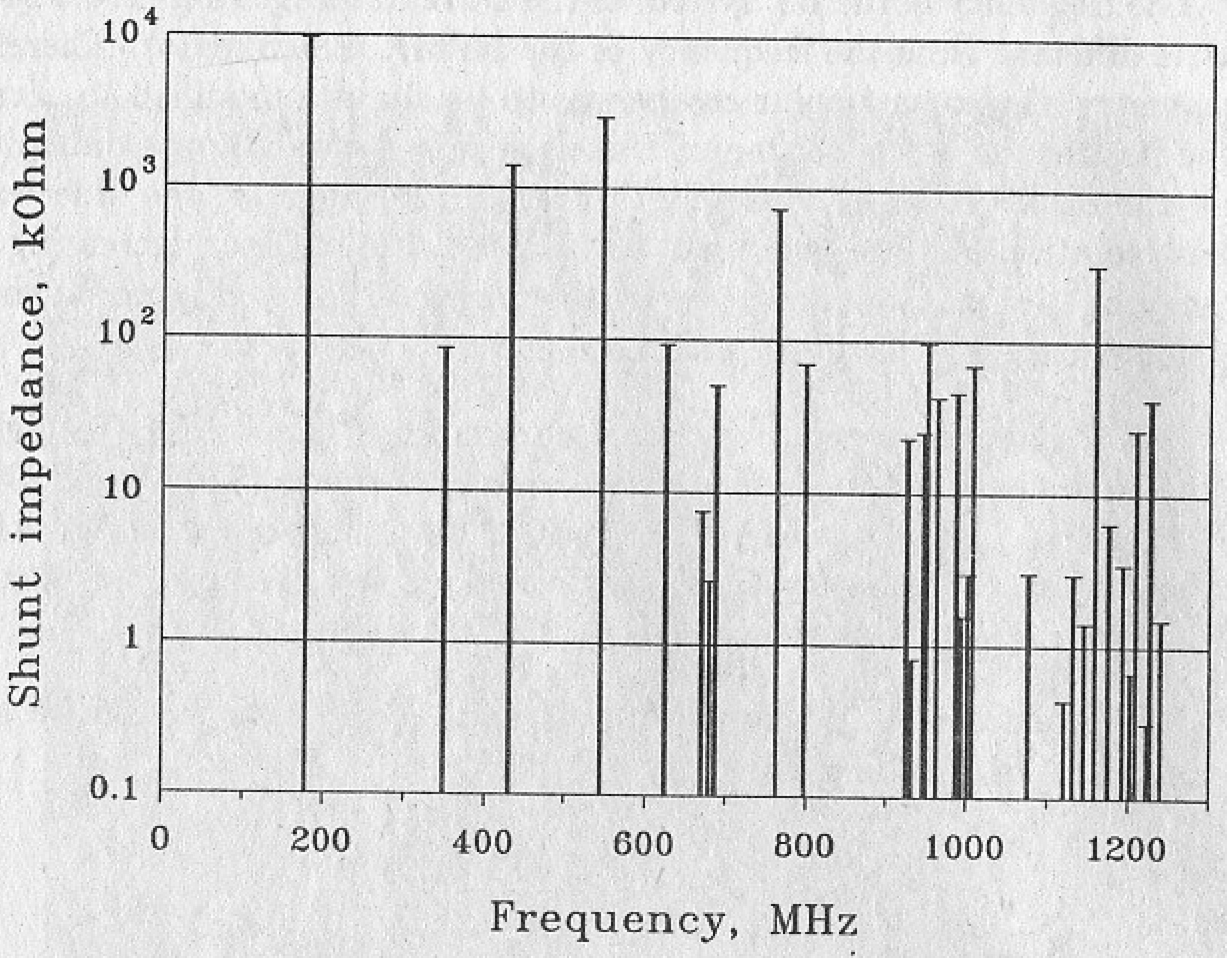


Figure 11: *Modes of the Duke cavity.*

Experimental data including shunt impedances, Q values, resonance frequencies and their dependencies on the tuner positions allow to compute the integral influence of the higher order modes of the cavity on longitudinal beam dynamics. That analysis was done for the single bunch mode of operation of the Duke's Storage Ring. 19 higher order modes of the cavity with greater impedances in the frequency range up to 1200 MHz were taken into account. The results are presented in Figure 13. The coordinates $X(n)$ at the diagrams are the positions of the cavity tuners of number n. For the top diagram, the position of the tuner #3 at each point depends in a unique fashion on the position of the tuner #4 so that the cavity is always kept tuned to the fundamental frequency.

For each point of the diagram, the value of

$$\sum_{n=1}^{N}(R_n^+ - R_n^-)$$

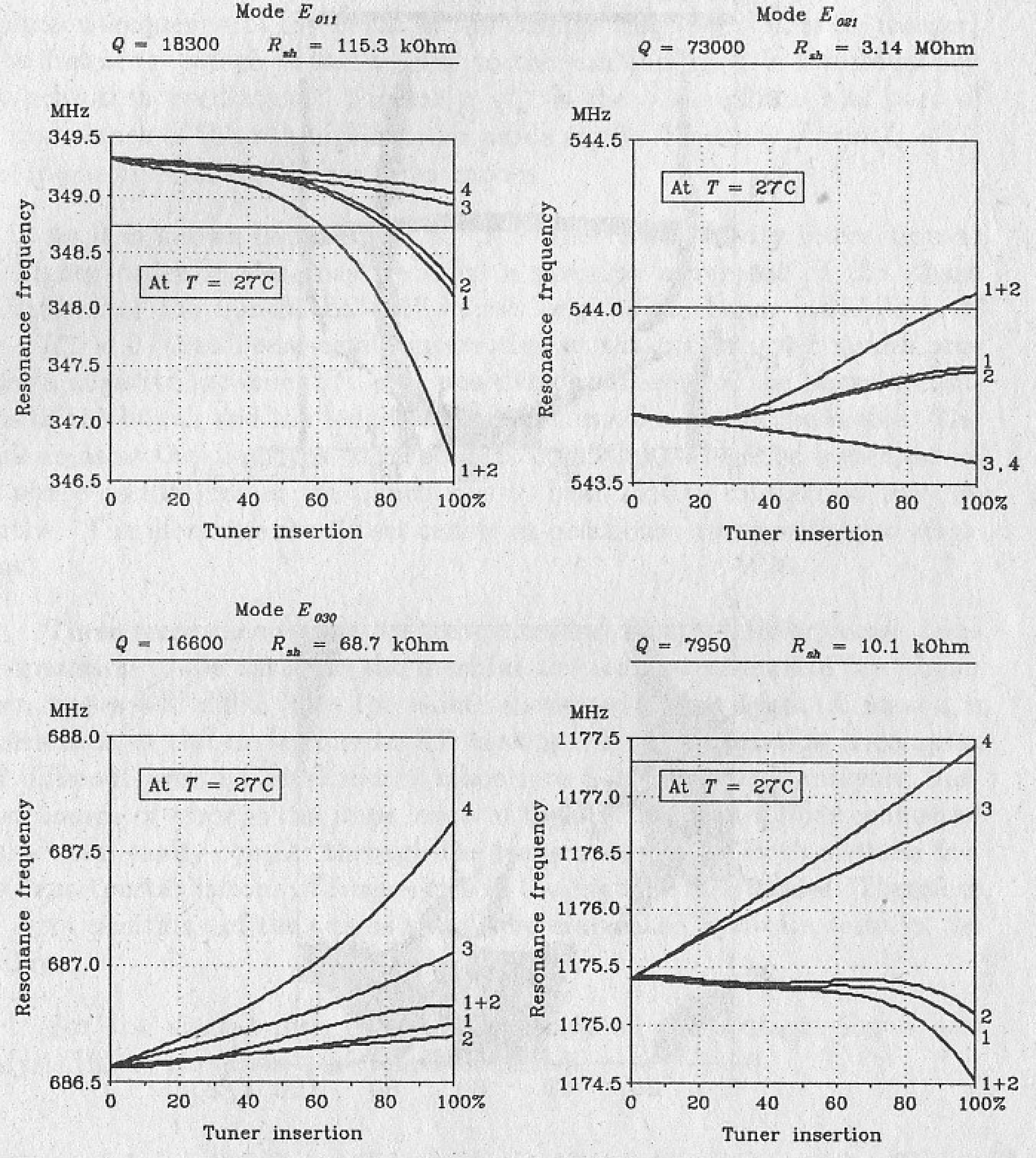


Figure 12: *Tuning curves of some higher order modes.*

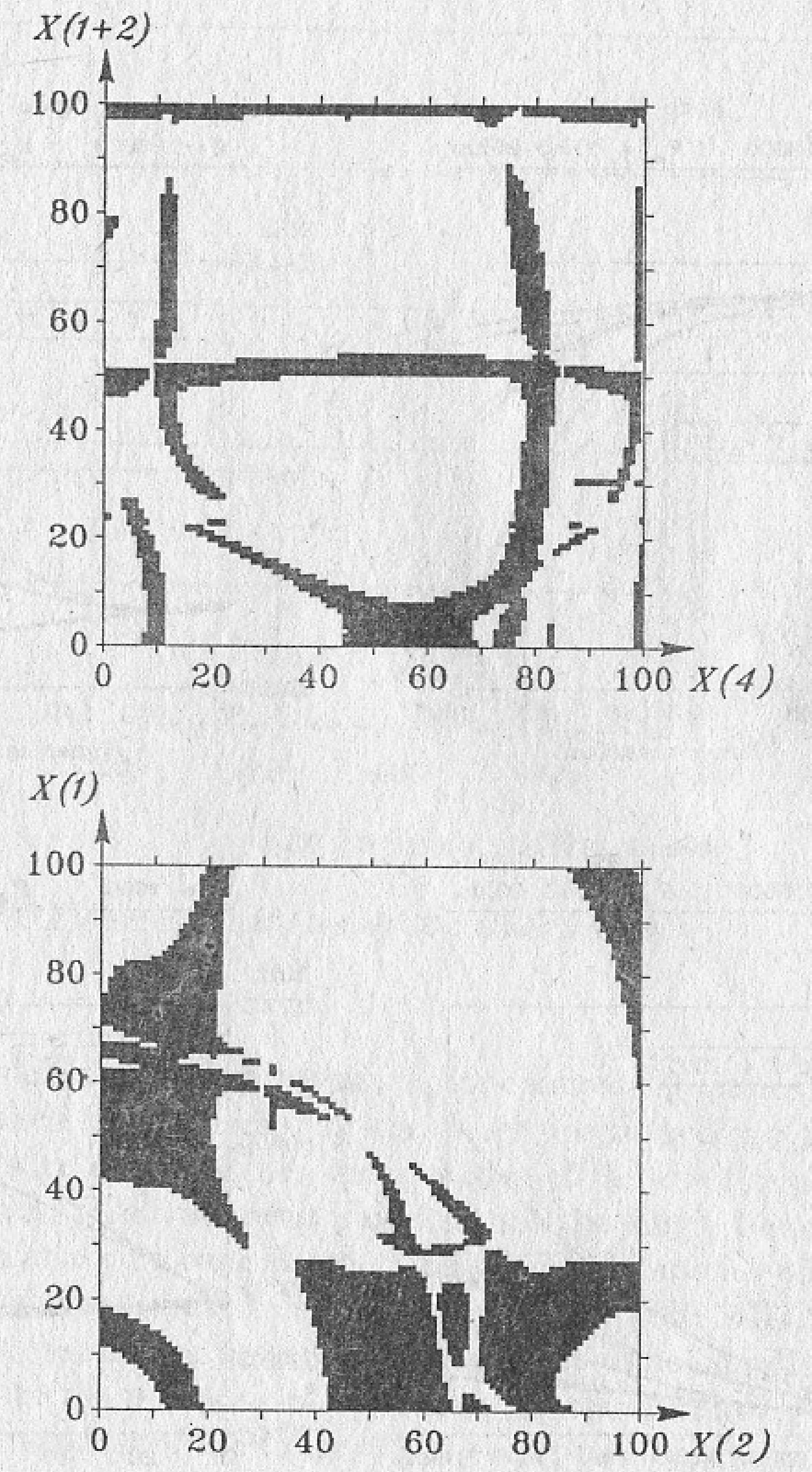


Figure 13: *Areas of possible longitudinal instability as functions of the cavity tuner positions.*
For the top diagram: $E = 1$ *GeV*, $V = 850$ *kV*, $T = 27°C$, *cavity is tuned to resonance at the fundamental frequency.*
For the bottom diagram: $E = 250$ *MeV*, $V = 100$ *kV*, $T = 27°C$, $X(4) = 35\,\%$, *cavity is detuned at the fundamental frequency, tuning phase angle is 30°.*

is computed. Here R_n^+ is the value of the real part of the impedance of the nth higher order mode at the frequency $f = mf_o + f_s$ where f_o is the revolution frequency of the beam in the storage ring, mf_o (m is an integer) is the frequency which is the nearest to the nth mode, f_s is the frequency of synchrotron oscillations. Similarly, R_n^- is the value of the real part of the impedance of the nth higher order mode at the frequency $f = mf_o - f_s$. N is the number of the higher order modes.

As it is known [9], if $R_n^+ - R_n^- > 0$ then beam-cavity interaction at the higher order modes may produce a positive increment of the phase oscillations of the bunch that will cause longitudinal beam instability. If $R_n^+ - R_n^- < 0$ then beam-cavity interaction at the higher order modes produces a negative increment (i. e. a positive decrement) of the phase oscillations of the bunch and the longitudinal bunch motion should be stable. The black areas at the diagrams correspond to conditions when the increment of the phase oscillations of the bunch due to beam-cavity interaction may be positive. Therefore one should set tuners at positions corresponding to white areas.

These recommendations are to be considered as preliminary ones. During operation of the cavity in the machine the real frequencies of the higher order modes will differ from the values measured at low level. A reason is deformation of the cavity due to RF heating. This deformation is complex and different from an ideal model taken into account in our analysis. Another source of error is the impedance of the RF power amplifier connected to the main cavity coupler through the transmission line. Both of these factors cause perturbations of frequencies of the higher order modes. Therefore the right positions of the tuners should be elucidated by beam tests in the machine.

For the multi-bunch mode of operation of the storage ring a new analysis [10] of the tuner positions is required.

HIGH POWER TESTS OF RF CAVITIES

Two RF cavities (one of RTMR cavities and the Duke cavity) have been successfully tested up to accelerating voltage of 1200 kV. There were

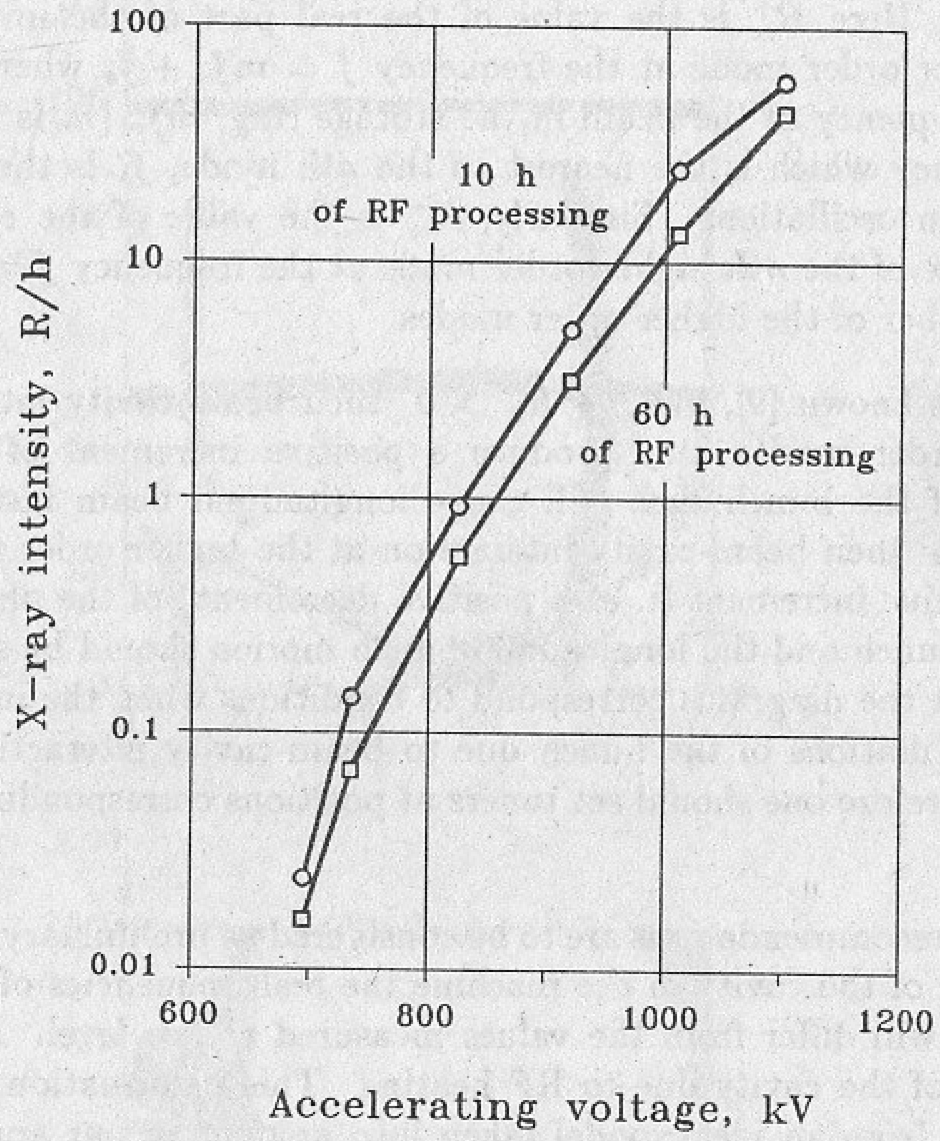


Figure 14: *X-ray rate of the cavity (on the axis, at 70 cm from the cavity).*

no fundamental limitations on increasing the voltage. Several levels of multipacting from $V = 300$ kV were found. Multipacting was detected by vacuum deterioration and faint glow in the cavity that could be seen through the glass window. At some levels small modulation of RF voltage appeared. Many hours of RF processing were called for suppressing this phenomenon. It was easy to process the lowest multipacting levels. But at high levels multipacting was much more severe.

Prior to the high power tests of each cavity, its main coupler had been tested with the cavity detuned far from the resonance. Therefore the cavity could not cause limitation in this case. The limiting factor was only the RF power available. There were standing wave conditions in the coaxial transmission line during those tests. This scheme gave a possibility to test the RF window in the main coupler to power levels even higher than those with tuned cavity. So, we could successfully test RF windows up to an RF power level which is equivalent to 170 kW with tuned cavity.

RF cavities produce X-rays during their operation due to field emission from the cavity surface in the areas of high electric field. The X-ray rate goes up very steeply with cavity voltage (see Fig. 14). At $V = 1000$ kV the X-ray rate on beam axis at a distance of 70 cm from the cavity is higher than 10 R/h.

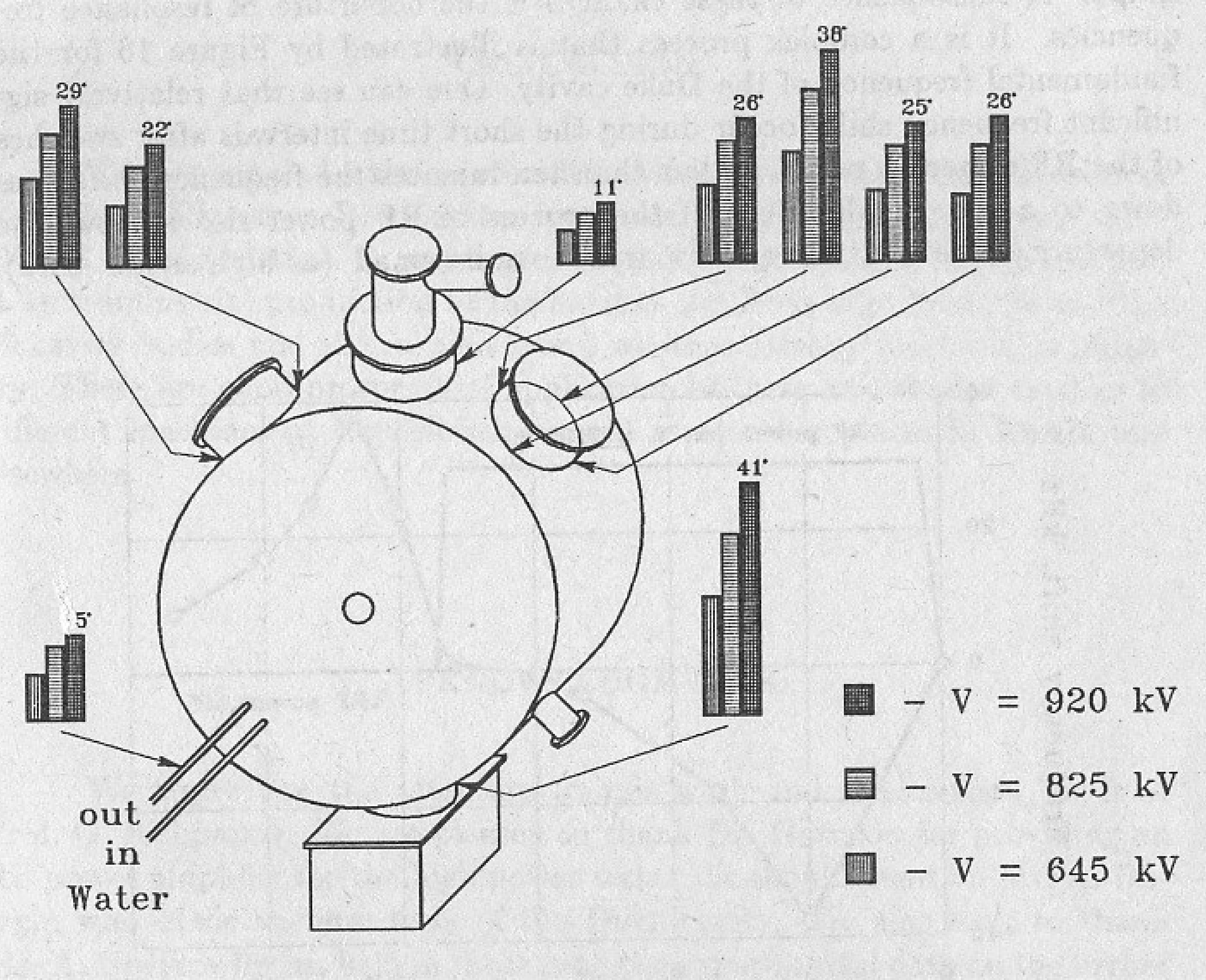


Figure 15: *Heating of the cavity by RF power.*

RF power dissipated in the cavity produces heating of the cavity despite its intensive water cooling. Different parts of the cavity are heated in different extent. Joints of ports with the cavity shell have the highest temperature. It is the result of concentration of RF currents due to field distortion by ports and less effective cooling of these areas. Figure 15 demonstrates the temperature rise at several control points of the cavity due to RF heating during RF power tests. Temperature of the tuner ports (hence the power dissipation in these cavity parts) is rather sensitive to the axial asymmetry of the tuners in ports. As one can see in Fig. 15, the hottest place is the joint point of pumping port to cavity shell. After the high power tests of the first cavities the design of this part of the cavity was modified and cooling was improved.

Heating of the cavity produces changes of cavity dimensions and its shape. A consequence of these changes is the departure of resonance frequencies. It is a complex process that is illustrated by Figure 16 for the fundamental frequency of the Duke cavity. One can see that relatively significant frequency shifts occur during the short time intervals after switches of the RF power on or off. In less than ten minutes the frequency shift goes down to a very small value. If the process of RF power rise is slow, the departure of the cavity frequency will be quite small (as high as few kHz).

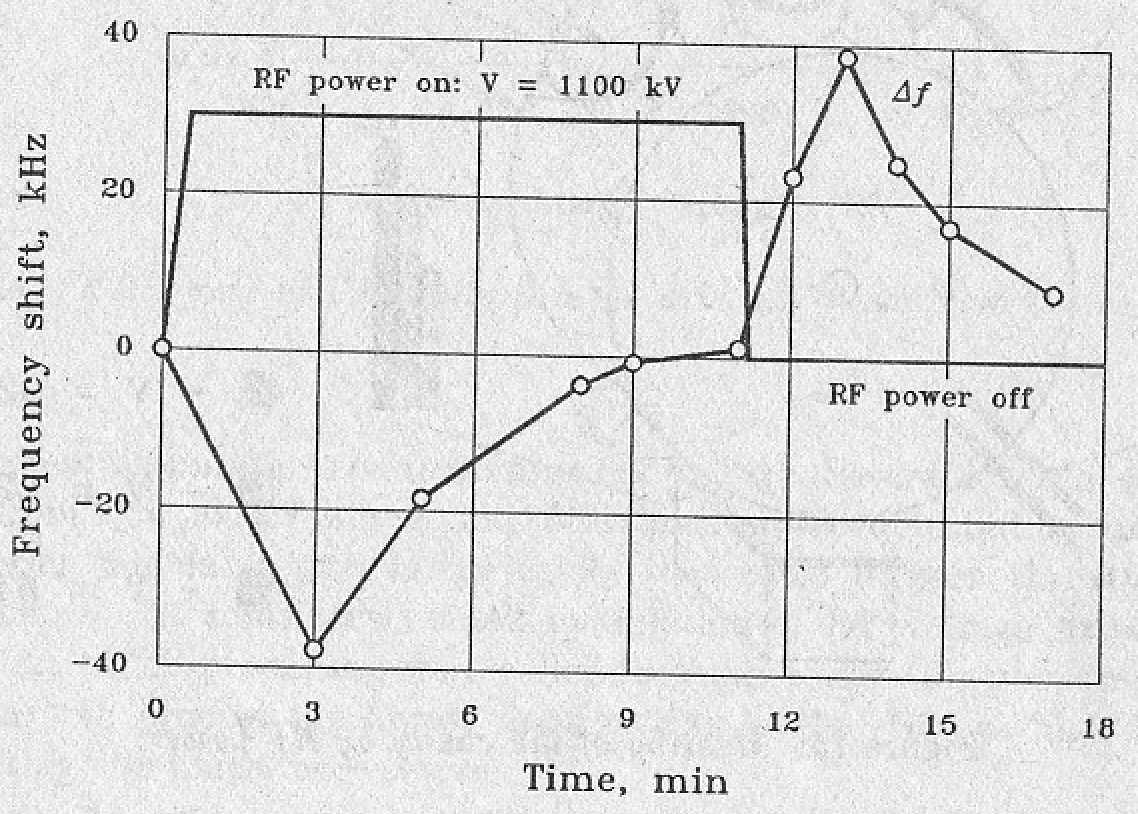


Figure 16: *Dynamics of the cavity frequency due to RF power on/off.*

The reason of this stabilizing performance of the cavity is a clever design of its cooling scheme.

The Duke cavity has been delivered to Duke University and installed into the storage ring. Without RF power the vacuum in the cavity is better than $1 \cdot 10^{-8}$ Pa. With the RF power on it is better than $1 \cdot 10^{-7}$ Pa. The highest accelerating voltage achieved at Duke (700 kV) was limited by the RF power amplifier available.

CONCLUSION

The copper clad stainless steel RF cavity developed for the Novosibirsk Race-Track Microtron-Recuperator has a good design and shows good operational characteristics. It was demonstrated by the tests of the prototypes. A semi-industrial production of the cavities has been organized. More than 20 cavity bodies and several unit sets have been already produced in industry. There are good prospects of application of these and similar cavities to different machines at Novosibirsk as well as at other places in Russia and elsewhere.

ACKNOWLEDGMENTS

We appreciate the attention to this work and the concern for it of Prof. G. Kulipanov. We are pleased to thank Dr. Gorniker for providing an RF power amplifier for the high power tests. We should mention Mr. A. Bulygin who made vacuum tests of the Duke cavity. We also have to thank Mr. A. Novikov for his help in processing the experimental data on the higher order modes. Finally, we are eager to express special thanks to Prof. J. Madey from Duke University for his interest to the Novosibirsk RF cavity; his order made a good push to this work.

RERERENCES

[1] G. I. Erg et al., "The Project of High Power Free Electron Laser Using Race-Track Microtron-Recuperator", *Preprint BudkerINP 93–75*, Novosibirsk, 1993. To be published also in *Proc. of the EPAC–94*, London, 1994.

[2] V. S. Arbuzov et al., "RF System of the CW Race-Track Microtron-Recuperator for FELs", *Proc. of the 1993 Particle Accelerator Conf. PAC–93*, Vol. 2, p. 1226.

[3] D. G. Myakishev and V. P. Yakovlev, "An Interactive Code SUPERLANS for Evaluation of RF Cavities and Accelerating Structures", *Proc. of the 1991 Particle Accelerator Conf. PAC–91*, Vol. 5, p. 3002.

[4] Komsomolets Factory, 392000 Tambov, Russia.

[5] D. K. Aitken, *Proc. IEE*, **105**, Pt. B, Suppl. 1, p. 824 (1958).

[6] V. G. Veshcherevich et al., "Longitudinal Effects during Storing Process of Electrons in VEPP-3", *Proc. of the Third All-Union Particle Accelerator Conf.*, Vol. 1, p. 397. Moscow, 1973 (in Russian).

[7] Machinery Factory, 633210 Iskitim, Novosibirsk region, Russia.

[8] V. M. Litvinenko et al., "UV–VUV FEL Program at DUKE Storage Ring with OK-4 Optical Klystron", *Proc. of the 1993 Particle Accelerator Conf. PAC–93*, Vol. 2, p. 1442.

[9] M. M. Karliner et al., "Stability Conditions of the Phase Motion of a Bunch in Storage Rings of Relativistic Particles", *J. of Technical Physics*, **58**, No. 11, p. 1945 (1968) *(in Russian)*. See English translation in *Sov. Phys.: Tech. Phys.*, **13**, No. 11 (1968).

[10] M. M. Karliner et al., "Longitudinal Stability of Colliding Beams in e^+e^- Storage Rings with the Account of Beam Coupling with the Environment", *Proc. of the Third Advanced ICFA Workshop on Beam-Beam Effects in Circular Colliders*, Novosibirsk, 1989, p. 131.

N. Gavrilov, I. Kuptsov, G. Kurkin, L. Mironenko,
V. Petrov, I. Sedlyarov, V. Veshcherevich

RF Cavity for the Novosibirsk Race-Track Microtron-Recuperator

Н.Г. Гаврилов, И.В. Купцов, Г.Я. Куркин, Л.А. Мироненко,
В.М. Петров, И.К. Седляров, В.Г. Вещеревич

ВЧ резонатор для разрезного микротрона-рекуператора в Новосибирске

Ответственный за выпуск С.Г. Попов
Работа поступила 21 ноября 1994 г.

Сдано в набор 22 ноября 1994 г.
Подписано в печать 24 ноября 1994 г.
Формат бумаги 60×90 1/16 Объем 1.7 печ.л., 1.4 уч.-изд.л.
Тираж 250 экз. Бесплатно. Заказ N° 92

Обработано на IBM PC и отпечатано на
ротапринте ИЯФ им. Г.И. Будкера СО РАН,
Новосибирск, 630090, пр. академика Лаврентьева, 11.