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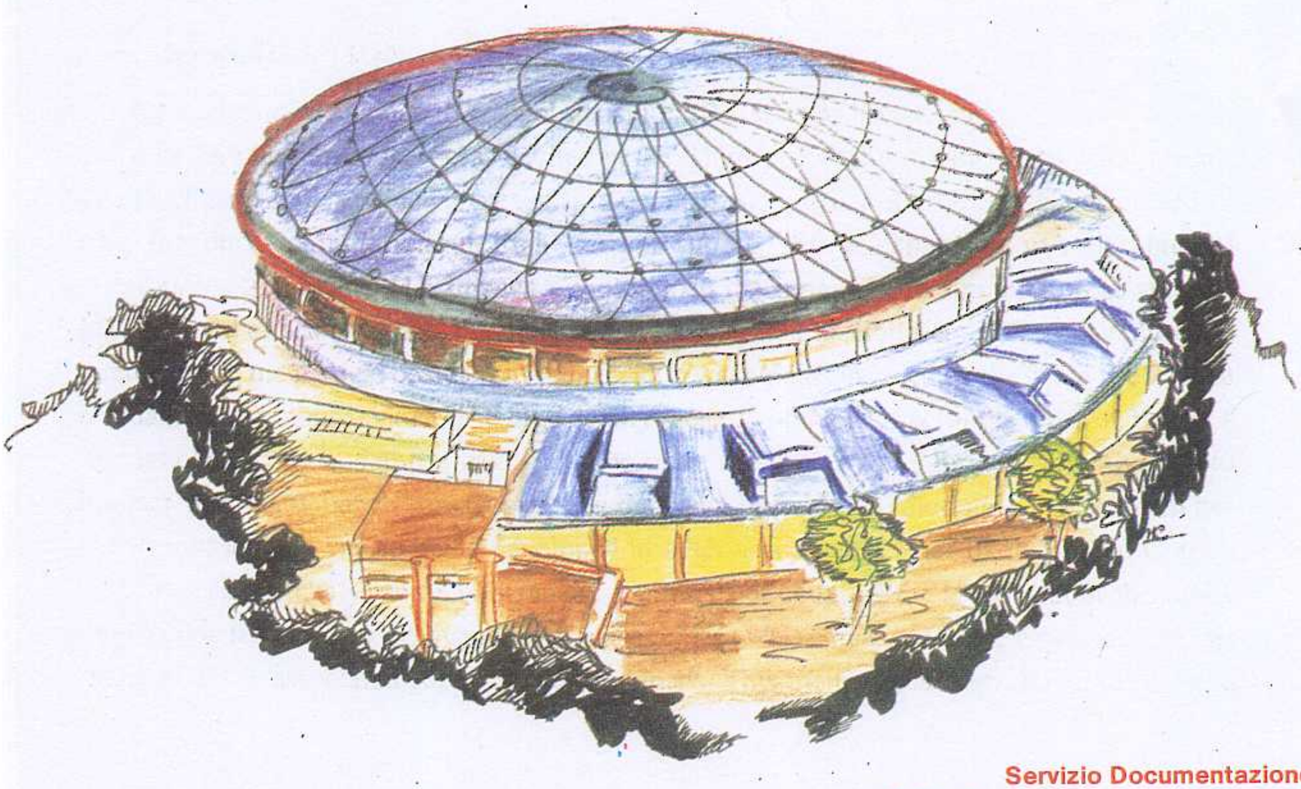

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A BROADBAND WAVEGUIDE TO COAXIAL TRANSITION FOR HIGH ORDER MODE DAMPING IN PARTICLE ACCELERATOR RF CAVITIES

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ABSTRACT

A novel Broadband Waveguide to Coaxial Transition for High Order Mode Damping in Particle Accelerator RF Cavities (BTHD) has been studied and developed in the framework of the Frascati Φ-Factory project DAΦNE. The cavity high order modes (HOM) are the primary source of coupled-bunch instabilities in multibunch storage rings. The energy delivered by the particle beam to the cavity HOMs and coupled out with waveguides is converted by BTHD into the TEM coaxial mode and dissipated by a 50 Ω load connected via a ceramic feedthrough. This article deals with the design and the low power tests performed on a BTHD prototype and the considerations for a real application to an accelerator.

1. - INTRODUCTION

A broadband waveguide to coaxial transition (BTHD) has been designed for coupling out and thus damping the wake fields excited in the RF cavities by the DAΦNE bunched beams. The machine complex, which is presently under construction, is a double intersecting 500 MeV ring for the accumulation of high current (up to 120 bunches, 46 mA per bunch) electron/positron beams [1]. In such a multibunch machine, like in similar storage rings in project in other Laboratories, coupled-bunch longitudinal instabilities can be excited by the interaction of the particle beams with the parasitic wake fields induced by the beam itself in the resonant accelerating cavities. The high quality factor Q of the HOMs (of the order of 10^4 for a normal conducting undamped cavity) let the wake fields decay in a time sufficiently long to interact with many bunch passages getting the beam unstable. A solution to this problem has been proposed and is also being developed in other accelerator center like LBL and Cornell (U.S.A.), Trieste (Italy) and KEK (Japan). It consists of coupling the HOMs out of the cavity over a wide frequency band by means of waveguides (WG) connected to the cavity surface and dissipating the associated energy in dummy loads. This method has been shown to permit a reduction of the HOM Qs and shunt impedances by some orders of magnitude, thus reducing the intensity and the decay time of the cavity induced wake fields. For DAΦNE, a reduction of the Q of some high impedance HOMs to a few hundred is considered sufficiently safe [2] for an initial machine operation with 30 bunches. Tests have been carried out on a full scale cavity prototype [3] equipped with three 305 x40 mm^2 WGs with cut–off at 492 MHz and terminated with lossy materials. Fig. 1 shows a picture of the cavity prototype equipped with the WGs. The HOM damping obtained with such a structure is satisfactory since the damped Qs are as low as a few hundred and even less over a wide frequency band (up to 2.6 GHz).

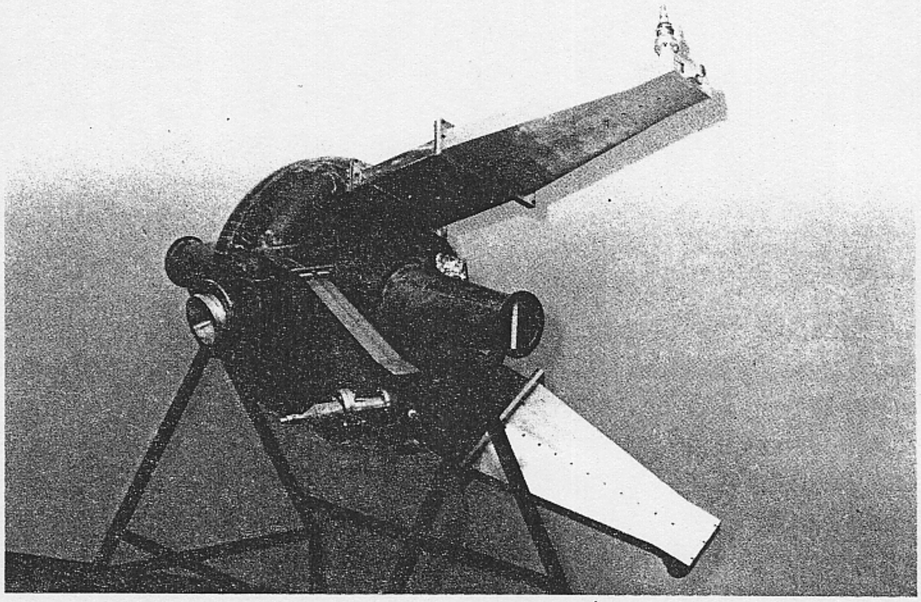


FIG. 1 – The DAΦNE Cavity Prototype.

Since the RF cavity in the ring must operate in ultra high vacuum (UHV) at 10^{-9} Torr, the lossy materials, based on ceramics or ferrites would be placed in UHV too and would require care for brazing to the internal WG surface and cooling when dissipating power. Although there is a good progress of the R&D in this field, to our knowledge, the capability of such materials to operate reliably for a long term in an accelerator UHV environment at high power dissipation rate (in the kW range) has not been exhaustively proved. On the other hand, the use of alumina vacuum windows in the WGs is of some concern due to the large size required.

A simpler and, in our opinion, more reliable solution to convey the HOM power to a dummy load is to use a transition from the rectangular WG to a coaxial 50 Ω line. Thus, the power can be absorbed by an external 50 Ω load via a vacuum feedthrough of standard design.

2. – GENERAL CONSIDERATIONS

Ridged WGs are more suitable than rectangular WGs to convert, in a wide frequency band, the fundamental TE_{10} WG mode to the coaxial TEM mode. For this reason the BTHD consists, as shown in Fig. 2, of two sections: a tapered transition from rectangular to double–ridged WG followed by a transformer to 50 Ω coaxial line.

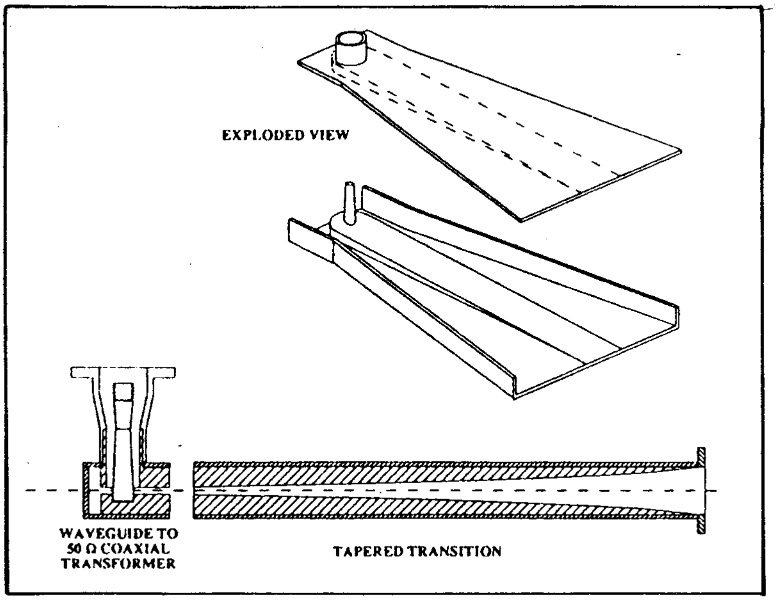


FIG. 2 – Sketch of the Broadband Transition.

Ridged WGs commonly used are single and double–ridged. The basic motivation for building ridged WGs is to lower the cut–off frequency of the fundamental TE_{10} mode without increasing the external dimensions. This is done by introducing a metallic ridge into a normal rectangular WG. As an advantage of these WGs, the ratio of the cut–off frequencies TE_{30}/TE_{10} may exceed a factor of 15 depending upon the aspect ratio of the WG and the ridges. These cut–off frequency ratios have been worked out by analytical as well as numerical methods and can be found in the literature for a wide variety of ridged and rectangular WG geometry. The TE_{20} mode is often not considered relevant in this contest, as it may not be excited or transmitted via the coaxial to WG transition due to its symmetry.

As a very narrow gap between the ridges would lower the maximum permissible voltage, caution should be exercised for high power applications or under vacuum resonant discharges (multipactoring). A method to reduce the maximum electrical field strength is to use semicircular ridges [4] instead of rectangular ones, thus avoiding high peak values for the electric field at the edges of a ridge.

Normalized ridged WG components (single and double ridge) are available from industry for use in wideband applications. For special requirements, ridged WG horn antennas (e.g. 1 to 12 GHz) for broadcasting are on the market. The basic ingredients of this subject have already been discussed in 1947 and in 1955 [5, 6, 7]. Ridged WGs can be loaded with dielectric and/or magnetic material (non reciprocal devices) [8]. As for standard WGs without partial dielectric or magnetic loading, the general dispersion relations for phase and group velocity still hold.

Coaxial to WG transitions are basically transformers and mode transducers. A large variety of structures are in use in order to obtain a good impedance matching over the bandwidth required. For a rectangular WG this mode transducer is often simply a probe with a small metallic ball attached to the end, protruding into the WG. However, the diameter, position and length of the probe have to be carefully evaluated. Other transitions have some sort of coupling loop, occasionally with dielectric loading. There exist no general synthesis methods for optimal coaxial line to WG transitions. Many designs [9, 10] are based on experience and intuition, but nevertheless work surprisingly well. As for the analysis of a given structure, a general analytical procedure would be a mode matching technique, i.e. describing the field in the vicinity of the transition as the infinite sum of propagating and evanescent WG modes and working out the coupling coefficient for each mode. This theoretically very elegant method meets many problems in its practical solution and thus, in the past, a design had often to go through many cut and try stages. With the availability of powerful computer codes, this tedious and time consuming cut–and–try work can be drastically reduced. Carefully done computer simulations usually lead to results close to measured values.

3. - BASIC BTHD SPECIFICATIONS

Coupling the cavity HOMs with WGs is favourable with respect to other techniques (such as loop or antenna couplers) which do not provide wide frequency response and require filtering to reject the accelerating cavity mode. The BTHD frequency response must extend from the first HOM to the beam pipe cut–off (510 MHz to 2.6 GHz for the DAΦNE cavity). A VSWR ≤ 2 is required at the BTHD input in that frequency range, corresponding to more than 88% of power transmission to the coaxial output.

The power handling capability is another relevant BTHD feature. The RF power, P_{HOM}, carried outside the cavity can be evaluated [11] from the beam and damped cavity spectra according to the following relation:

$$P_{HOM} = \sum_{\substack{n=-\infty \\ k=\text{all HOMs}}}^{+\infty} \frac{2(R/Q)_k \, Q_{extk} \, I_n^2}{1 + Q_k^2 \, (nf_r/f_t - f_t/nf_r)^2}$$

where I_n is the amplitude of a beam spectrum line, $(R/Q)_k$ is the ratio between the impedance peak value and the quality factor of a longitudinal HOM, Q_{extk} and Q_k are respectively the external and loaded HOM quality factors, f_r is the beam revolution frequency (i.e. 3.07 MHz for DAΦNE) and f_k is the HOM resonant frequency. The beam spectrum strongly depends upon the distribution of the beam charge in the bunches, while the damped cavity spectrum can be determined from computer code simulations and from prototype measurements. The estimated extracted power, in a 30 bunch machine operation, is below 1 kW for the DAΦNE cavity. The BTHD must handle this amount of power without discharges or multipactoring over the complete frequency range.

4. - THE BTHD DESIGN

The BTHD tapered transition and the mode transducer have been at first separately designed using analytical approximations and then improved via a step–by–step refinement procedure based on the use of the 3D electromagnetic (e.m.) computer code High Frequency Structure Simulator (HFSS HP trademark) [12]. The two sections mentioned above have been finally joined in a single model for the computer code simulation.

This transition has not been designed to couple to the TE_{20} mode that could in principle be excited by the cavity HOMs. In our case, the cavity HOMs to be heavily damped are monopoles and dipoles which can practically launch only the TE_{10} WG mode due to their azimuth symmetry.

For those applications which also require transmission of TE_{20} mode, the transition design should be implemented with a different geometry of the ridges. In addition, a dedicated and more selective TE_{20}–TEM transducer must be foreseen.

4.1 – Rectangular to Double–Ridged Waveguide Transition

The rectangular WG connected to the cavity surface smoothly adapts to a double–ridge to coaxial transformer through a 500 mm tapered section. This can be considered a double–ridged WG with a continuously variable cross–section (inhomogeneous WG) from 305 x 40 mm^2 rectangle at the cavity side to 140 x 40 mm^2 with two 62 x 17 mm^2 ridges. The minimum ridge distance is kept at 6 mm to reduce the risk of discharges; this conservative choice limits the maximum obtainable frequency bandwidth. The width of the structure varies linearly from 305 to 140 mm while the height has a constant value of 40 mm.

Mechanical or electrical discontinuities in the WG taper can convert the TE_{10} to the TE_{20} mode which cannot be transformed to the TEM coaxial mode. For this reason much care is required in avoiding any roughness of the internal surfaces. The electromagnetic discontinuities can be avoided by shaping the ridge in order to keep the TE_{10} cut–off frequency of any cross section at a constant value. In fact, electric and magnetic field vectors are orthogonal for TE and TM modes in the transverse plane regardless of the WG shape; for the TE_{10} mode (and generally speaking for any propagating mode) the ratio of the modules of the two vectors depends only upon the ratio between the mode cut–off and the operating frequencies f_c/f as follows:

$$\frac{|E_t|}{|H_t|} = \frac{\eta}{\sqrt{1 - (f_c/f)^2}} = Z_{TE10}$$

where $\eta = \sqrt{\mu/\varepsilon}$, often called characteristic wave impedance, is a constant of the filling dielectric material (377 Ω for vacuum) and Z_{TE10} is the "field impedance" which does not depend on the WG shape. The field impedance must be distinguished from the characteristic WG impedance Z_0 that depends by the WG shape and is defined as:

$$Z_0 = \frac{V^2}{2P}$$

where V is the voltage across the WG gap and P is the transported power. For the TE_{10} mode of a rectangular WG the simple following relation holds:

$$Z_0 = \frac{2b}{a} \cdot Z_{TE10}$$

where b and a are respectively the WG height and width. So, by keeping the cut–off frequency along the tapered section constant, the ratio between the transverse components of the electric and magnetic field vectors is a constant at any operating frequency. The ridged profile has been computed in order to keep the cut–off frequency at 490 ± 1.5 MHz along the longitudinal axis of the tapered WG. The result of the BTHD tapered WG transition simulation is given in Fig. 3 and shows that an input VSWR lower than 2 is achievable in the range 540 to 2800 MHz.

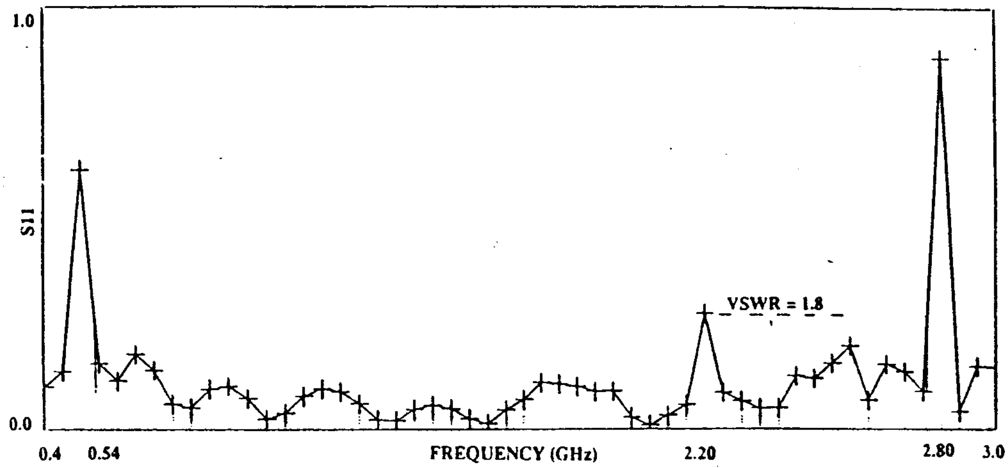


FIG. 3 – Code Simulation of the Tapered Waveguide Transition Response (S11 vs Frequency).

4.2 – Double–ridged Waveguide to Coaxial Transducer

The transducer consists of the inner conductor of the coaxial line protruding into the double–ridged WG through the H plane. It is in contact with the opposite ridge and guides the e.m. field of the WG out in the TEM mode of the coaxial cable. A short section of WG, terminated with a metallic plate (also called back–cavity) is situated beyond the transducer. It behaves like a shorted line for matching the coaxial and the double–ridged WG impedances.

Useful design criteria to initially define the main parameters of the transition were obtained from [9, 10] and the first design of the transducer is shown in Fig. 4 . As a first guess, a 7 mm (outer conductor diameter) coaxial line was chosen since this is a standard size of commercially available UHV feedthroughs.

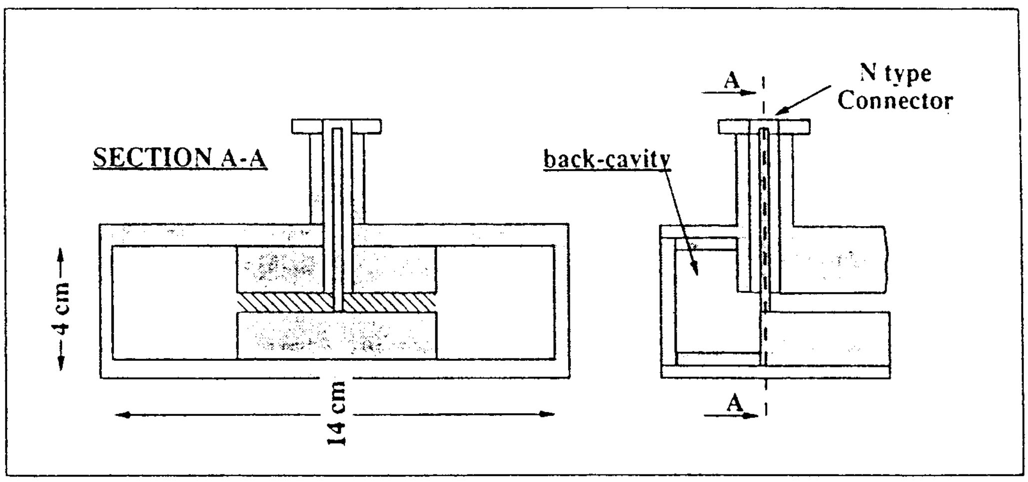


FIG. 4 – Preliminary Design of the Mode Transducer.

The results of the HFSS simulation are shown in Fig. 5 and could not be considered as satisfactory. The S_{11} parameter curve exhibits some narrow peaks in the upper band of the spectrum corresponding to a VSWR as high as 7. Variations to the back–cavity dimensions did not significantly improve the response. By examining the HFSS field plot of the transducer at the frequency of the peaks, the regions hatched in Fig. 4 were found to resonate as a λ/4–like line producing sharp notches in the power transmission. This unwanted behavior has been eliminated by rounding the profile of the ridge end and increasing the diameter of the inner conductor of the coaxial line. In this way, the length of the λ/4–like line is reduced and its resonant frequencies shift out of the BTHD bandwidth. Moreover, the ridged WG characteristic impedance of about 30 Ω can better match to the coaxial line which is then tapered to fit with a 1–5/8" output flange. The actual geometry of the transducer is shown in Fig. 6 and the computed S parameters are depicted in Fig. 7.

The S_{11} response of the complete BTHD, shown in Fig. 8, has been considered satisfactory to proceed with the fabrication of a prototype.

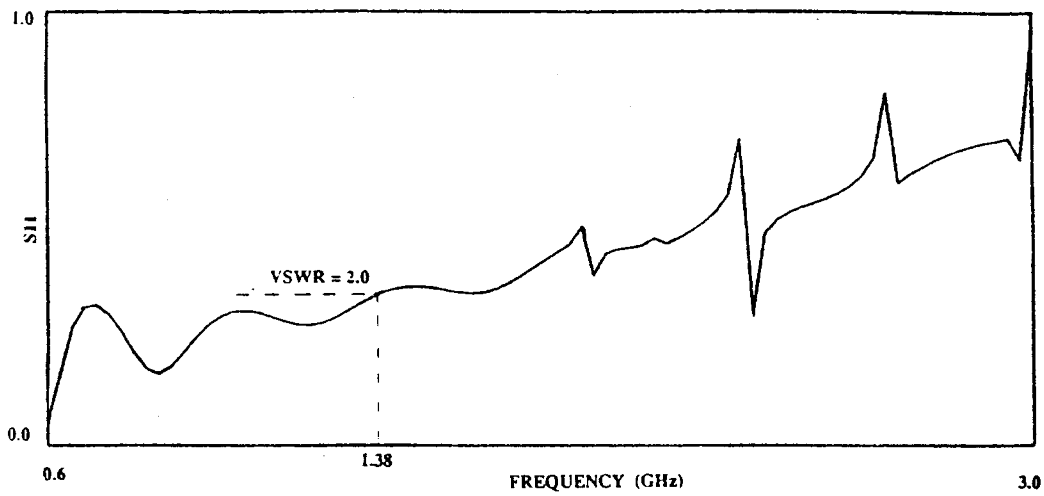


FIG. 5 – Frequency Response of the Preliminary Mode Transducer (Code Simulation).

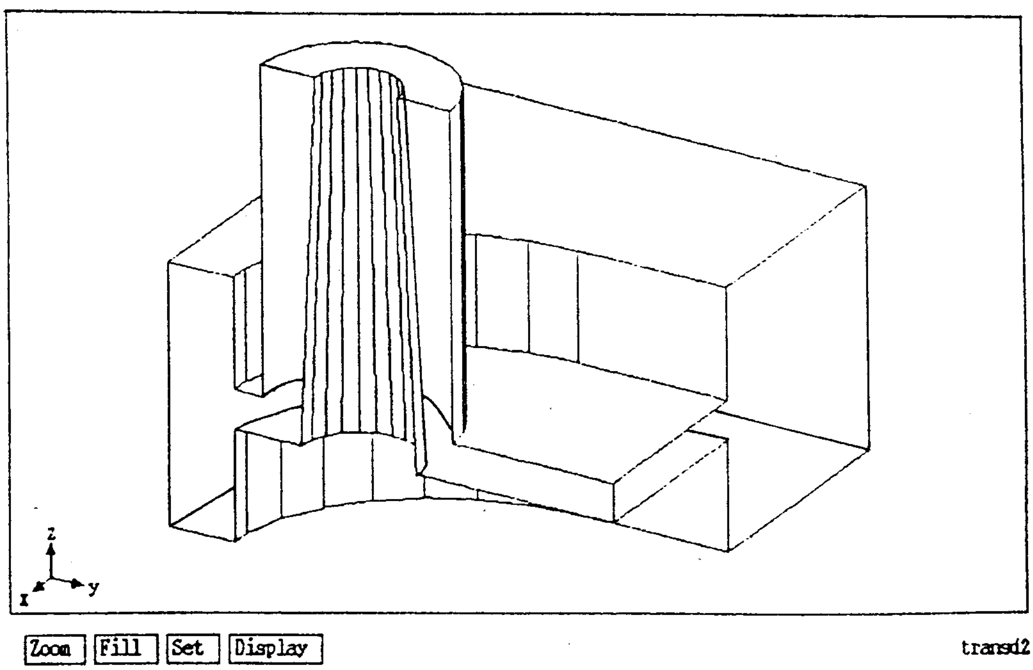


FIG. 6 – Final Geometry of the Mode Transducer (HFSS Plot).

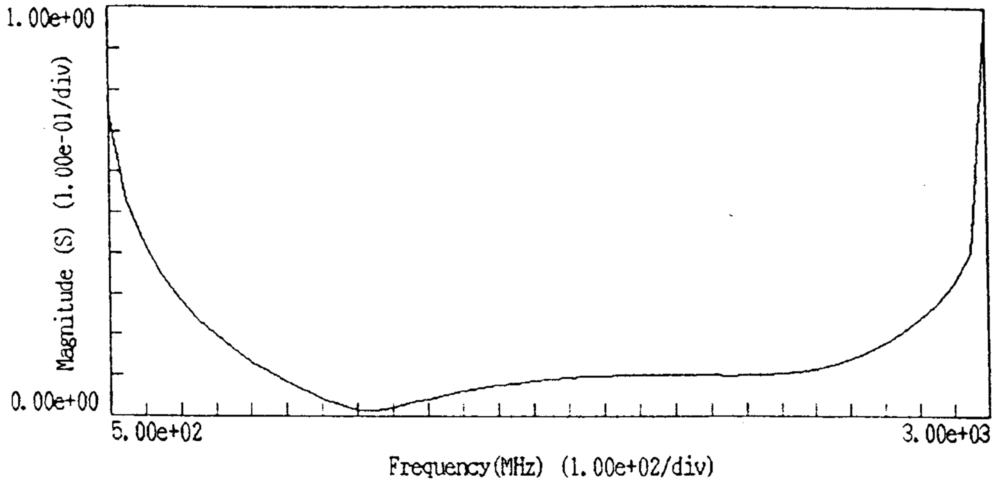


FIG. 7 – Frequency Response of the Final Mode Transducer (Code Simulation).

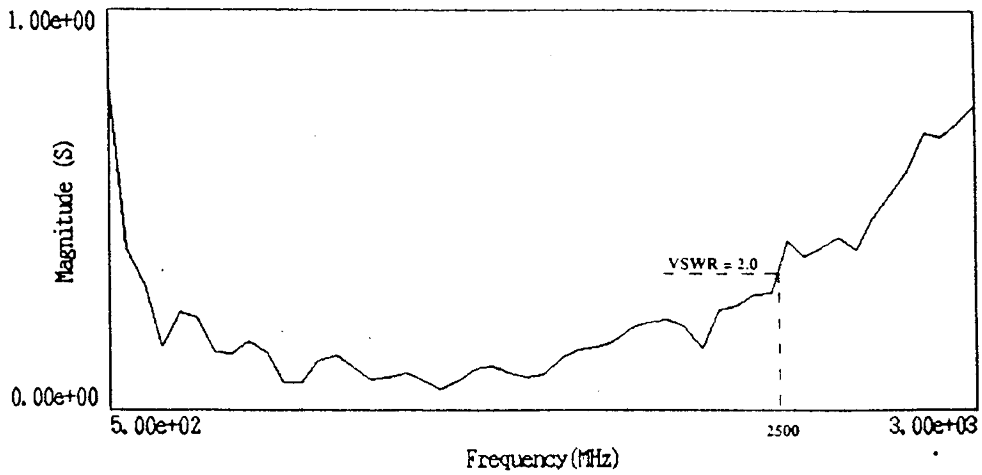
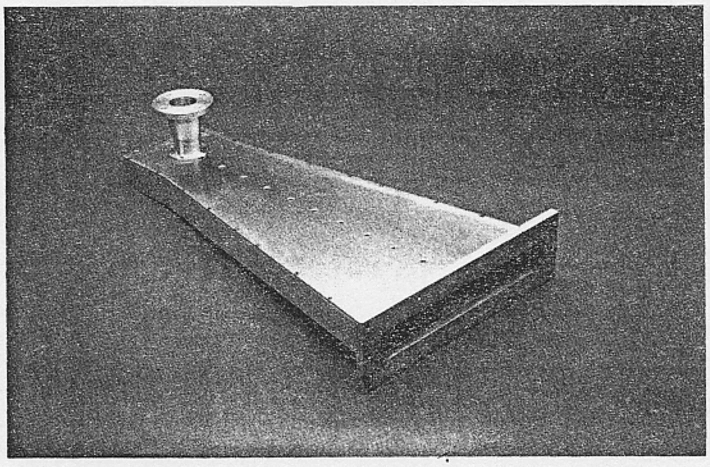


FIG. 8 – Frequency Response Simulation of the Final BTHD.

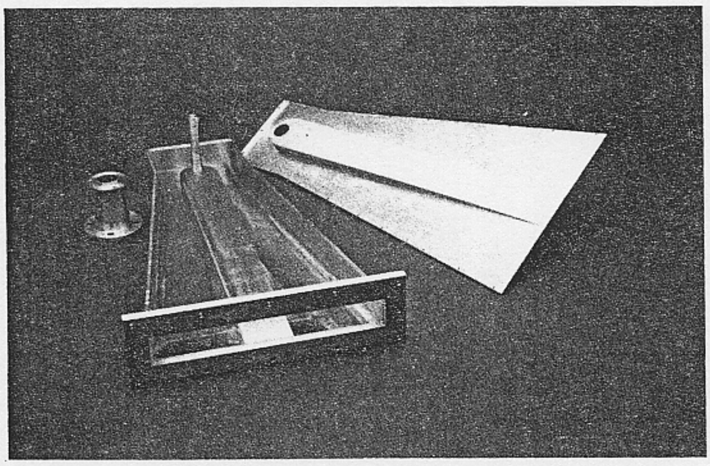
5. - EXPERIMENTAL RESULTS

Three full scale aluminum BTHD prototypes have been manufactured and RF tested at low power. Figs. 9a,b and 10 show respectively a picture of the prototype and a sketch of the RF test bench. The S_{11} parameter of one prototype at its coaxial input has been measured with a network analyzer by connecting two BTHDs through the rectangular WG ports and gating the total response to isolate the device under test. The result, presented in Fig. 11, is better than that expected from simulations, the VSWR being lower than 2.1 in the range 510 to 3000 MHz. Small tuning of the back–cavity length can optimize the BTHD bandwidth and VSWR $\leq$ 1.6 is obtained in the 570 to 2600 MHz band.

The BTHD prototypes, loaded with 50 Ω terminations, have been connected to the DAΦNE cavity model and the quality factor Q of the highest impedance HOMs has been compared with that obtained with the ferrite loaded WGs. The results, listed in Table I, are almost the same in both cases.



a – Assembled



b – Open

FIG. 9 – The BTHD Prototype.

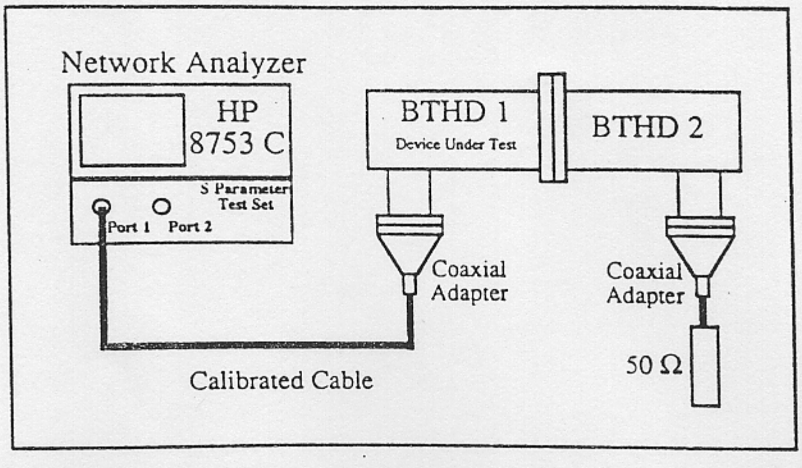


FIG. 10 – Scheme of the RF Test Bench.

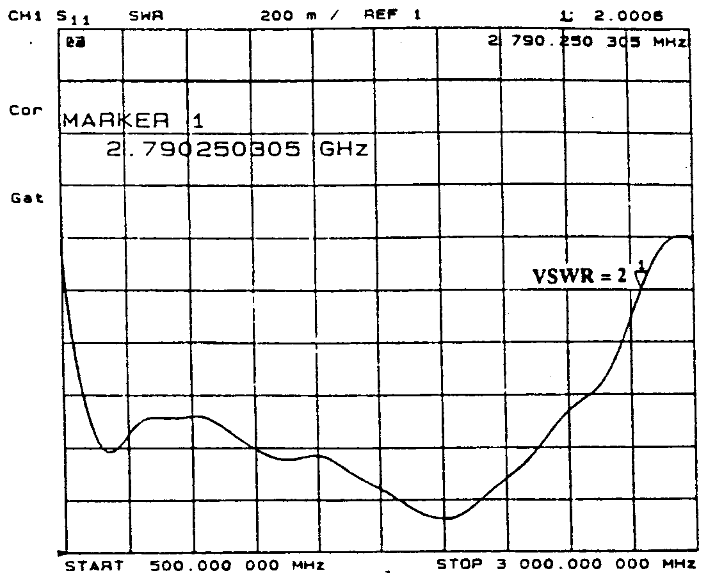


FIG. 11 – The Measured Frequency Response of the BTHD.

TABLE I – Cavity Prototype HOM Quality Factors.

FREQ. (MHz)	UNDAMPED Q	FERRITE DAMPED Q	BTHD DAMPED Q
745.7	24000	70	68
796.8	40000	230	216
1023.6	28000	150	90
1121.1	12000	300	300
1175.9	5000	100	90
1201.5	9000	130	180
1369.0	5000	300	170
1431.7	4000	750	550
490 (*)	30500	350	650
491.3 (*)	28500	250	830
523.5 (*)	31500	280	150
549.7 (*)	32000	270	50

(*) Dipole Modes

6. – THE REAL APPLICATION

The experimental results are fully satisfactory with respect to the accelerator demands. The main troubles in a RF device operating under vacuum are the discharges due to field emission and multipactoring. All the discharges depend upon the local e.m. field strength and distribution but some simple rules can give information about the discharge thresholds. A largely accepted safety limit for vacuum discharge is a surface electric field of about 3 MV/m. Since the WG characteristic impedance along the tapered section varies from 50 Ω to 30 Ω at the coaxial insertion, a surface field of 3 MV/m in the ridge gap corresponds to 5.4 MW of transported power that is more than 3 orders of magnitude higher than in the DAΦNE case. Therefore, by providing an accurate finishing of the internal surfaces, vacuum discharges due to field emission should be very unlikely.

Multipactoring can occur in RF devices under vacuum and it strongly depends on the field distribution. Thus, due to the limited reliability of the simulation codes dealing with electron discharges, only full power tests can give complete information. Nevertheless, from multipactoring theory [13], it arises that the propagating HOM power should not cause multipactoring in our BTHD. Titanium coating must be in any case foreseen to prevent the multipactoring due to the penetration of the accelerating cavity mode in the region near the WG openings.

The final transition will be made, as the accelerating cavity, of oxygen free, high conductivity copper.

The BTHDs need a low VSWR, wideband 50 Ω ceramic vacuum feedthrough. The use of a 1 kW standard N type device, available on the market, has been rejected since a bigger safety margin on the extracted power is advisable. Simulations carried out with the 3D code show that a 7/8" ceramic feedthrough with a low VSWR in the 0.5 to 3 GHz band is feasible.

The BTHD also allows the sampling of the HOM power by connecting a directional coupler at the 50 Ω output.

7. - CONCLUSIONS

A novel device (BTHD) for coupling the high order mode power out of the DAΦNE accelerating cavities has been developed and three aluminum prototypes have been successfully tested on bench at atmospheric pressure and low power. The experimental results confirm the code simulations. The BTHDs operate as mode transducers from the TE_{10} waveguide mode to the TEM coaxial mode; therefore the high order mode power can be dissipated on standard 50 Ω loads instead of on lossy materials brazed and operating in vacuum. The high order mode damping obtained with the BTHD system fully meets the requirements of the DAΦNE beam longitudinal dynamics [2].

Power levels of hundreds of kilowatts can in principle be handled in ultra–vacuum by the BTHD, the operating limit depending only on the size of the output coaxial connector. In our case, the 7/8" standard is sufficiently oversized to handle the high order mode power transmitted by each DAΦNE cavity waveguide. Multipactoring is unlikely to occur in our BTHD; anyhow it can be inhibited with a titanium or other low secondary emission coating of the internal surfaces. Power tests in vacuum are in the programme to check the reliability of BTHD furtherly .

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