BNL-104755-2014-TECH

AGS/AD/Tech Note No. 339;BNL-104755-2014-IR

AGS CAVITIES UPGRADE: COUPLING THE POWER AMPLIFIER TO THE CAVITY

W. Pirkl

June 1990

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

Accelerator Division
Alternating Gradient Synchrotron Department
BROOKHAVEN NATIONAL LABORATORY
Upton, New York 11973

Accelerator Division
Technical Note

AGS/AD/Tech. Note No. 339

AGS CAVITIES UPGRADE: COUPLING THE POWER AMPLIFIER TO THE CAVITY

W. Pirkl*

June 11, 1990

Introduction

The AGS cavities will be upgraded to accept the high intensity proton beam coming from the Booster. Lowering the output impedance is of paramount importance and all the schemes proposed to this end (low impedance tube, local feedback, local feedforward) rely on the mounting of the final amplifier near to the cavity. A coupling link has to be developed.

This amplifier-cavity coupling is constrained by a number of conditions. Three possibilities have been investigated in detail and implemented in low level on the test cavity. Measurement data are presented and the results discussed.

1.0 General

The AGS cavities had been initially designed to be driven from a remote rf amplifier via coaxial cables. Their four-gap structure is optimized for this mode, but less suitable for direct amplifier connection. If to be redesigned from scratch, one would certainly choose a two-gap structure with provisions for proper phasing, such as the new cavities designed for the Booster. In maintaining the present configuration, the following points have to be considered:

- assure push-pull operation of the gaps while driving the cavity from a single-ended amplifier, with voltage ratio about 1/1,

- minimize resonances seen by the beam or the amplifier, inside and beyond the operating frequency range (1.7 to 4.5 MHz),

*CERN.

- find solutions which fit into the very restricted space inside the cavity and which withstand high radiation doses.

The three most promising schemes (and a subscheme) have been retained for detailed investigations from a larger number of possibilities; they are represented in Figures 1.A to 1.D and discussed below.

2.0 The Different Coupling Schemes

2.1 **Transformer Coupling (Figure 1.A)**

The creation of a second voltage component of opposite phase, complementing the component directly available at the amplifier output, is achieved by a line-type autotransformer. This scheme allows the reduction of stray inductance to less than half as compared with the usual configuration of a primary with separated double secondary windings.

The main problems are the magnetic core and the insulation. Coreless designs would present a much too large winding length creating parasitic resonances within the operating frequency band. The insulation, on the other hand, has to exhibit low rf losses, low capacitance and high radiation resistance. Liquid dielectric would introduce additional complications when operated in the tunnel; dry dielectrics that are radiation resistant like Polyimides (Kapton) would necessitate special cooling to prevent their thermal runaway.

The design sketched in Figure 2 uses ferrite bricks of material 4L2 as magnetic core. This material has the best combination of permeability and power handling capability; the shape of available bricks allows the assembly of a core which can probably be operated with natural cooling since the power density remains below 0.1 W/cm^3 under CW operating conditions at 3.5 MHz. The primary and secondary windings consist of copper tubes with outside diameter of 7/8 inch (12.7 mm) spaced 9/32 inch (7.14 mm) apart. The voltage-holding capability of this configuration is sufficient under normal ambient conditions, but it is proposed to pressurize the assembly with dry air or nitrogen for additional operating reliability. This solution circumvents the above-mentioned problems with minimum expenditure, but necessitates nevertheless an enclosure (pressurized by a gas cylinder) together with three rf feedthroughs.

A low-level transformer with a single window-frame core has been used for the comparative measurements. It models a high-power transformer capable of full-voltage operation down to about 3.5 MHz. The extension in frequency range down to 1.7 MHz requires an increase in the number of turns and leads to proportionally increased parasitic elements; the parasitic resonance will therefore come closer to the operating frequency range than shown in the figures.

2.2 "Distributed" Transformer (Figure 1.B)

A variant of the line transformer with several turns, this solution uses a single-turn line enclosed by 4C4 ferrite toroids (which are no longer catalog items but may be manufactured on order); to achieve sufficient cross section, the overall length has to be about 3 meters. This possibility presents lower electrical performance, but may be attractive if the amplifier cannot be housed in the direct vicinity of the cavity. No low-level measurements have been made.

2.3 Direct Couping Via Two Half-Resonators (Figure 1.C)

Each of the four gaps of an accelerating station is connected to two half-resonators, opposite in orientation and opposite in rf phase. Due to this double inversion, the magnetic flux in the two half-resonators points in the same direction as does the flux in adjacent cells. A straight conductor enclosing the ferrite stacks of two half-resonators will therefore pick up a voltage of the wanted magnitude, or inversely, will excite the gaps in push-pull when driven by a single-ended amplifier.

The basic coupling mode is purely magnetic. Stray capacitances between the coupling conductor and the central stem of the half resonators add also capacitive coupling, which have little effect in the operating frequency band.

Software simulation using PSICE has shown that the coupling conductor may even be completely enclosed by a shield connected to the respective central stems of the half-resonators. This allows, in principle, the use of a coaxial cable with well-defined dielectric and voltage-holding properties as a coupling device.

For a high-power implementation, the big problem lies however in the insulation; the cable is subject to high rf field strength and to radiation. Radiation-resistant dielectrics exhibit high dielectric losses and/or high permittivity, and lead to cable diameters that cannot be accommodated in the available space.

One solution would consist of replacing the original vacuum pipe of circular cross-section by an elliptic one, and to house a cable of generous diameter in the space thus freed on top or bottom of the small axis. Or, if the round vacuum chamber is to be retained, it is possible to run a vacuum-insluated conductor inside, in regions free of beam, with feedthroughs to connect to the outside.

This coupling mode is the only one that would permit one to feed d.c. power to the plate via the rf output. This would of course stress the coupling cable even more, but avoid the use of a high voltage capacitor and a choke. Since both elements can be reliably implemented by well-proven methods, this advantage is not decisive.

For the low-level measurements, a thin 50 Ohm cable was used that connected the two central half-resonators through a hole machined for that purpose.

2.4 **Direct Coupling to a Gap (Figure 1.D)**

The most direct coupling possible is a straight connection to the gap, with the connecting cable routed through the inside of one ferrite stack; the push-pull voltage of the gap is thus available ground referenced at the outside. This arrangement is equivalent to the line transformer, Figure 1.A, with the ferrite stack itself acting as the transformer core.

A possible high-power implementation is sketched in Figure 3. The power is fed to a gap from the mid-plane of the cavity, the only place where the vacuum pipe of two adjacent ferrite resonators lies at that the same d.c. potential. The standard sandwich of five metallic plates, which provides d.c. insulation at the other interface planes, can be replaced here by a non-insulating sandwich of three plates. The middle plate can thus be wide enough to house a coaxial line of about 20 mm inner diameter. Its center conductor is prolonged inside the vacuum chamber to feed the rf power to one of the central gaps; a simple shield prevents the transverse field components from influencing the beam.

The whole assembly is under the general machine vacuum, the best conceivable dielectric in this environment (radiation resistant/self-healing/low epsilon). The vacuum seal is provided outside the cavity envelope by an overdimensioned rf feedthrough. Its overall requirements are comparable to those for the gaps; the ceramic will however be much larger to guarantee perfect reliability. Note that the coupling conductor may also be implemented as a stripline (by extension in azimuthal direction) to increase its surface and reduce the I^2R losses.

For the model measurements, the connection was made to an outer rather than to a central gap for reasons of simplicity. This created different measurement conditions for this particular scheme with consequences that are detailed in Paragraphs 3.3 and 3.5 below.

3.0 Low-Level Measurements

All measurements were taken with the Hewlett-Packard network analyzer, HP-87534, at a full-size test cavity. The ferrite bias current was zero throughout, as the very high ripple of the available bias current supply would introduce excessive FM and render the data useless.

3.1 **Transfer Function Amplifier Full Gap, Differential**

Figures 4.A, to 4.C show the transfer functions between a simulated amplifier port (150 pF in parallel to 470 Ohm) and the "gap" voltage , measured as the differential (push-pull) voltage across the bus bars in the vicinity of the central plane.

All three coupling schemes are satisfactory for the cavity resonance around 1.8 MHz (tuning current zero). The first parasitic resonance, formed by the output capacitance of the simulated amplifier together with the stray inductance of the coupling device, occurs already at 8 MHz for the "two half-resonator" scheme; direct gap coupling is best in this respect with a resonance around 12 MHz.

3.2 **Transfer Function Amplifier to Half Gap, Single Ended**

Figures 5.A to 5.C show the voltage between a single bus bar and ground, all other conditions remaining the same.

One notes the strong "zero" mode of the cavities around 5.5 MHz, where the two gap electrodes oscillate at the same phase. The capacitances across the gaps displace no current under these conditions and are inoperative; gaps may therefore be short circuited with virtually no effect on this resonance, which does not couple to the beam. Nevertheless, its relative amplitude reveals how well the different schemes suppress any common-mode excitation.

Direct gap coupling is best, followed closely by transformer coupling, the half-cavity coupling being worst.

3.3 **Transfer Function with Feedback Amplifier**

A low-level feedback amplifier was connected to the different coupling schemes in order to check if any resonances would preclude the use of a closed-loop amplifier for the reduction of the effects of beam loading. The closed-loop gain was in excess of 35 dB, i.e., much higher than the value of 25 dB envisaged for the high-power amplifier.

No such resonances were found for either coupling scheme. Figures 6 and 7 show the results for push-pull and single-ended measurement. Direct and transformer coupling behave best, half-cavity coupling worst.

The resonance around 14 MHz seen only in the scheme of direct gap coupling is the TM 011 mode of the resonator chain, as sketched in Figure 1. It does not couple to the beam and cannot be excited or damped at the midplane of the cavity where its amplitude vanishes. This explains why it is not present with the other couping schemes which were connected at that place.

3.4 Impedance Seen by the Final Amplifier

The impedance into which the intrinsic final amplifier has to work is shown in Figure 8. The tube output capacitance is modeled by a 150 pF capacitor connected in parallel with the output port. This measurement confirms the results obtained by the open-loop transfer function: direct gap coupling leads to the widest margin between operating frequency range and the first parasitic resonance.

3.5 Impedance Measured at a Single Gap

The impedance across a single gap was measured via the "test line", connected across an outer gap (see Figure 1). The results are presented in Figure 9; for each coupling scheme, the respective amplifier port was loaded by either 150 pF or the feedback amplifier. The "beam impedance" around the fundamental mode would be 16 times higher.*

The flattest response with feedback is obtained for direct gap coupling; the two other schemes produce some peaking above the fundamental mode due to dephasing. One notes again the presence of the TM 011 mode, visible since the measurement has been taken at one of the two external gaps. Damping of this mode by the feedback amplifier is only effective if the latter is located outside the midplane, as is the case for the direct coupling recorded in the rightmost plot. This effect is, of course, an artifact of the specific measurement setup and not a property of the direct gap coupling.

---

*"Beam impedance" in this context designates the term "voltage induced in a complete accelerating station per ampere of a.c. beam current". In other words: multiplied by the fundamental component of the beam current, the beam impedance leads to the "beam voltage" as defined in the Robinson criterion. The latter has to be related to the station voltage (max. 40 kV) for the evaluation of the criterion. The conversion factor of 16 mentioned above supposes:

- perfect electrical symmetry of the accelerating station,
- negligible transit times between gaps for the beam (stimulus) and the individual induced voltages (responses to be superimposed).

4.0 Conclusion

All three coupling schemes can in principle be used for the conversion of the AGS cavities. However, direct coupling to two cavity halves can be ruled out since its implementation would involve a maximum of mechanical complications for a minimum of electrical performance.

Transformer coupling provides acceptable performance, at least under the idealized low-level test conditions, and is attractive as an external add-on to essentially unmodified cavities. It requires no handling of radioactive components. On the other hand, the solution is relatively bulky and involves some operational as well as development risks.

Direct gap coupling leads to the highest electrical performance and should be considered as the first choice. It must be pointed out that the low-level measurements taken could not show the full superiority of this scheme over the entire operating frequency range and under high-power conditions in the presence of harmonics from the amplifier and the beam. This scheme is the only one where the first parasitic resonance can be shifted outside the range of the second harmonic of the operating frequency. The connection to the amplifier is of the shortest length compatible with mechanical constraints and consists of a well-behaved coaxial line. Although necessitating partial disassembly and mechanical routine operations on the radioactive cavity (welding on the vacuum chamber and exchange of center plates), it finally counts the least number of high-power elements like feedthroughs, necessitates no additional ferrites and can thus be considered as the most reliable of the three presented schemes.

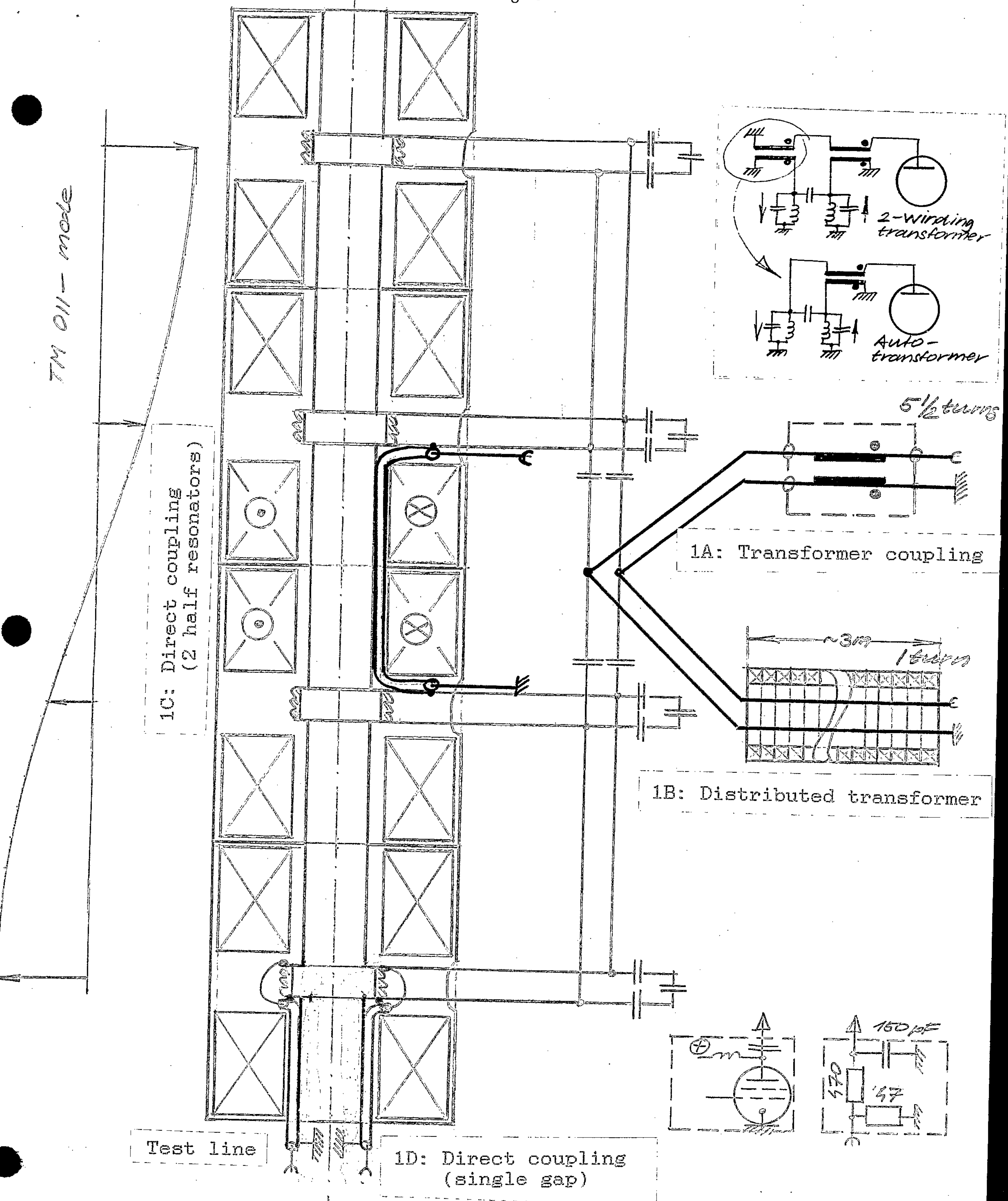

Figure 1: The different coupling possibilities.

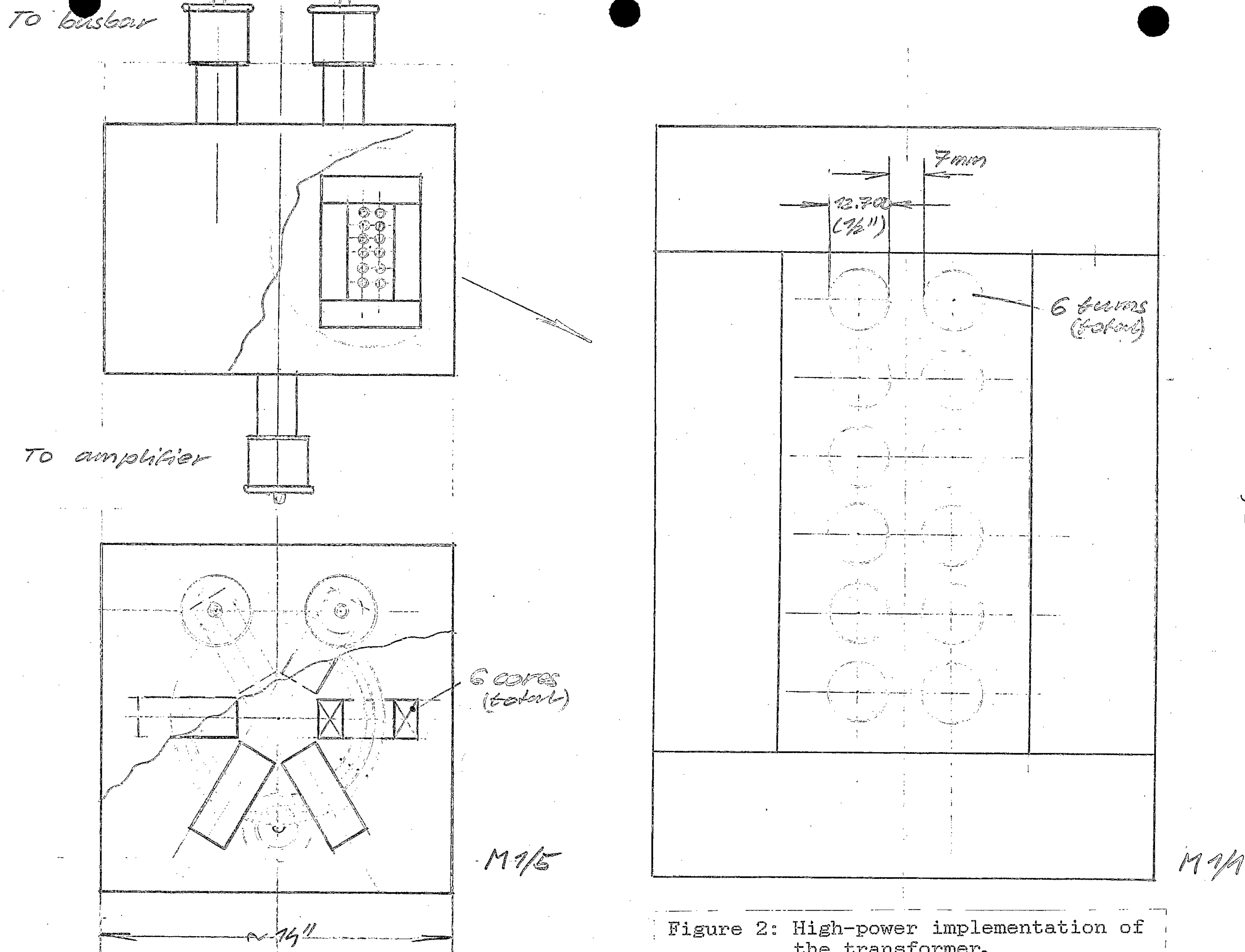

Figure 2: High-power implementation of the transformer.

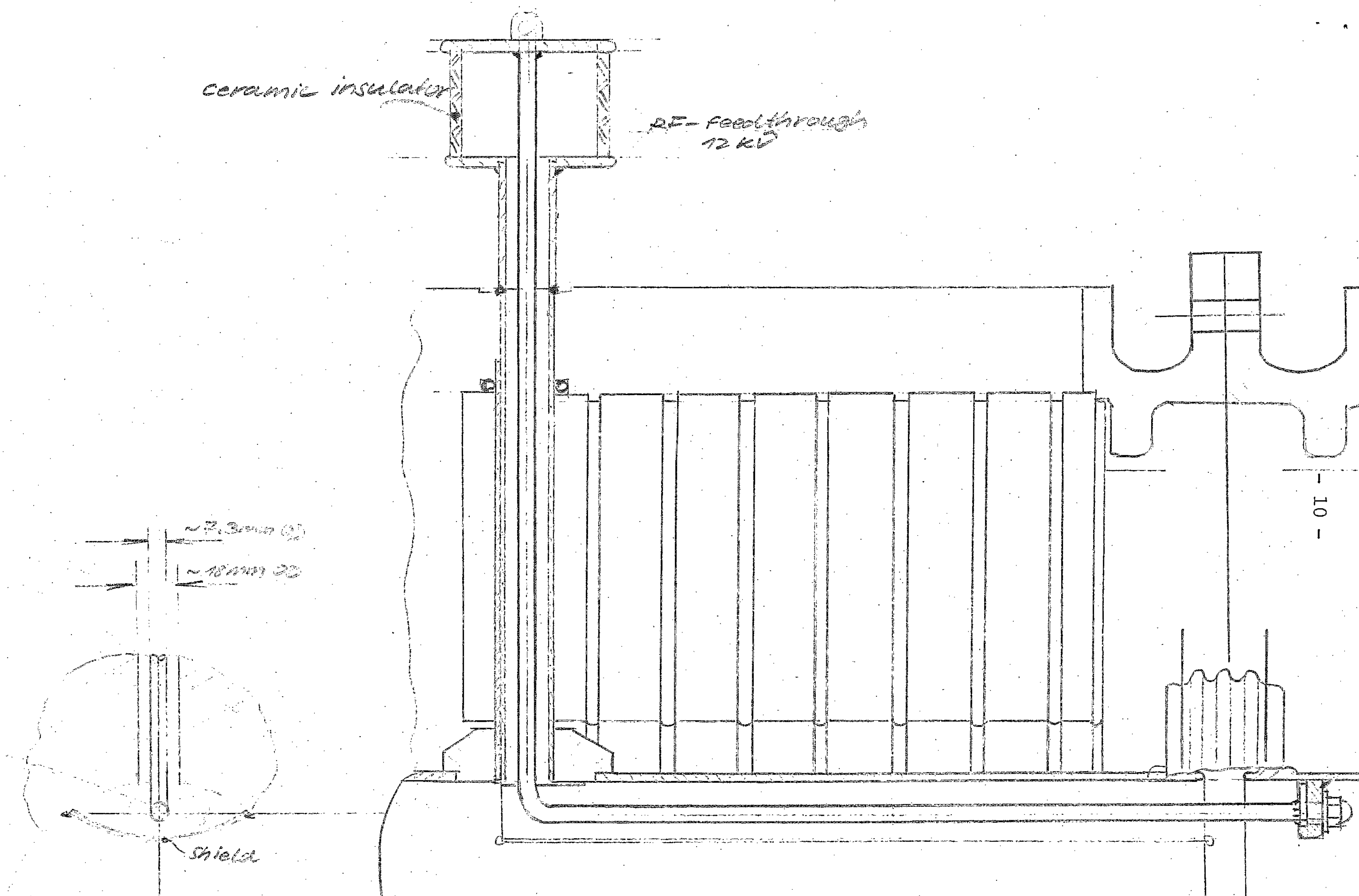

Figure 3: High-power implementation of direct single gap coupling.

TRANSFORMER | DIRECT COUPLING (2 half resonators) | DIRECT COUPLING (single gap)

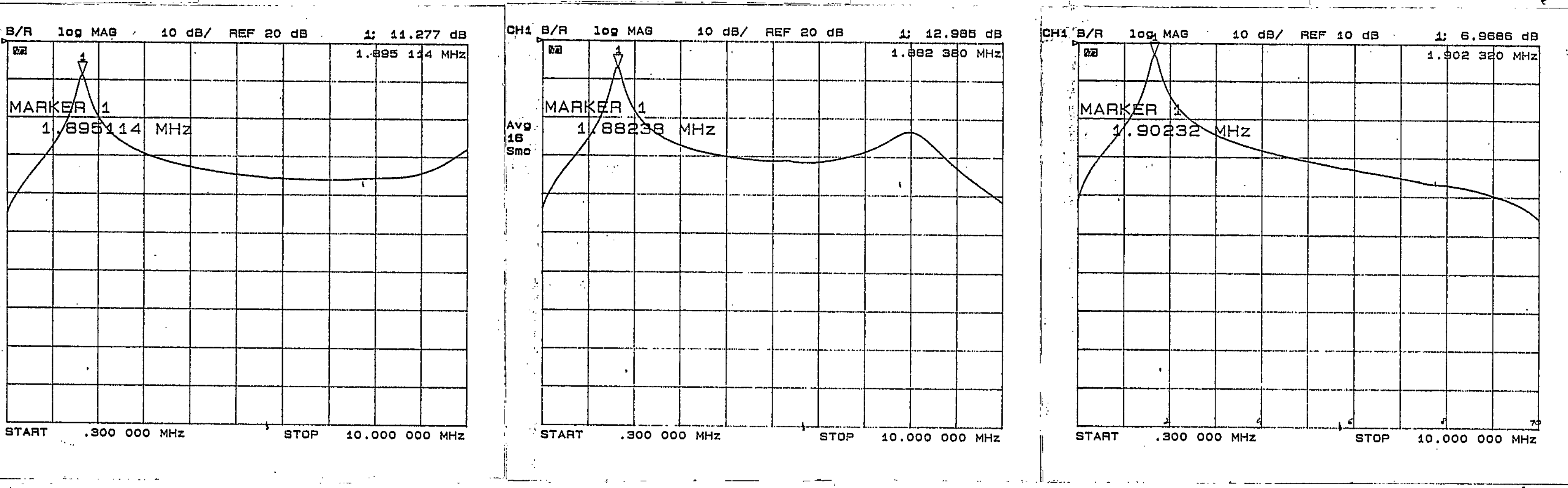

Figure 4: Open-loop response, push-pull measurement.

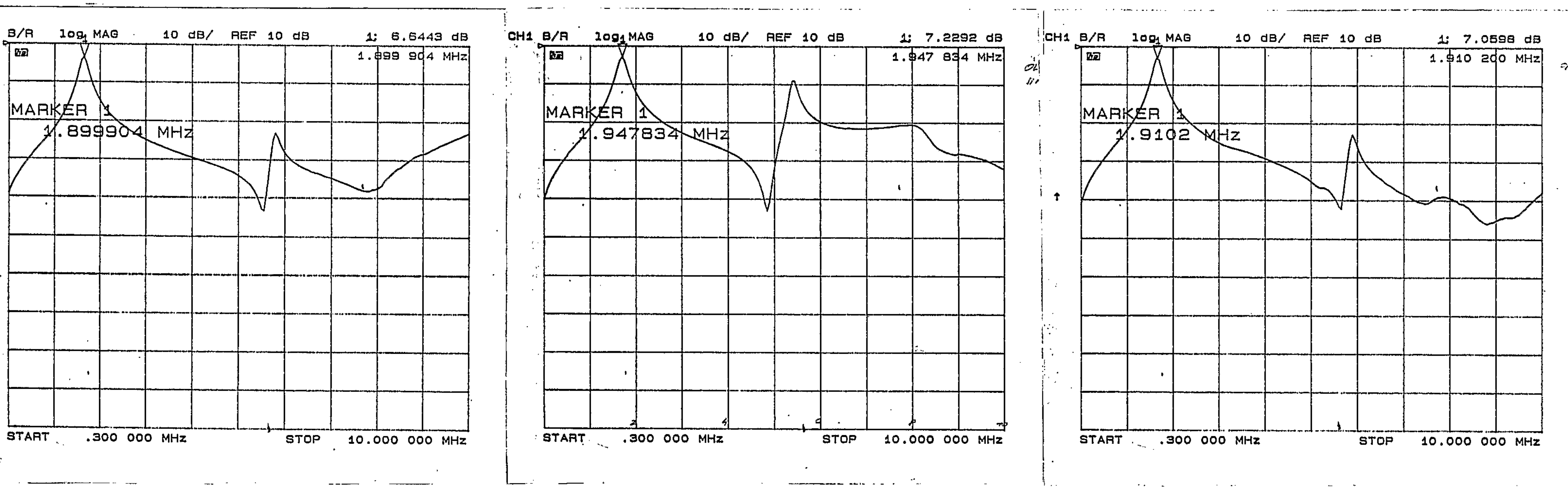

Figure 5: Open-loop response, single-ended measurement.

TRANSFORMER | DIRECT COUPLING (2 half resonators) | DIRECT COUPLING (single gap)

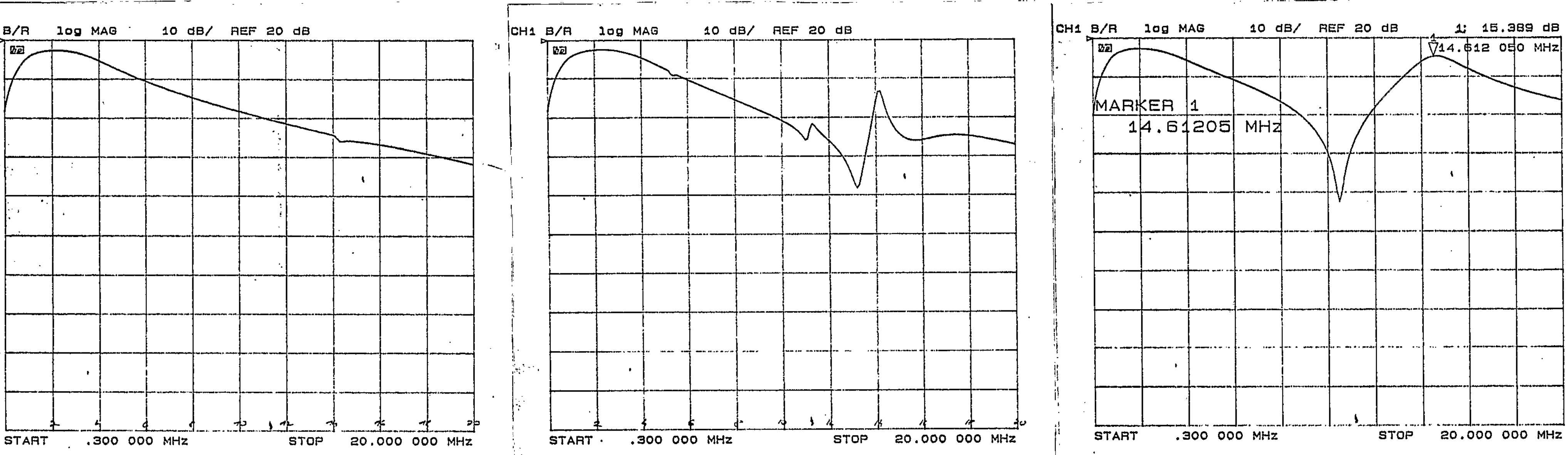

Figure 6: Closed-loop response, push-pull measurement.

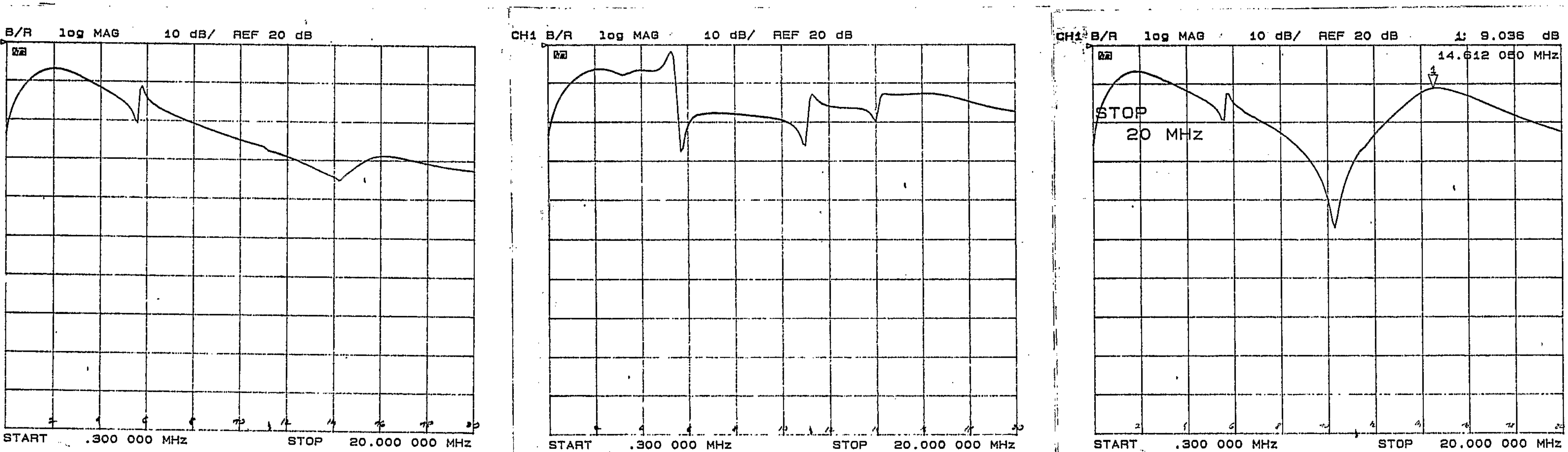

Figure 7: Closed-loop response, single-ended measurement.

TRANSFORMER

DIRECT COUPLING (2 half resonators)

DIRECT COUPLING (single gap)

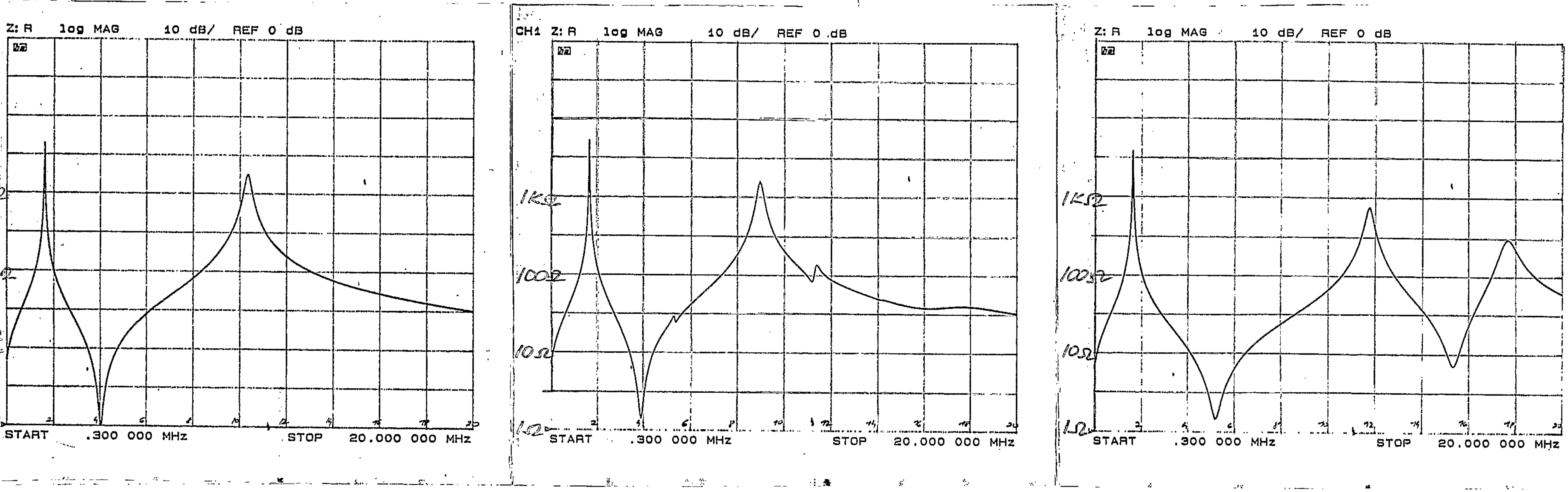

Figure 8: Cavity impedance at amplifier output (Tube simulated 150 pF).

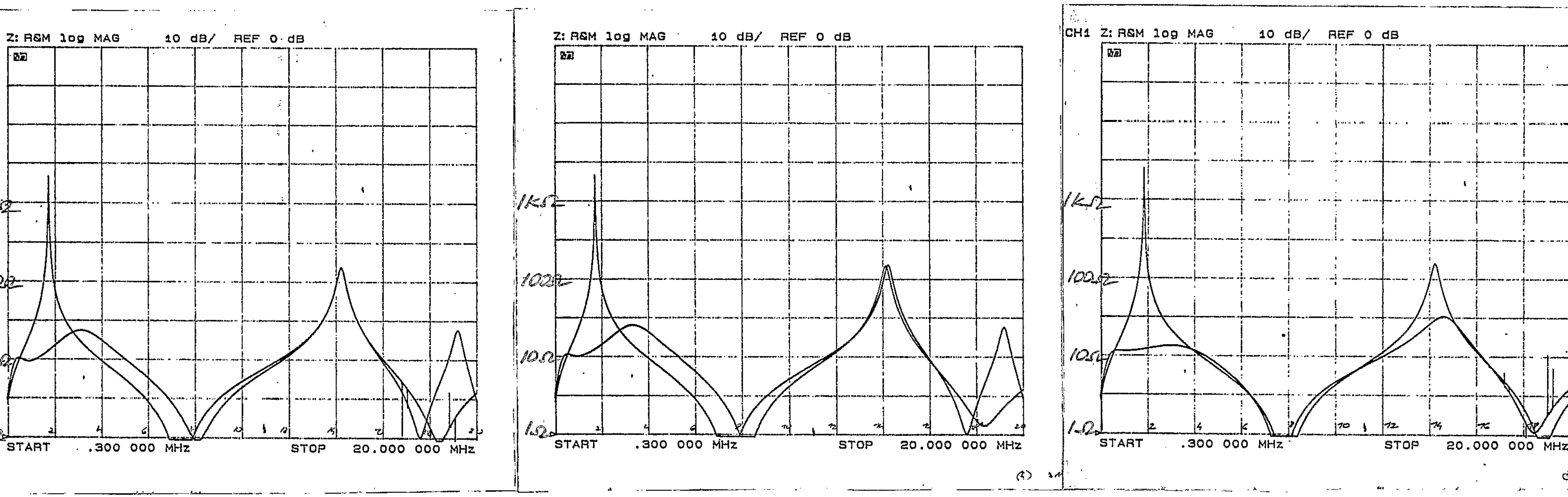

Figure 9: Cavity impedance at single outer gap
two terminations.... high trace: 150 pF low trace: feedback amplifier.
The BEAM IMPEDANCE is higher by a factor of 16.