Joints, Couplers, and Tuners

Ronald M. Sundelin
Cornell University
Ithaca, New York 14853 USA

I. Joints

Only demountable joints will be discussed here, as welded joints are discussed as part of Cavity Fabrication.

Demountable joints are used for several purposes. They are used to connect short structure sections. The use of short sections facilitates fabrication, chemical processing, and firing; it also permits defective sections to be rejected without rejecting the entire structure. Demountable joints are also useful for attaching couplers, tuners, and beam pipes when it may be desirable to remove and alter these objects at a later time, or when the location of these joints makes them accessible for bolting but not welding.

Considerations in the design of demountable joints include avoiding RF losses (by placing the joint at a low field region or by making low loss contact), using a superconducting joint material, avoiding damage to the structure sections, maintaining leak tightness during temperature cycling, avoiding an unpredictable shift in the structure frequency, avoiding contamination of the structure vacuum, and permitting a low temperature bakeout of the system.

The HEPL recyclotron accelerating structures (Fig. 1) are assembled using indium seals.[1] Each structure has $\lambda/2$ cells in the center and $\lambda/3$ cells at the ends, leading to a null in the magnetic field at the joint location. This joint has proven to be satisfactory.

The muffin-tin accelerating structure tested in the Cornell synchrotron[2] (Fig. 2) used the principle of waveguide-beyond-cutoff to produce a low field region for the use of indium seals (Fig. 3). Simultaneous niobium-to-niobium contact outside the seal prevented unpredictable frequency disturbances upon assembly. Some spring was provided to one of the niobium members in contact with the indium to prevent the development of leaks upon temperature cycling. Long tantalum bolts, which provide good strength, an expansion coefficient similar to that of niobium, and springiness by virtue of their length, were used together with conical beryllium copper washers (for additional springiness) and aluminum alloy nuts (to avoid galling) for joint assembly. An exponential taper in the crack leading to the joint was necessary to eliminate resonant stripline modes from this region, which modes otherwise are excited by slight asymmetries in the structure. The indium wire was chemically cleaned to remove the kerosene used in its extrusion. This joint has been satisfactory.

A choke joint (Fig. 4) has been used by Wuppertal[3] to join accelerator sections in an X-band test accelerator. The joint is placed at a nominal null in the magnetic field, and the use of a choke joint provides added insurance against joint losses. Indium is the sealing material. A separate test cavity in which the choke joint could be exposed to high or low magnetic fields demonstrated that its contribution to losses was minimal. Except for one incident in which apparent chemical residues degraded the joint's performance, this joint has been satisfactory. A 65 cell structure employing this joint recently reached an E_{peak} of 41.6 MV/m, B_{peak} of 78.7 mT and Q of $1x10^9$.

A joint with high conductivity is the crocodile joint (Fig. 5) used in the Karlsruhe-CERN separator[4] and in the Karlsruhe-DORIS cavity[5] (Fig. 6). This joint uses a niobium ring with two inwardly protruding niobium rims. These rims deform slightly when the joint is assembled, and provide enough transverse motion to abrade through the oxide layer and provide excellent electrical contact. Vacuum sealing is provided by indium seals outside the RF joint. Long bolts are used to provide springiness. This joint has been found to reliably support fields in excess of 7 to 20 mT. This property is important in the separator not only because cell tuning imperfections cause fields in nominally empty cells, but also because it has been found useful to operate the separators in different modes to accommodate different velocity beams. The crocodile sealing rings are prepared by rough machining, annealing at 1200°C for 2-3 hours, fine machining with trichloroethane, and etching in cold polish for 30 seconds.[6] It has been found advisable to slightly change the diameter of the contact location on successive assemblies because the structure surface is dented by the sealing ring. The crocodile joints provide satisfactory performance; their principal disadvantages are that they are difficult to machine, can be used only once, that the structure sealing surface must be remachined after no undented sealing regions remain, and that the cell frequency disturbance caused by the joint is somewhat unpredictable.

Another style of high conductivity joint developed at Karlsruhe[5] has proven to be unsatisfactory. This joint consisted of a niobium ring with an H-shaped cross-section placed in a hexagonal groove. The primary problem with this joint was that the ring was not self-aligning, and did not provide uniform azimuthal contact. It was also in poor contact with the liquid helium[6].

An H-shaped gasket (Fig. 7) is used to seal the end plates to the Argonne split-ring accelerator structures[7]. The gasket and structure are made of niobium, and the joint will support a field in excess of 2 mT, which is quite adequate for use in the split ring resonator. Conical spring washers are used in assembly.

Several materials other than indium have been used as vacuum sealing materials.

The Cal Tech-Stony Brook split-ring lead plated accelerator[8] uses indium to seal the resonator end plates, but uses a Sn-In alloy to seal the split ring to its housing.

The Karlsruhe-CERN separator[9] uses Kapton windows to separate the structure and insulating vacua, and to separate the insulating and beam pipe vacua.

The CERN LEP cavity[10] uses lead joints at the end of cut-off tubes to permit baking at 200°C, but this seal has not yet been subjected to a large number of temperature cycles.

In summary, a number of demountable joints have been devised which do not appreciably degrade the performance of the structures in which they are used. It is clear that an even higher conductance joint would simplify cavity construction, but the absence of such a joint is not limiting progress in superconducting RF.

II. Couplers

Couplers used on superconducting cavities are used to couple either fundamental frequency power or higher mode power. First consider fundamental frequency couplers designed to handle moderate to high levels of RF power.

Primary considerations in the design of high power input couplers include simultaneous minimizing of thermal conduction losses and RF heating losses in the portions of the feedline connecting the LHe temperature structure to the LN_2 temperature structure, and the LN_2 temperature structure to the room temperature structure, minimizing refrigerator loading caused by window dissipation, minimizing magnetic and electric field enhancements in the cavity, avoiding multipacting engendered by perturbing the cavity fields, avoiding interferences with the cryostat assembly associated with the feed line penetration, avoiding resonances associated with unwanted transmission modes within the line, avoiding multipacting at the ceramic windows, providing variable coupling if required, and providing damping of other modes if required.

The HEPL recyclotron[11] has a hybrid coaxial and waveguide coupling system capable of coupling several kilowatts into the beam in each structure. This system works well, except that some of the feed-throughs have been found to have miniscule helium leaks which shift the frequency of the structure[12].

The Cornell 11-cell S-band muffin-tin structure tested in the synchrotron[2] at 4 GeV used a coaxial electric probe (Fig. 2) which provided variable coupling. The center conductor of this probe entered the cut-off region from the side. and was in line with the iris between two cells. The center conductor was maintained at LN_2 temperature, with a transition to room temperature. The outer conductor used a stainless steel bellows for the transition from

LHe to LN_2 temperatures. This probe was capable of handling 1 kW, and provided satisfactory performance.

The Karlsruhe-DORIS cavity[13], incorporates a coaxial magnetic probe (Fig. 8) in which the LHe to LN_2 and LN_2 to room temperature transitions use inner and outer choke joints. One window is at LN_2 temperature and a second at room temperature. A field transformer is used in conjunction with the coaxial loop. Care has been taken to keep the VSWR of each probe section below 1.02. This probe is being prepared for high power testing.

Wuppertal has developed a hybrid waveguide and coaxial coupler[14]. (Fig. 9.) The center conductor of the coaxial line is hollow and is coaxial with the beam line, providing a passage for the beam. This type of coupler has the advantages that it minimally disturbs the fields within a cell, and does not destroy the axial symmetry in the neighborhood of the cells. It can be made to have variable or fixed coupling. The problem of providing a thermal break in the center conductor between LHe and LN_2 temperatures is eliminated because the entire center conductor is at LHe temperature. One disadvantage of this type of coupler is that, if the coaxial line diameter is large, modes other than the TEM can propagate, and the line length must be made non-resonant for these other modes.

A coupling system for a muffin-tin cavity (Fig. 10) is being developed at Cornell[15] to handle 60 kW at 1500 MHz. The cavity consists essentially of eleven cells, with the bottom of one of the cups replaced with a waveguide which acts as a continuation of the cup. A ceramic waveguide window at LN_2 temperature will be used. Copper plated stainless steel waveguide will be used for the two heat breaks.

Higher mode damping requirements vary greatly depending on the nature of the accelerator. For some accelerators, no damping other than that provided by the main power coupler and the finite accelerator Q is required. Linacs require relatively little coupling, as transverse instabilities are caused primarily by the propagation of higher mode power from the beam output end of the structure toward the beam input end. The required damping is relatively small, and is proportional to the square of the length of the accelerating structures. Recyclotrons and microtrons require more extensive damping because the beam, deflected on its first pass, tends to amplify its generation of higher mode power on each successive pass. Operation with integer or half-integer optics helps to suppress this effect. Storage rings require even more extensive damping because integer and half-integer optics are not stable, the currents tend to be much higher, and longitudinal instabilities require damping because synchrotron oscillations are present. Operation with a long time between bunch passages reduces the damping requirements.

General considerations in the design of higher mode damping probes include determining the required damping for each mode, selecting accessible locations in the structure where the modes requiring the most damping have the highest fields, determining whether or not the higher mode propagation between cells is sufficient (transmission stop-bands can occur at certain frequencies), and minimizing the number of probes required to achieve the necessary damping. The probes can be electric, magnetic, or hybrid electric and magnetic, or some combination of these types. The hybrid can sometimes be used to advantage to increase the coupling to modes requiring damping while decreasing the coupling to the fundamental mode. Notch filters, sometimes incorporated directly into the coupling mechanism, are used to avoid damping the fundamental mode; it is important that the filter location be such that no part of the coupling structure is resonant at the fundamental frequency. Electric and magnetic field enhancement near the coupling probe should be minimized, and probe-engendered multipactoring needs to be avoided. Transverse modes have two orthogonal polarizations, and care must be taken that a probe does not alter the polarization axes in such a way that one polarization is not coupled by the probe.

Regenerative beam break-up has been encountered in the HEPL linac and recyclotron[11]. A combination of 16 H_z, H_θ, and E_r probes (Fig. 1) were adequate to damp the break-up modes in a 23 cell structure and permit the one-pass acceleration of a 100μA CW electron beam. The required Q_{ext} values were typically 10^8. The H-probes are equipped with half-wave stub notch filters to reject the fundamental mode; the E_r probes, by virtue of their location, have intrinsic rejection. The probe and filter are niobium to avoid excessive refrigerator loading; the coaxial niobium center conductor is conduction cooled. The probe tips are 3 to 4 mm outside the cavity. A total of 52 modes in the TM_{01}, TE_{11}, and TM_{11} bands were considered to be potentially dangerous, and were measured and provided with adequate damping.

Upon recirculation, additional modes were found troublesome in the Illinois-HEPL microtron[16]. A hybrid E and H probe is being used to damp these modes. The break-up threshold in the HEPL recyclotron[11] has also been found to decrease as the number of turns increases.

The Karlsruhe-DORIS cavity[13] is equipped with two Szecsi couplers (Fig. 11). These couplers damp all modes with frequency less than four times the fundamental to a Q_{ext} of less than $10.^4$ The couplers use field transformers and coaxial loops, followed by an exponentially tapered coaxial line. The geometry of these components is such that the fundamental is rejected with better than 50 dB rejection, and higher modes are well matched to an external load. Work on these couplers is continuing.

As previously mentioned, the Wuppertal[14] fundamental coupler damps higher modes, a process which is helped by the large beam holes between cells.

One probe (Fig. 12) is presently used per cell on each of the normal conducting Cornell CESR cavities[17], together with a separate polarizing stub elsewhere in the cell. Damping requirements in this case are particularly stringent, since the bunch spacing during injection is 42 nsec with anticipated currents up to 94 mA. Q_{ext} values below 10^2 are achieved for some modes, and all modes are adequately damped. The coupling loop is an E and H hybrid. A concentric copper coaxial notch filter provides a fundamental rejection of 56 dB. The two-stage design of this filter avoids additional notches below 4 times the fundamental frequency. This probe,which has been operated in a structure with E_{acc} = 1.62 MeV/m, CW,could be readily adapted for superconducting use, although its implications for multipacting enhancement are not known in the superconducting case.

A niobium loop coupler has been tested in an S-band muffin-tin structure at Cornell. This structure exhibited a low Q value which further decreased as the power was increased. This problem is attributed to difficulties in making, bending, and welding the small tube which forms the center conductor. However, further investigations of this problem have not yet been made.

A slot coupler, designed to couple to H_z (Fig. 10),has been tested in an S-band muffin-tin cavity at Cornell.[15] This slot penetrates the cup bottom and also enters the end of a waveguide which propagates the higher modes, but not the fundamental. This structure yielded an E_{acc} of 5 MV/m and a Q_0 of greater than $2x10^9$. Three subsequent tests with an H_x coupler yielded,at best, an E_{acc} of 2 MV/m and a Q_0 of $1.5x10^9$. This coupler causes a 60% local field enhancement. The breakdown was magnetic, and is under investigation. Both of these tests used cups with grooved bottoms to suppress multipacting. Room temperature measurements on both of these couplers has shown that one of each type in a 5-cell 1500 MHz structure would be nearly sufficient to prevent transverse and longitudinal instabilities if used in CESR at 5.5 GeV with a 60 mA beam having a 2.5μsec passage interval.

Higher mode couplers have become an extremely complex problem as the required damping has increased with the application of superconducting RF to high current e^+e^- storage rings. The only relief in sight comes from the increased damping time permitted by low rates of bunch passage.

III. Tuners

Permanent tuning methods, slow dynamic tuners, and fast dynamic tuners will be discussed. Requirements depend on the number of cells, intercell coupling, operating mode, structure rigidity, vibration sources, reactive beam loading, and loaded bandwidth.

Permanent fine tuning on the HEPL recyclotron[11] structures has been performed by selectively cold polishing various cells of the structure. Bead pulls taken between polishing cycles are processed using a computer to indicate the degree of etching required in each cell.

A similar process has been used in the Cornell 11 cell muffin-tin structure[18] using differential and integral electropolishing. Differential electropolishing was accomplished by using a tight Teflon barrier between cells. A field flatness of ±0.4% was achieved.

More recent Cornell muffin-tin structures made out of stamped sheet niobium[19] have been tuned by deforming the cup bottoms. This is a simple process because the cup bottoms are flat.

Slow dynamic tuners in use consist of plungers or elastic squeeze tuners. Care must be used to avoid coupling vibrations into the structure and to avoid a large, partially isolated thermal mass.

Plungers (Fig. 13) have been used in the Karlsruhe-CERN separator[9]. One coarse and one fine tuner is used per section. One problem encountered is that a change in tuner position induces multipacting, which subsequently processes away. Tuning during beam operation has been found to be unnecessary.

Wuppertal has used motor-driven squeeze tuners to deform thin-walled regions in their 8 GHz structure[14], and plans to use axial squeezing to tune a bellows-shaped S-band structure by ±200 KHz[20] (Fig. 14).

Cornell used a motor driven squeeze tuner to tune its 11-cell S-band muffin-tin structure.[2] The structure was designed so that the cup region was rigid, but could be moved elastically relative to the opposite cup region. The motor drive was linked through an elastic member so that small motor motions would not represent a large frequency change. Dynamic tuning under beam conditions was done, but was not found to be necessary. A small amplitude frequency modulation with a 33 Hz period was observed, but its origin was never determined.

Karlsruhe uses motor driven squeeze tuners on its helix accelerator[21]. End plate deformation is employed.

The Cal Tech-Stony Brook lead plated split ring cavities[8] also use end plate squeeze tuners.

The Karlsruhe-DORIS cavity[13] uses an end plate squeeze tuner linked through a flexible band.

Fast dynamic tuners are used when frequency shifts caused by vibrations, radiation pressure, ponderomotive forces, or beam loading can cause a frequency shift which is a significant fraction of a cavity's loaded bandwidth.

The Karlsruhe helical accelerator[22] uses feedback on amplitude and on a voltage controlled reactance to stabilize the structure against ponderomotive oscillations which would otherwise occur. This same feedback also reduces the effects of external vibrations. The reactances are switched in and out by a set of PIN diodes.

The Argonne split ring accelerator[23] also uses a voltage controlled reactance, switches by pin diodes.

Wuppertal[14] has used piezoelectric tuners on thin-walled portions of cavities and is planning to use them on an S-band structure (Fig. 14) to obtain a range of ±4 KHz[20].

In conclusion, tuners have been devised which satisfactorily meet the requirements of all intended applications.

Acknowledgments:

The author wishes to thank P. Kneisel, W. Bauer, H. Lengeler, W. Weingarten, C. Lyneis, and K. Shepard for supplying information for this paper.

REFERENCES

1) K. Mittag, H. A. Schwettman, and H. D. Schwarz, "Beam Break-up in a Superconducting Electron Accelerator," HEPL-685 (1972), High Energy Physics Laboratory, Stanford University, and Proceedings of the 1972 Proton Linear Accelerator Conference, Los Alamos, New Mexico.

2) J. Kirchgessner, H. Padamsee, H. L. Phillips, D. Rice, R. Sundelin, M. Tigner, and E. von Borstel, "Superconducting Cavities for Synchrotron Use," IEEE Transactions on Nuclear Science, Vol. NS-22, No. 3, June 1975, p. 1141.

3) H. Heinrichs and W. Weingarten, "An RF Contact for Superconducting Cavities", Nuclear Instruments and Methods 171 (1980), p. 185.

4) M. Grundner, H. Lengeler, and E. Rathgeber, "RF Contact for Superconducting Cavities," Nuclear Instruments and Methods 141 (1977), p. 57.

5) W. Bauer, private communication.

6) P. Kneisel, private communication.

7) K. Shepard, private communication.

8) J. R. Delayen, G. J. Dick, J. E. Mercereau, J. W. Noe, P. Paul and G. D. Sprouse, "Status of the Stony Brook Superconducting Heavy-Ion Linac", IEEE Transactions on Nuclear Science, Vol. NS-26, no. 3, June 1979, p. 3664.

9) A. Citron, G. Dammertz, M. Grundner, L. Husson, R. Lehm, and H. Lengeler, "The Karlsruhe-CERN Superconducting RF Separator", Nuclear Instruments and Methods 164 (1979), p. 31.

10) H. Lengeler, private communication.

11) C. M. Lyneis, M. S. McAshan, R. E. Rand, H. A. Schwettman, T. I. Smith, and J. P. Turneaure, "The Stanford Superconducting Recyclotron," IEEE Transactions on Nuclear Science, Vol. NS-26, no. 3, June 1979, p. 3246.

12) C. M. Lyneis, J. Sayag, H. A. Schwettman, and J. P. Turneaure, "Performance of a Superconducting Accelerating Structure with a Modified Geometry," IEEE Transactions on Nuclear Science, Vol. NS-26, no. 3, June 1979, p. 3755.

13) W. Bauer, A. Brandelik, A. Citron, W. Lehmann, L. Szecsi, and M. Yoshioka, "Superconducting Accelerating Cavities for High Energy e^+e^- Storage Rings," IEEE Transactions on Nuclear Science, Vol. NS-26, no. 3, June 1979, p. 3252.

14) G. Arnolds, H. Heinrichs, R. Mayer, N. Minatti, H. Piel, and W. Weingarten, "Design and Status of an Experimental Superconducting Linear Accelerator for Electrons." IEEE Transactions on Nuclear Science, Vol. NS-26, no. 3, June 1979, p. 3775.

15) J. Kirchgessner, P. Kneisel, H. Padamsee, J. Peters, D. Proch, R. Sundelin, and M. Tigner, "Design Studies for a 1500 MHz Superconducting Accelerator Cavity for use in an e^+e^- Storage Ring," to be presented at the XIth International Conference on High Energy Accelerators, CERN, Geneva, 1980.

16) P. Axel, L. S. Cardman, H. D. Graef, A. O. Hanson, R. A. Hoffswell, D. Jamnik, D. C. Sutton, R. H. Taylor, and L. M. Young, "Operating Experience with MUSL-2," IEEE Transactions on Nuclear Science, Vol. NS-26, no. 3, June 1979, p. 3143.

17) R. M. Sundelin, J. L. Kirchgessner, and M. Tigner, "Parallel Coupled Cavity Structure," IEEE Transactions on Nuclear Science, Vol. NS-24, no. 3, June 1977, p. 1686.

18) R. M. Sundelin, J. Kirchgessner, H. Padamsee, H. L. Phillips, D. Rice, M. Tigner, and E. von Borstel, "Application of Superconducting RF Accelerating Sections to an Electron Synchrotron-A Progress Report," Proceedings of the IXth International Conference on High Energy Accelerators, Stanford Linear Accelerator Center, Stanford, CA (1974), p. 128.

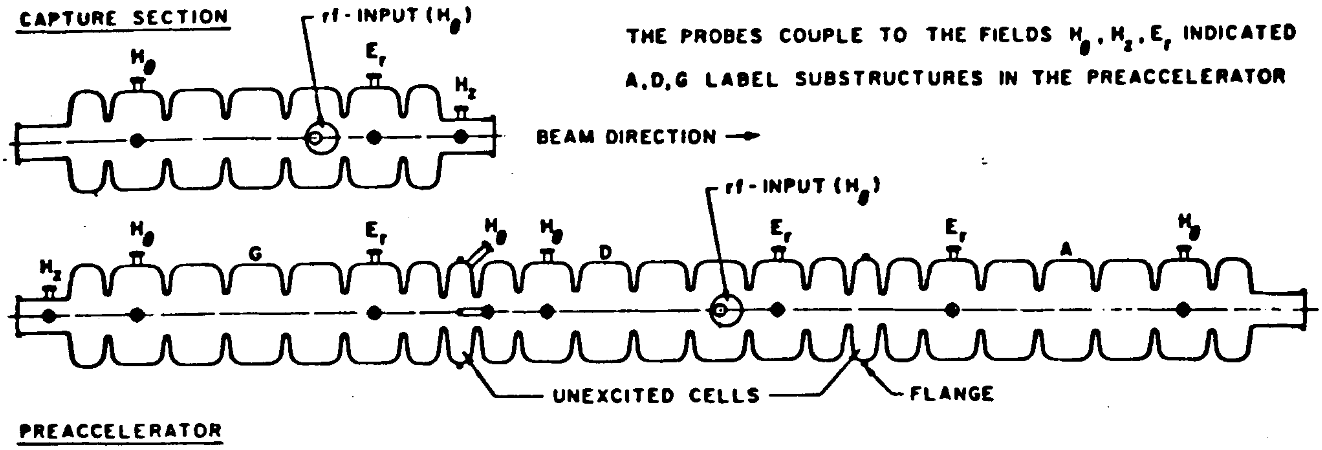
19) H. Padamsee et al., IEEE Trans., MAG-13 (1977), p. 346.

20) W. Weingarten, private communication.

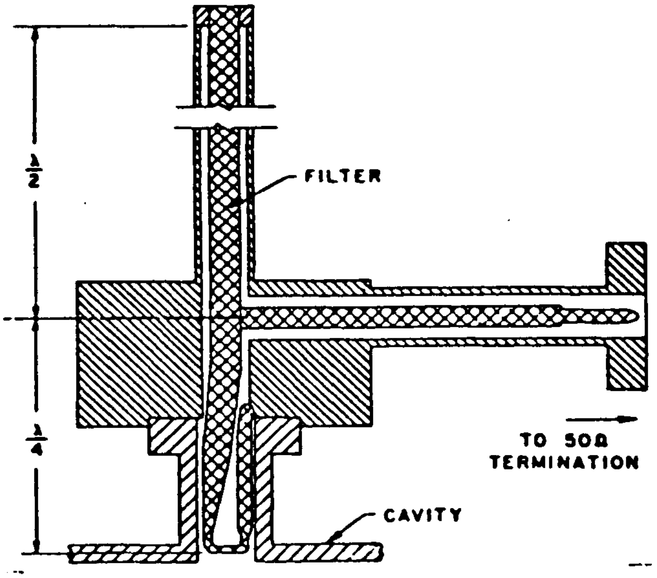
21) A. Citron, M. Kuntze, A. Brandelik, W. Herz, R. Hietschold, A. Hornung, W. Kuhn, D. Schulze, and K. W. Zieher, "Performance of the Karlsruhe Superconducting Proton Linear Testaccelerator," IEEE Transactions on Nuclear Science, Vol. NS-26, no. 3, June 1979, p. 3751.

22) D. Schulze, A. Hornung, and P. Schlick, "Progress in Electronic Frequency Control of Superconducting Helix Resonators," IEEE Transactions on Nuclear Science, Vol. NS-26, no. 3, June 1979, p. 3748.

23) K. W. Shepard, "Initial Operation of the Argonne Superconducting Heavy-Ion Linac," IEEE Transactions on Nuclear Science, Vol. NS-26, no. 3, June 1979, p. 3659.



Schematic of the Cryogenic Injector.



Schematic of Band-stop Filter.

Fig. 1

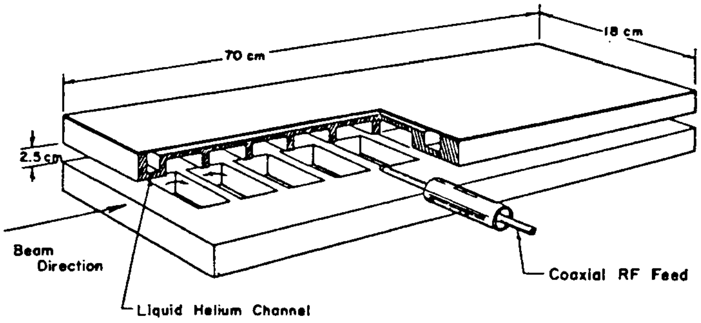
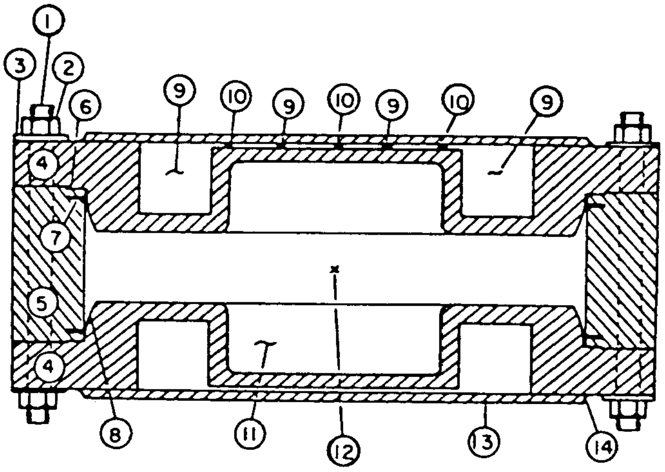
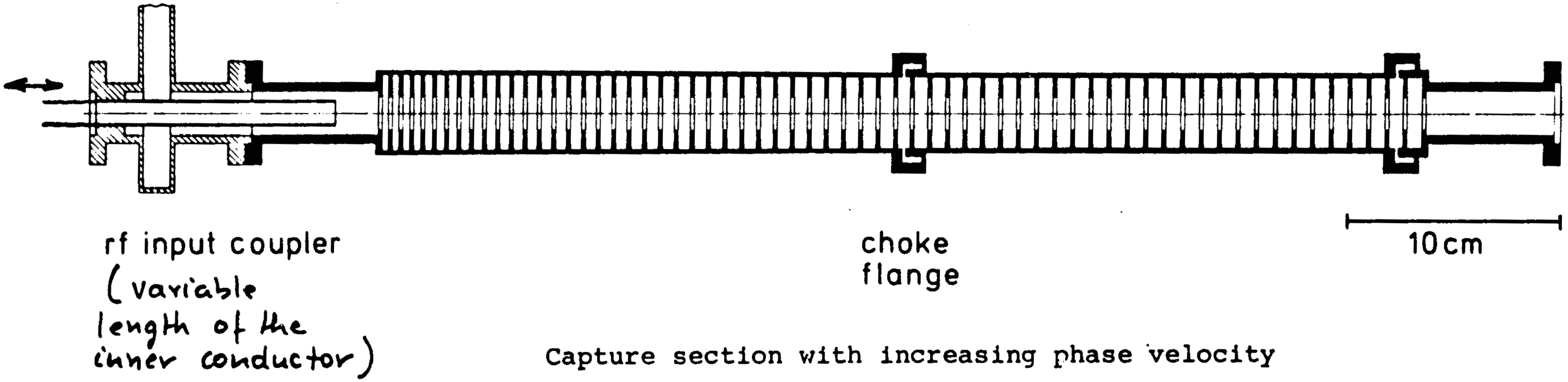


Fig. 2



1. Ta bolt
2. Al nut
3. Spring washer
4. Nb cavity half
5. Spacer ring
6. In wire seal
7. Spring slot
8. Exponential slot
9. He channel
10. Spacer pad
11. Cavity cell
12. Beam line
13. Nb back plate
14. Electron beam weld

Fig. 3



Capture section with increasing phase velocity

8 GHz

Fig. 4

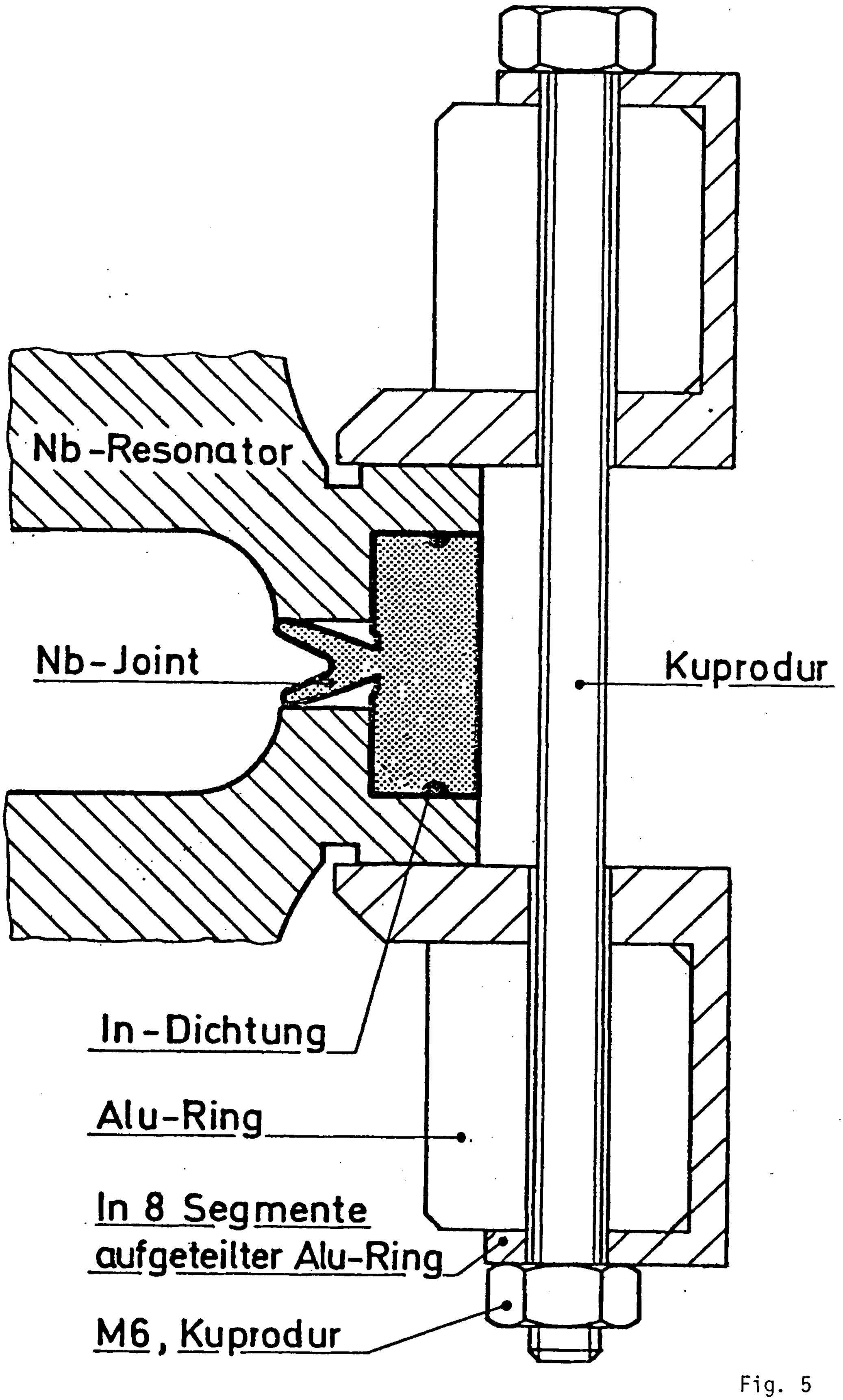

Nb-Resonator
Nb-Joint
Kuprodur
In-Dichtung
Alu-Ring
In 8 Segmente aufgeteilter Alu-Ring
M6, Kuprodur

Fig. 5

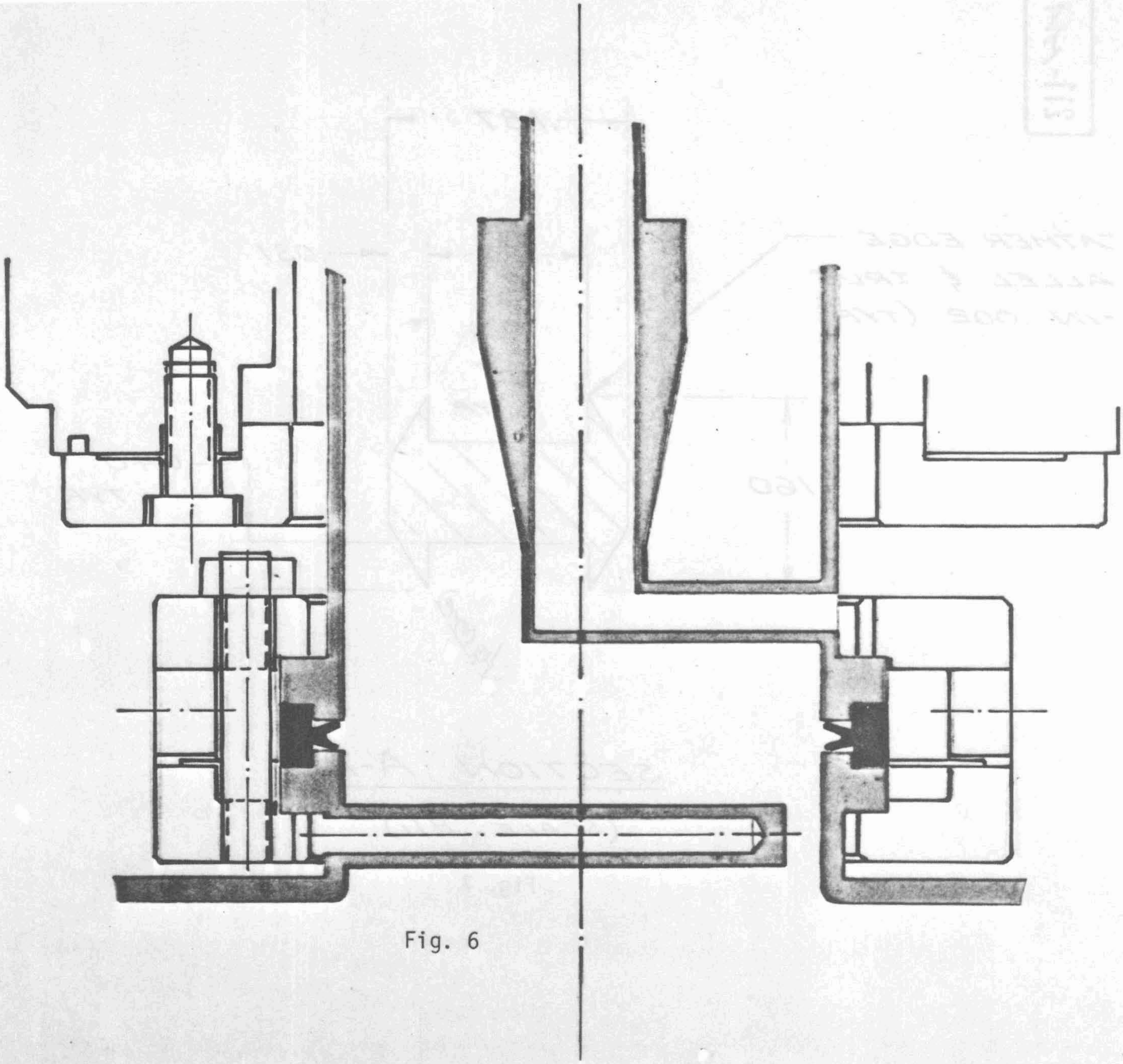


Fig. 6

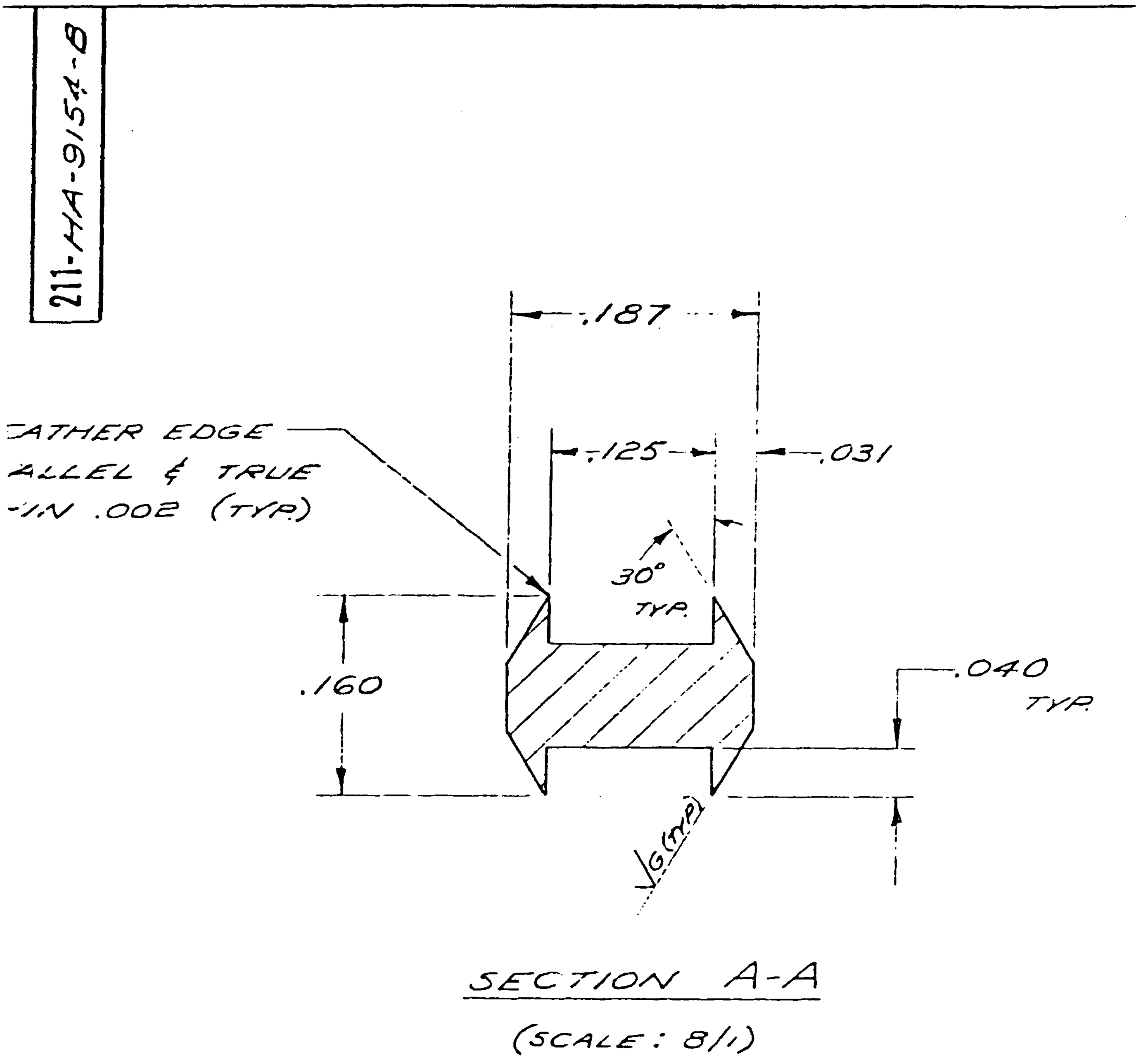
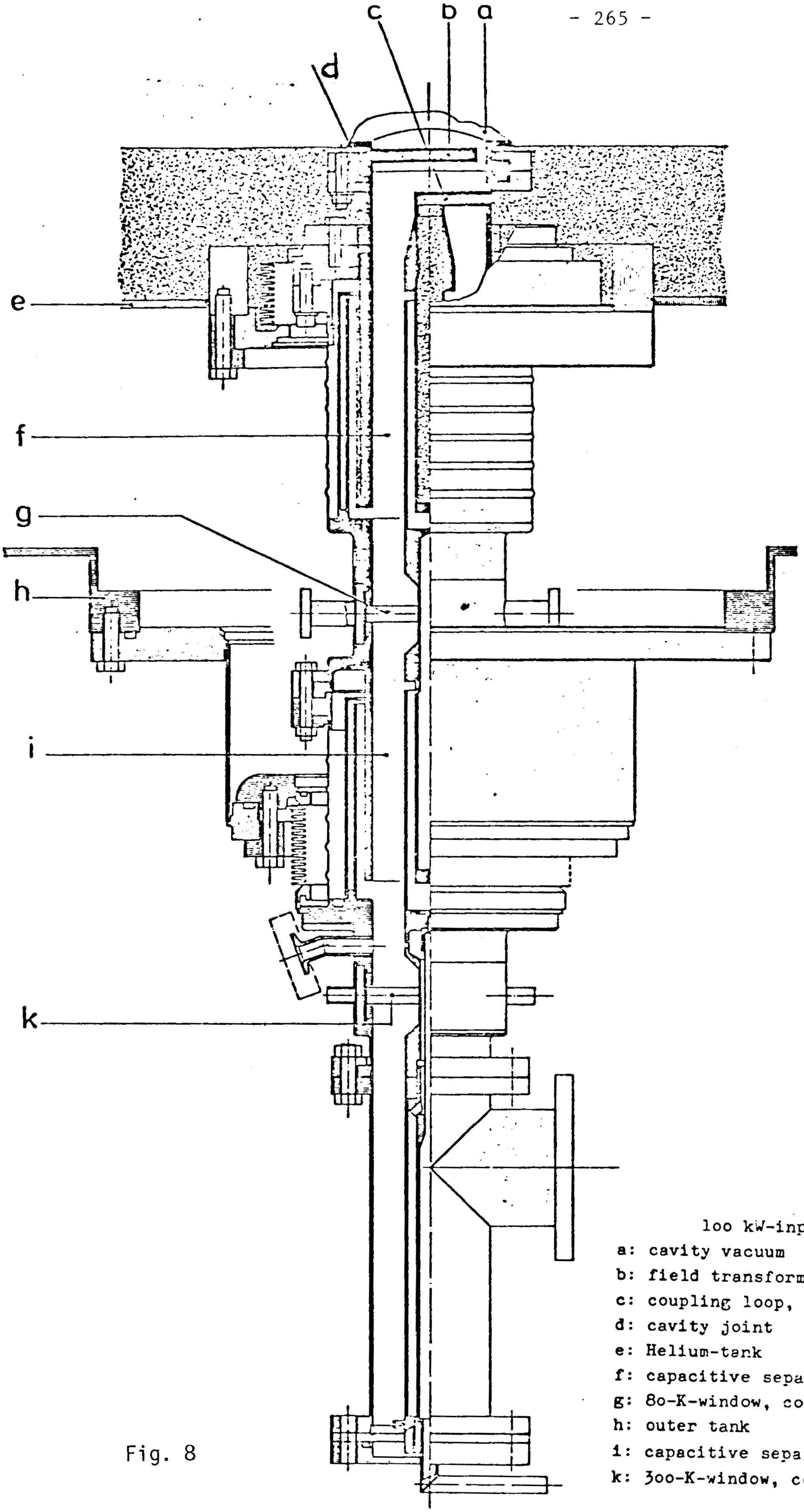

211-HA-9154-B
.187
ATHER EDGE
ALLEL & TRUE
IN .002 (TYP)
.125
.031
30° TYP.
.160
.040 TYP.
G (TYP)
SECTION A-A
(SCALE: 8/1)

Fig. 7



1oo kW-input coupling

a: cavity vacuum
b: field transformer, flooded with lHe
c: coupling loop, " " "
d: cavity joint
e: Helium-tank
f: capacitive separation 4K/8oK
g: 8o-K-window, cooled by lN_2
h: outer tank
i: capacitive separation 8oK/3ooK
k: 3oo-K-window, cooled by water.

Fig. 8

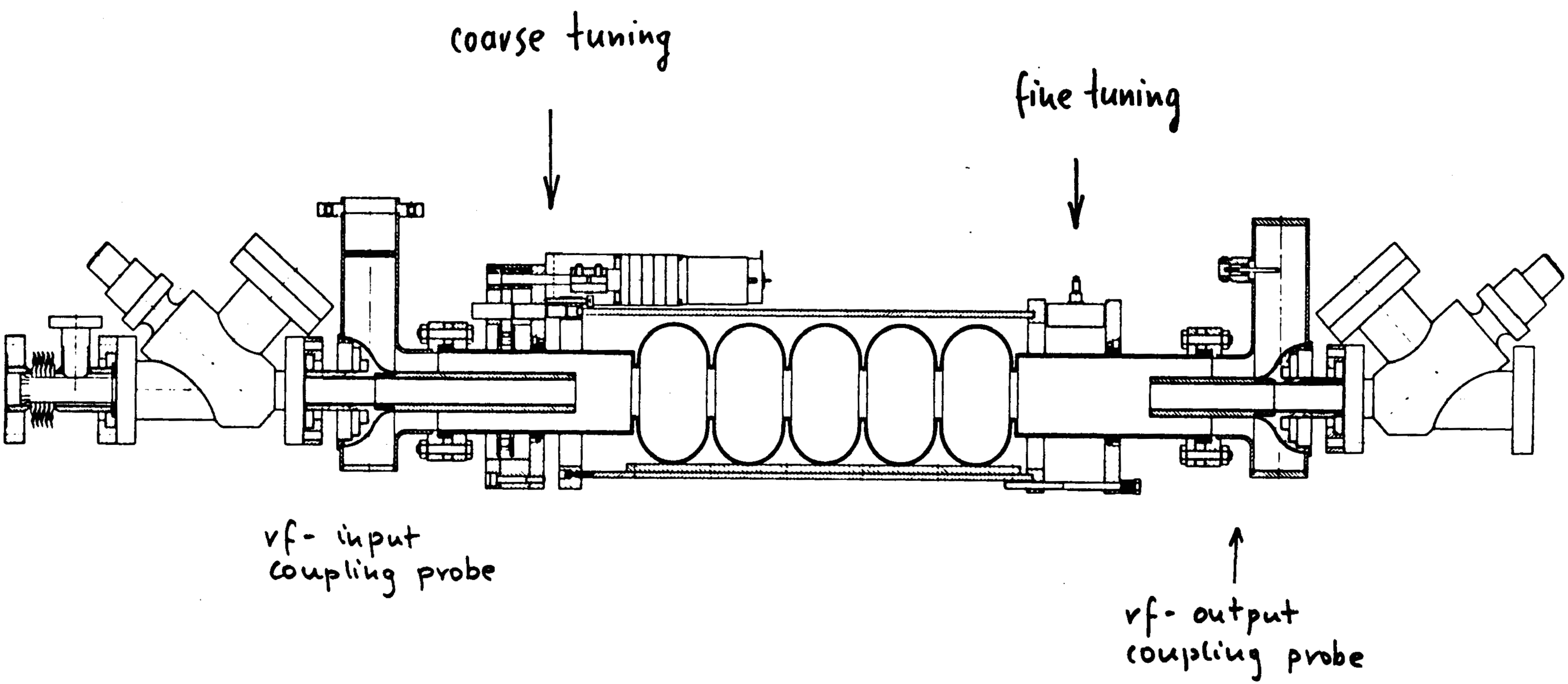


Fig. 9 Die fünfzellige Struktur mit Frequenzabstimmung und Ein- und Auskopplung

This 3GHz - structure
is now being built at
Interatom - company, Bergisch-
Gladbach 2, W. Germany

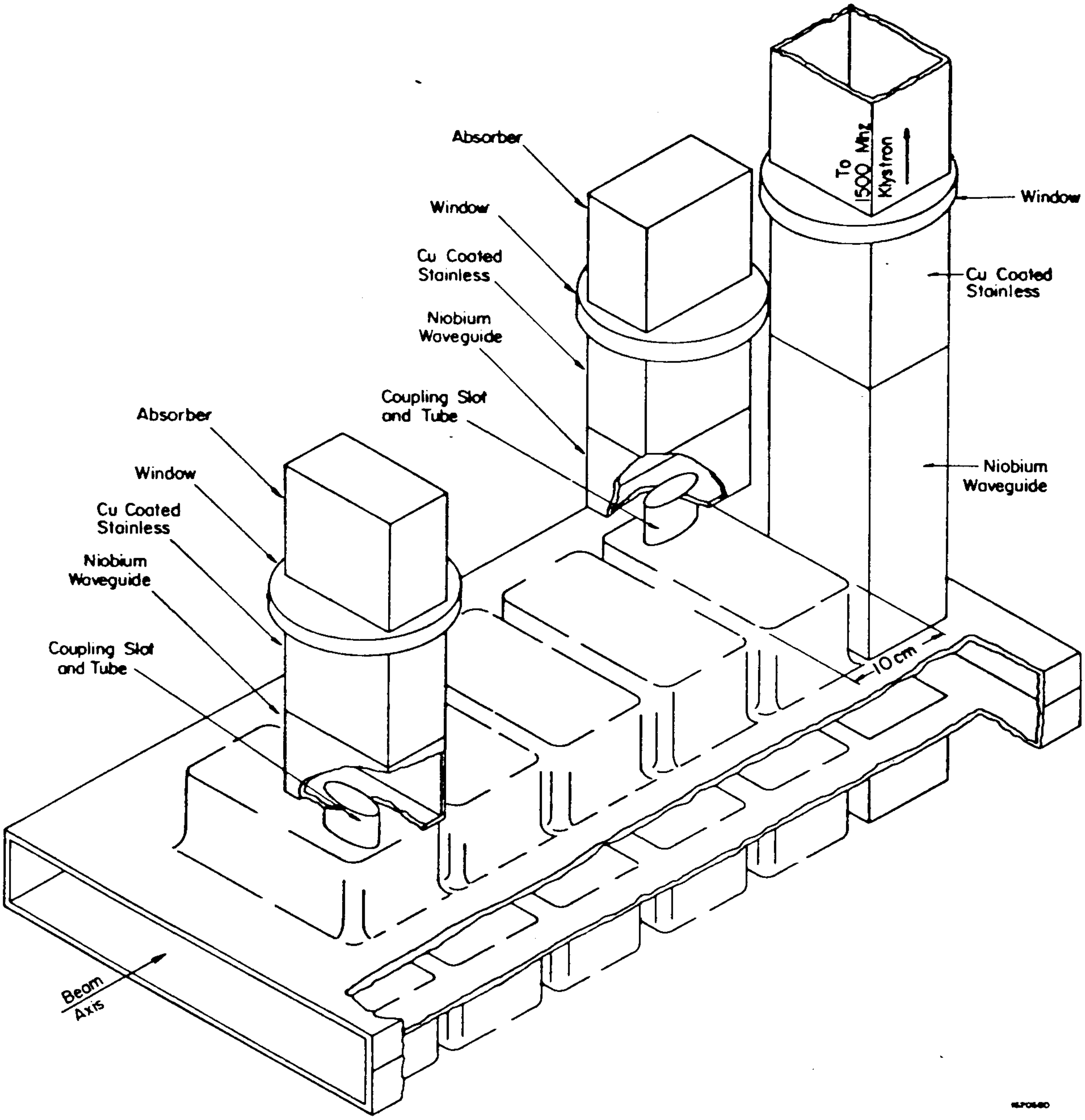
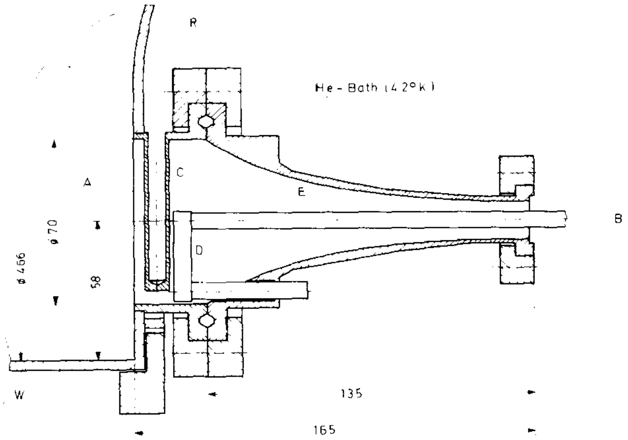

Absorber
Window
Cu Coated Stainless
Niobium Waveguide
Coupling Slot and Tube
Absorber
Window
Cu Coated Stainless
Niobium Waveguide
Coupling Slot and Tube
To 1500 Mhz Klystron
Window
Cu Coated Stainless
Niobium Waveguide
10 cm
Beam Axis

Fig. 10

Fig. 11: Higher mode output coupler developed by Szecsi

A: cavity interiour,
B: coaxial line
C: field transformer
D: coupling loop
E: exponential outer conductor of coaxial line
R: cavity endplate
W: cavity cylinder wall



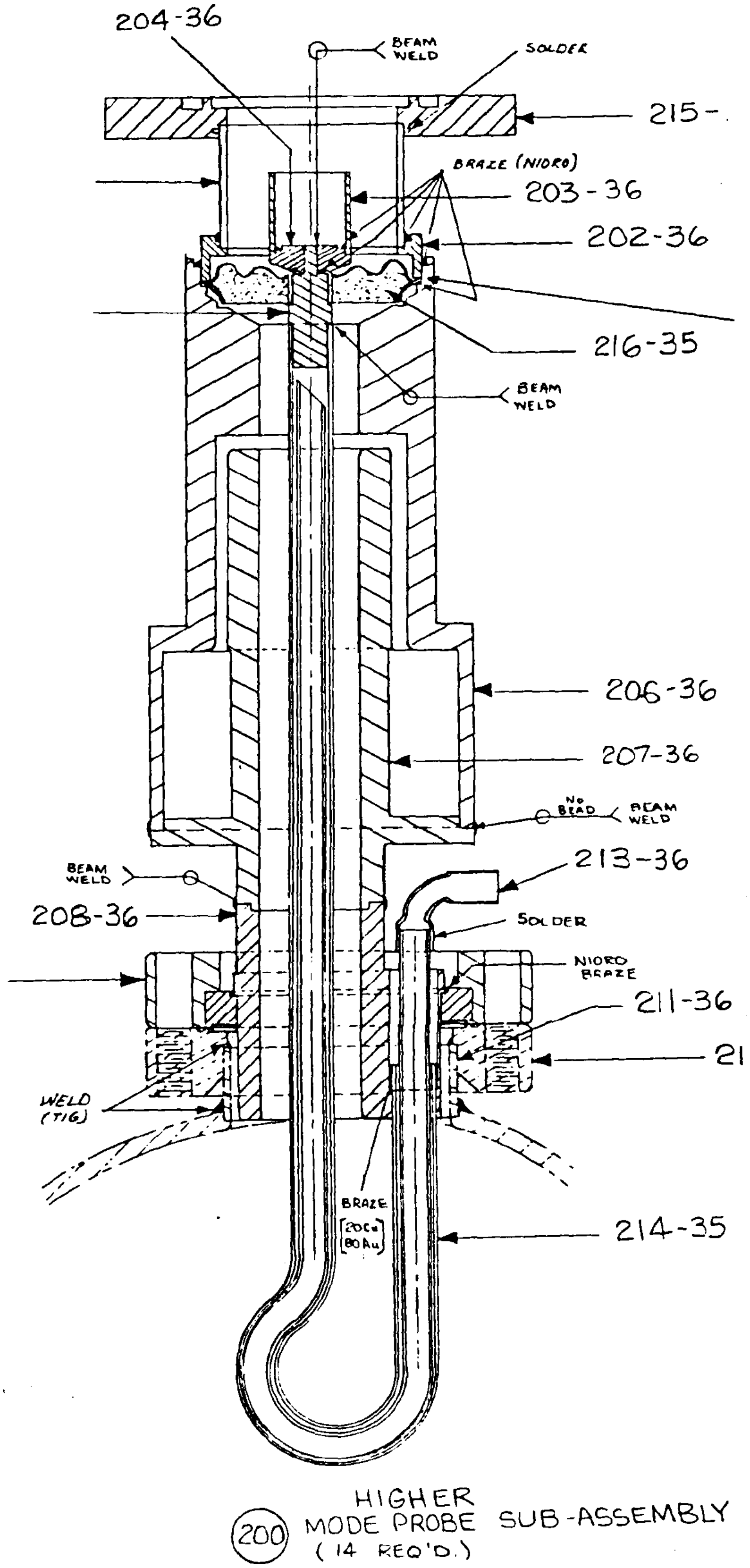
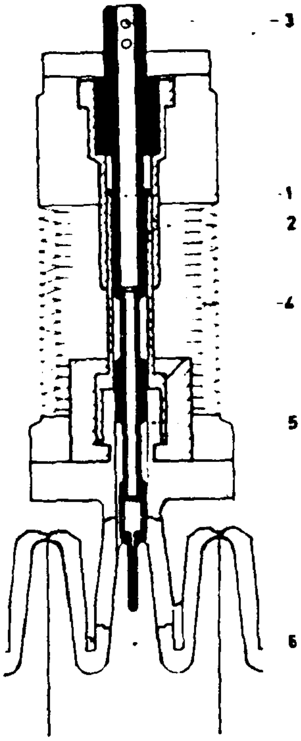

204-36
BEAM WELD
SOLDER
215-
BRAZE (NIORO)
203-36
202-36
216-35
BEAM WELD
206-36
207-36
NO BEAD
BEAM WELD
BEAM WELD
213-36
208-36
SOLDER
NIORO BRAZE
211-36
21
WELD (TIG)
BRAZE
20Cu
80Au
214-35
HIGHER MODE PROBE SUB-ASSEMBLY
200
(14 REQ'D.)

Fig. 12



Mechanical layout of a frequency tuner (fine tuner) (1) Nb-plunger with a cooling channel, (2) Cu-guiding cylinders, (3) hole for He-II entry, (4) bellows, (5) Nb-cylinder of deflector and (6) tuner cell.

Fig. .13

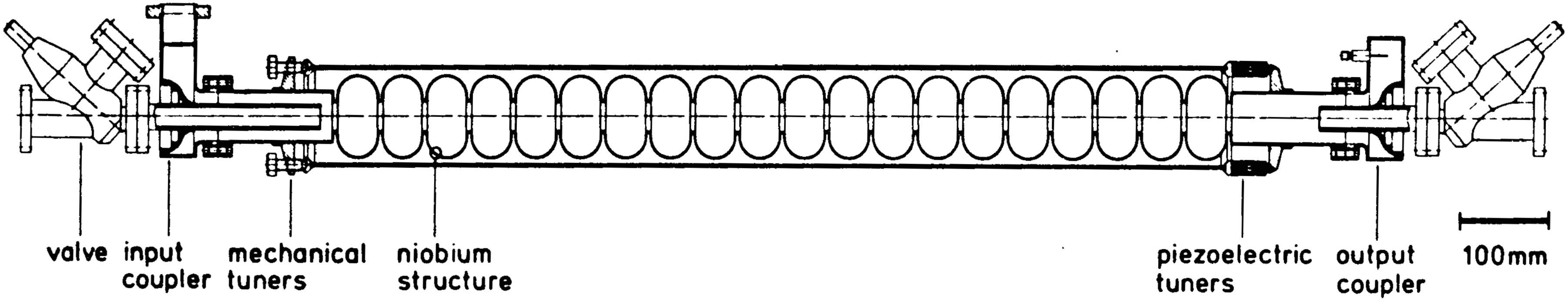


Fig. 14 Die 1m- Struktur mit Frequenzabstimmung und Ein- und Auskopplung

This 3 GHz -structure is ordered now.