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Abstract

The design of magnetic probes (Mirnov coils) is described in this report. These probes are used in ASDEX to investigate MHD modes and measure the plasma displacement together with magnetic flux loops. Concerning the high temperature rise during a plasma shot proper material for the coil form of the magnetic probes and the suitable wire and cable in the high vacuum chamber in conjunction with special geometrical construction have been selected.

The electrical circuit updated to operate in a high noise environment is shown and first MHD mode signals demonstrate the effeciency of the system.

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A) Introduction

In tokamaks magnetic probes are used to measure the poloidal field strength and its variation (e.g. amplitude, mode number, (m,n) and phase angle of MHD oscillations) /1/.

To detect high frequencies (∼1oo kHz) e.g. in disruptive processes, the magnetic probes should be placed inside the vacuum vessel. The difficulty in this case is that the energy deposition on the probe case during the plasma shots may be very high. The second difficulty is presented by the wiring of the magnetic probe inside the stainless-steel vessel, which should not disturb the high vacuum ($1o^{-8}$ mbar) by outgassing of the wire insulation. On the other hand, electric and magnetic fields from sources other than the MHD modes should not influence the measurements.

The ampere windings of the magnetic probes in ASDEX /2/ should have such a value that the rotation of an interesting mode number induces a voltage not less than about 0,5 volts. This value is known by experience with Pulsator Tokamak /3,4/.

B) Design of the magnetic probes

The design principle to support the magnetic probes is to use two poloidal stainless-steel rings (6 and 8 mm thick) and place the magnetic probes between the two rings. The magnetic probes are covered with 2 mm thick Alumina plates (Al_2O_3) within sight of the plasma. Plasma particles are thereby prevented from hitting the magnetic probes. Eddy currents, which would reduce the time constant and shift the phase of the probes, cannot occur. The coil arrangement is shown in Fig. 1.

One problem of the magnetic probes in a tokamak is the heat deposition because the probes should be as close as possible to the plasma. During pulse cleaning and normal plasma shots in ASDEX the temperature of the external edge of the magnetic probe case may rise to about 25o^{o} C. Therefore, care has to be taken to select the right materials for the probes. The coil arrangement is shown in Fig. 1.

Because of its good heat resistance and good machinability we used glass ceramic+) I) for the slotted insulating coil body. This material has a temperature coefficient of $\alpha = 9.4 \times 10^{-6}$ per degree C and a maximum operation temperature of 1ooo^{o} C with excellent vacuum properties. The wire, which is wound around the machinable glass ceramic, should have approximately the same temperature coefficient as the ceramic. Otherwise either the wire itself or the insulation will break or the wire will touch the metallic shielding. Platinum (7o %) rhodium (3o %)++) wire or titanum wire could be used. Platinum--rhodium wire would be better for vacuum application because no oxidation takes place.

+) Machinable Glass Ceramic, approx. o.6o DM per cm^3, Down Corning Glass, NY, USA; delivered by DISC Corporation, Stanford, Conn., USA

++) Platinum-rhodium wire o.25 mm in diam.,approx. 25.-- DM per metre; Degussa,Hanau ,Germany

Figure 2 shows a drawing of the body of one magnetic probe. In this figure one can see four 2 mm holes where the platinum--rhodium wire is attached before it is wound,inside the slots, around the machinable glass ceramic (see Fig. 2, detail X). Also shown in this drawing is the crossing of the wire. One of these crossing slots is 1 mm and the other slot 2 mm deep.

It should be noted that the winding, which starts on the lower part of the coil form of Fig. 2, uses the 2 mm deep slots and the return winding, which goes from the upper part to the lower part of the coil form in Fig.2, uses the 1 mm slots. The magnetic probes are mounted between a 6 mm and an 8 mm thick stainless-steel ring (see Fig.3), each of them with a slot. A spring made of beryllium copper is used to fix the magnetic probes. Between the coils and the plasma is a 2 mm Alumina plate to shield the coil from plasma particles. The poloidal magnetic field can penetrate into the magnetic probe without delay because no eddy currents can flow in the Alumina plates. To protect the Alumina during glow discharges, sections of 5o mm long and 1 mm thick overlapping stainless-steel plates are used to cover the Alumina (see Fig.3, part 12).

To reduce pick-up signals, the two wires of the magnetic probe has to be twisted. A 2-pair Teflon copper wire (AWG 26; 0.4 mm in diam.) with one strand each and two twists per 1 cm cable length is used (made in our workshop by electric drill). With that kind of cable we measured a noise level <1 mV in the ASDEX environment during the rise time of the plasma current.

For vacuum conditions this wire is located inside a stainless--steel tube (4 mm inside and 6 mm outside diameter). A vacuum feed-through+) is used to connect the magnetic probe with the

+) Feed-through, glass and Inconel X-75o; approx. DM 4o.-- per item. FCT Electronic, Eisvogelweg 32a, 8ooo München 82,Germany wire inside the stainless-steel tubes (see Fig.4). All soldered parts have to be gold-plated so that a special kind of resin (Kolophonium) can be used as flux. (By using the resin for stainless-steel an electrical element is formed. In this case the DC voltage of the element can reach values up to 0,2 volts). The solder temperature is 23o^{o} C (Castolin 157). For even better performance a welded type of feed-through should be used.

A photograph of the magnetic probes is shown in Figs.5 and 6. To reduce stray light (e.g. Thomson scattering), the magnetic probe case is plated with black nickel. Each magnetic probe was tested between one wire and the stainless-steel case with a voltage of 5oo V DC. The insulation resistance has been greater than 5o MΩ.

The poloidal and toroidal magnetic probe arrangement inside the ASDEX vacuum vessel is shown in Table 1.

Table 1

toroidal angle (north ≙ 0°)	number of magnetic probes (see Fig.1)		
	inside	outside	
57° 3o'		1	
78°		1	+)
1o6°	9	15	+)
143° 3o'		1	
162°	9		+)
168°		15	+)
192°		15	
198°	9		
231° 3o'		1	
258°		1	
286°	9	15	
323° 3o'		1	
342°	9		
348°		15	

+) not yet mounted inside the ASDEX vacuum vessel

C) Electrical circuit and calculations

The electrical circuit for the magnetic probes with active differential integrator (triggered after plasma current rise) is shown in Fig. 7. The integrated signals from the different magnetic probes are conveyed with weights (cosine, sine and other characteristics) to an analog computer to detect different movements and modes of the plasma (instead of using mode-selective coils /5/). To reduce the induced voltage by coupling of stray fields, we used twisted and shielded cable (2 twists per 1 cm cable length).

An example of the expected voltage induced in the magnetic probes using normal plasma parameters in ASDEX is mentioned below.

1. Cross-sectional area of magnetic probes
   $A = 10 \times 46 \text{ mm}^2 = 460 \times 10^{-6} \text{ m}^2$

2. Windings $N = 42$

3. Plasma current $J = 500{,}000$ A

4. Limiter radius $a_L = 0.40$ m

5. Distance between magnetic probes and plasma centre $\delta = 0.507$ m

Poloidal magnetic field (toroidal effect neglected)

$$B_\vartheta = \frac{\mu_0 \cdot J}{2\pi\delta} = \frac{4\cdot\pi\cdot 10^{-7}\cdot 5\cdot 10^5}{2\pi\cdot 0.507} = 0.2 \text{ T} = 2000 \text{ G}$$

Induced voltage for dt = 5o ms (rise time of plasma current)

$$e = \frac{d\phi}{dt} = \frac{A \cdot N \cdot dB_{\vartheta}}{dt} = \frac{460 \cdot 10^{-6} \cdot 42 \cdot 0,2}{50 \cdot 10^{-3}} = 77.3 \text{ mV}$$

The measured voltage oscillation of the m = 2 MHD mode is about 4oo mV (peak-to-peak voltage) without integration.

During the disruptive instability of the plasma we measured a current change of 36o kA per 4 ms. This is equivalent to an induced voltage of e = 2.74 V (shot No.658). From this it can be concluded that the marginal induced voltage cannot be dangerous for the insulation of the magnetic probes.
The common mode voltage is reduced by using differential amplifiers after the active integration of the magnetic probe signal and grounding of the cable shield on the stainless--steel vessel.

In the start-up phase of ASDEX we were not able to use active integrators to measure the magnetic probe signal because the active integrators were not available in time.

For that reason we used very precise symmetrically passive integrators to attain in connection with the Preston differential amplifier (1 kV CMV; 65 dB at 10 kHz) a high common mode rejection (to reduce the induced voltage in the circuitry made by thyristor spikes of the main field, ohmic heating, vertical field and divertor coils), see Fig.8.

The time constant of the passive integrator is 4 ms. The tolerance of the 1o kΩ resistors is ± o.1 %,and of the 0.4 μF capacitors ± o.5 %. Even these tolerances are still too high. We therefore adjust the circuit with two 1oo Ω potentiometers. The electrical adjustment of the circuit was done according to Figs. 8 and 9.

With the passive integrator it is possible to integrate the magnetic probe signals with frequencies higher than fg=31 Hz (see Fig. 1o). We measured frequencies between 2oo Hz and 3 kHz.

D) Experimental test results

The MHD oscillations have been found to be much weaker on the inside than on the outside ($\tilde{A}$ outside/$\tilde{A}$ inside ≥ 4). During the disruption of the plasma the MHD activities are more pronounced on the outside of the magnetic probe arrangement. The mode velocity on the "top" or "bottom" can be very different - faster or slower - from the velocity at the inside or outside (nonlinear deformation of the mode) shortly before a disruption. Because of the separatrix it is not possible to mount magnetic probes in the upper or lower region of the plasma boundary (see Fig. 1). For this reason and because of the nonlinearity of the mode it is sometimes difficult to distinguish e.g. between a m=3 or m=4 or any higher MHD mode. We found that most of the MHD activities during the shot are linear (sinusoidal).

The MHD activity is correlated with the soft X-ray and the micro-wave interferometer signals. The MHD mode frequency obtained so far is between 0.2 kHz and 3 kHz.

During the first plasma shots with divertor we found that the MHD oscillations with magnetic limiter are much weaker than with stainless-steel limiter.

The MHD activity at the beginning of the plasma current is shown in Fig. 11.

Figure 12 shows the MHD phase angle (maximum voltage signal) of a certain magnetic probe) versus the poloidal angle and calculates the number of m modes.

During tests we found it to be very important that the magnetic probes are completely covered by stainless-steel or Alumina, even on the side not facing the plasma. Otherwise the plasma in the limiter shadow or on the outside of the separatrix can be the source for spurios current pick ups.

Acknowledgements:

We thank W.Iraschko and S.Schraub for designing the magnetic probes; H.J.Berger for the wiring, installation and the cable-laying-work of the pick-up coils, K.Sahner and our workshop for constructing the magnetic probe segments.

I. Note:

Reference to a company product or name does not imply approval or recommendation of the product by IPP to the exclusion of others that maybe suitable.

References

/1/ L.A.Artsimovich, Nuclear Fusion 2 (1972) page 235.

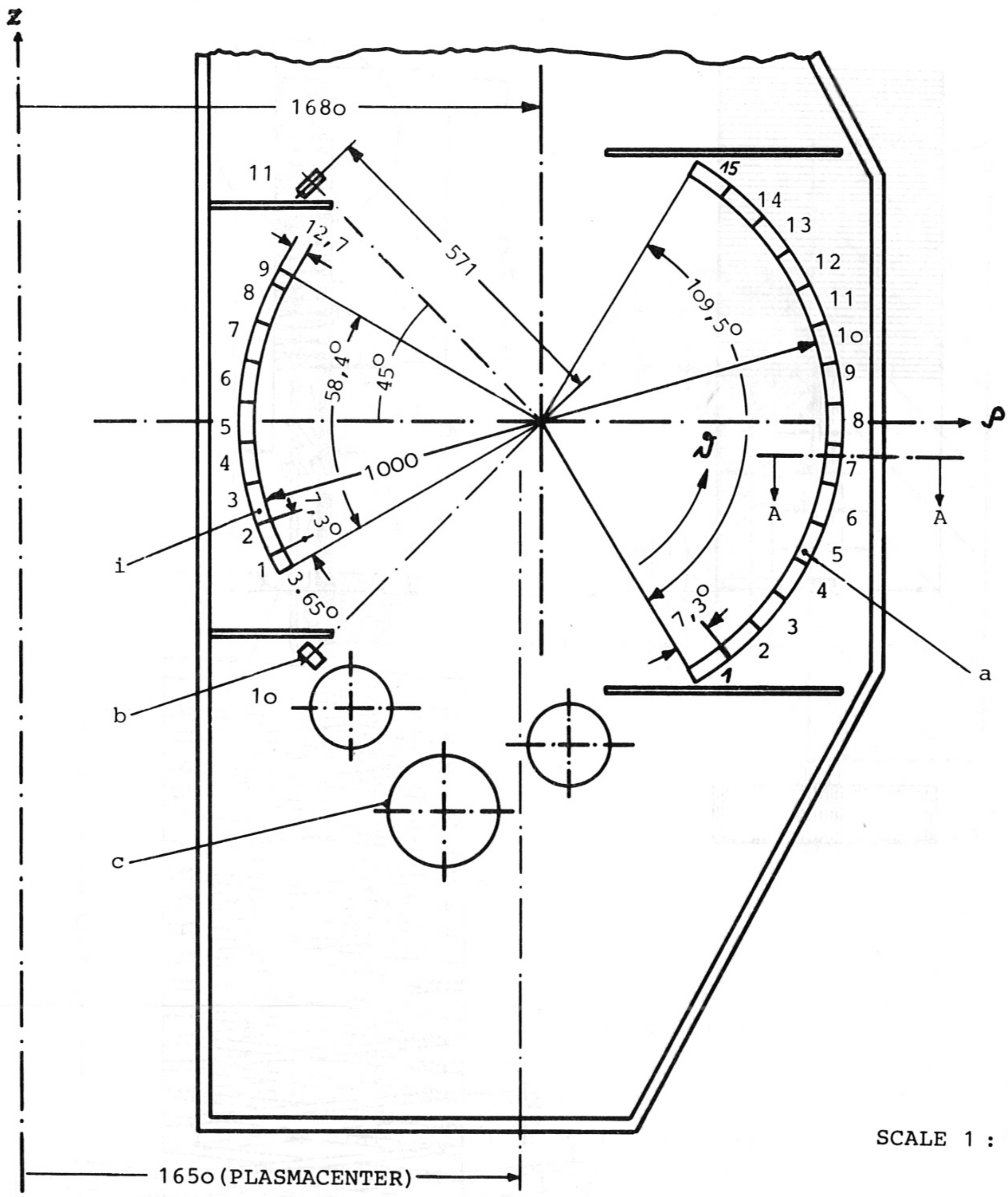
/2/ The ASDEX Group, Divertor Tokamak ASDEX, IPP-Report III/47, Nov. 1978

/3/ F.Karger et al., "On the Origin of the Disruptive Instability in the Pulsator I Tokamak", 6th Int.Conf.on Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, Germany, 1976.

/4/ J. Gernhardt et al., Tokamak Limiter with Built-in Magnetic (Mirnov) Probes for Temperatures of up to 450 ^{o}C, IPP-Report III/26, August 1976.

/5/ L.C.J.M.de Kock et al., "Measurements of Poloidal Magnetic Field Perturbations in Alcator", Rijnhuizen Report 74-86, October 1974.

Figure Captions



SCALE 1 : 1o

a OUTSIDE MAGNETIC PROBE SEGMENT(1o9,5°) WITH COIL No. 1 to 15

i INSIDE MAGNETIC PROBE SEGMENT (58,4°) WITH COIL No. 1 to 9

b MAGNETIC PROBE (45°)

c DIVERTOR COILS (TRIPLET)

FIG.1: OVERALL VIEW OF THE MAGNETIC PROBES MOUNTED INSIDE THE VACUUM VESSEL.

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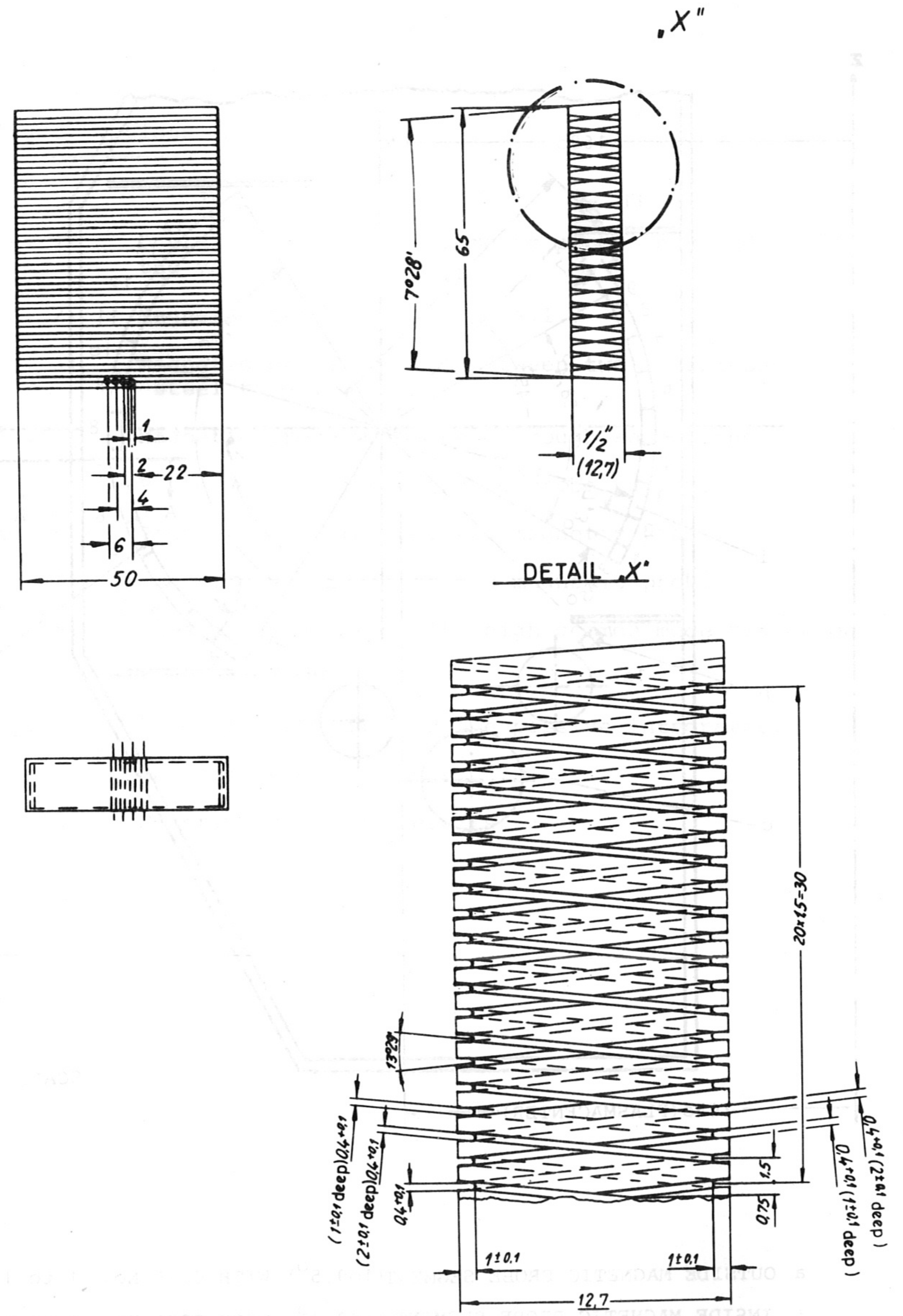

FIG.2: MAGNETIC PROBE BODY IN DETAIL.

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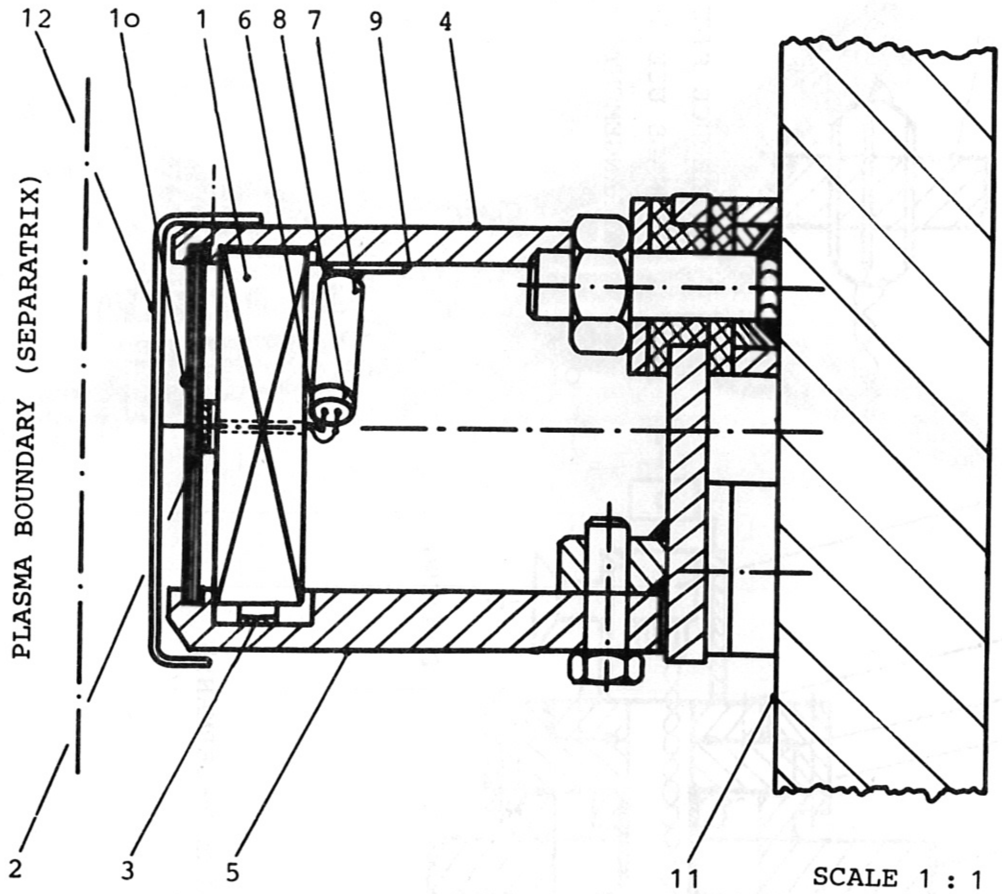
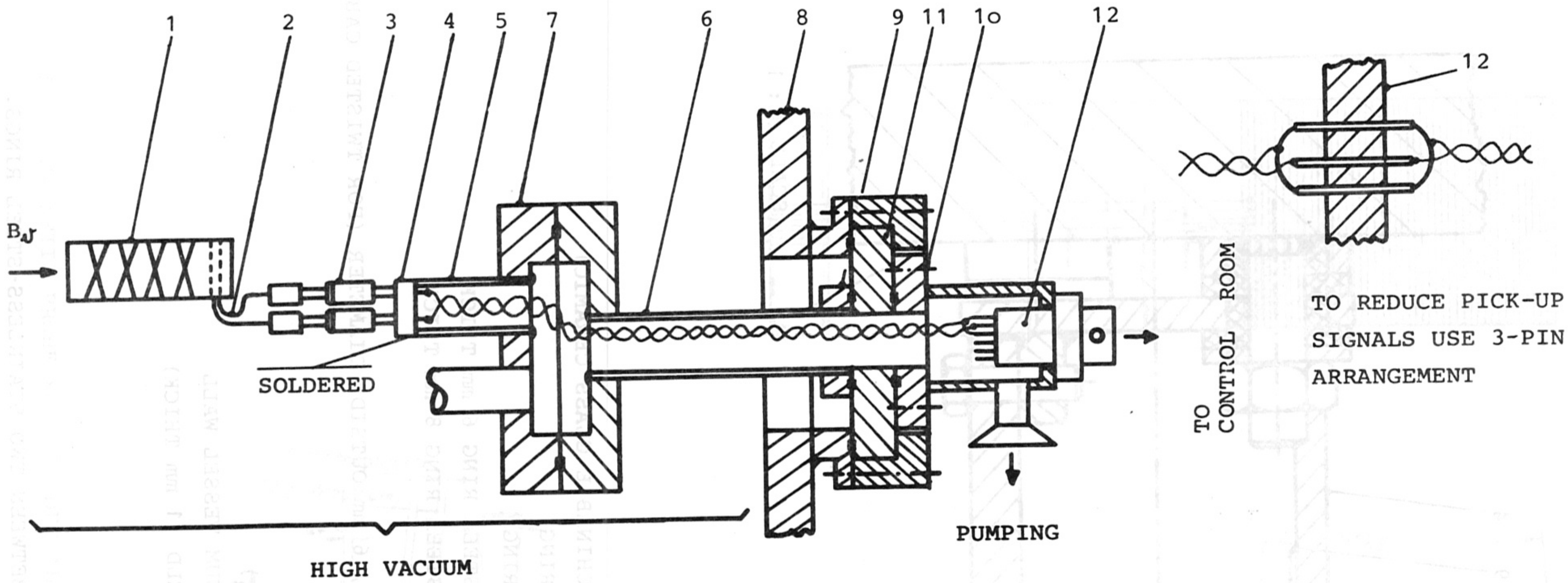
SECTION A-A (SEE FIG. 1)



1 MAGNETIC PROBE (MASCHINABLE GLASS CERAMIC)
2 BERYLLIUM-COPPER-SPRING
3 BERYLLIUM-COPPER-SPRING
4 CIRCULAR STAINLESS-STEEL RING 6 mm THICK
5 CIRCULAR STAINLESS-STEEL RING 8 mm THICK
6 CONNECTORS
7 STAINLESS-STEEL TUBE, 6 mm OUTSIDE DIAMETER (FOR TWISTED CABLE)
8 FEED-THROUGH
9 SPOT WELDED
1o ALUMINA PLATE (AL_2O_3)
11 STAINLESS-STEEL VACUUM VESSEL WALL
12 STAINLESS-STEEL SHIELD (1 mm THICK)

FIG.3: MAGNETIC PROBE MOUNTED BETWEEN TWO STAINLESS-STEEL RINGS.



1 MAGNETIC PROBE
2 PLATINUM-RHODIUM WIRE
3 SOLDERLESS TERMINAL TYP CC- (COMPONENTA OTTOBRUNN, W-GERMANY)
4 FEED THROUGH
5 STAINLESS-STEEL TUBE DIAMETER 6/4 mm
6 STAINLESS-STEEL TUBE DIAMETER 15/13 mm
7 FLANGE NW 35 CF
8 WALL OF STAINLESS-STEEL VACUUM VESSEL
9 FLANGE NW 63 CF
1o FLANGE NW 63 CF
11 FLANGE NW 1oo CF
12 FEEDTHROUGH TYP EFT55; 7A; 7oo V; 55 PIN; NW 35 CF (VACUUM GENERATORS; VG)

FIG.4: MAGNETIC PROBE WITH FEED-THROUGH AND WIRING

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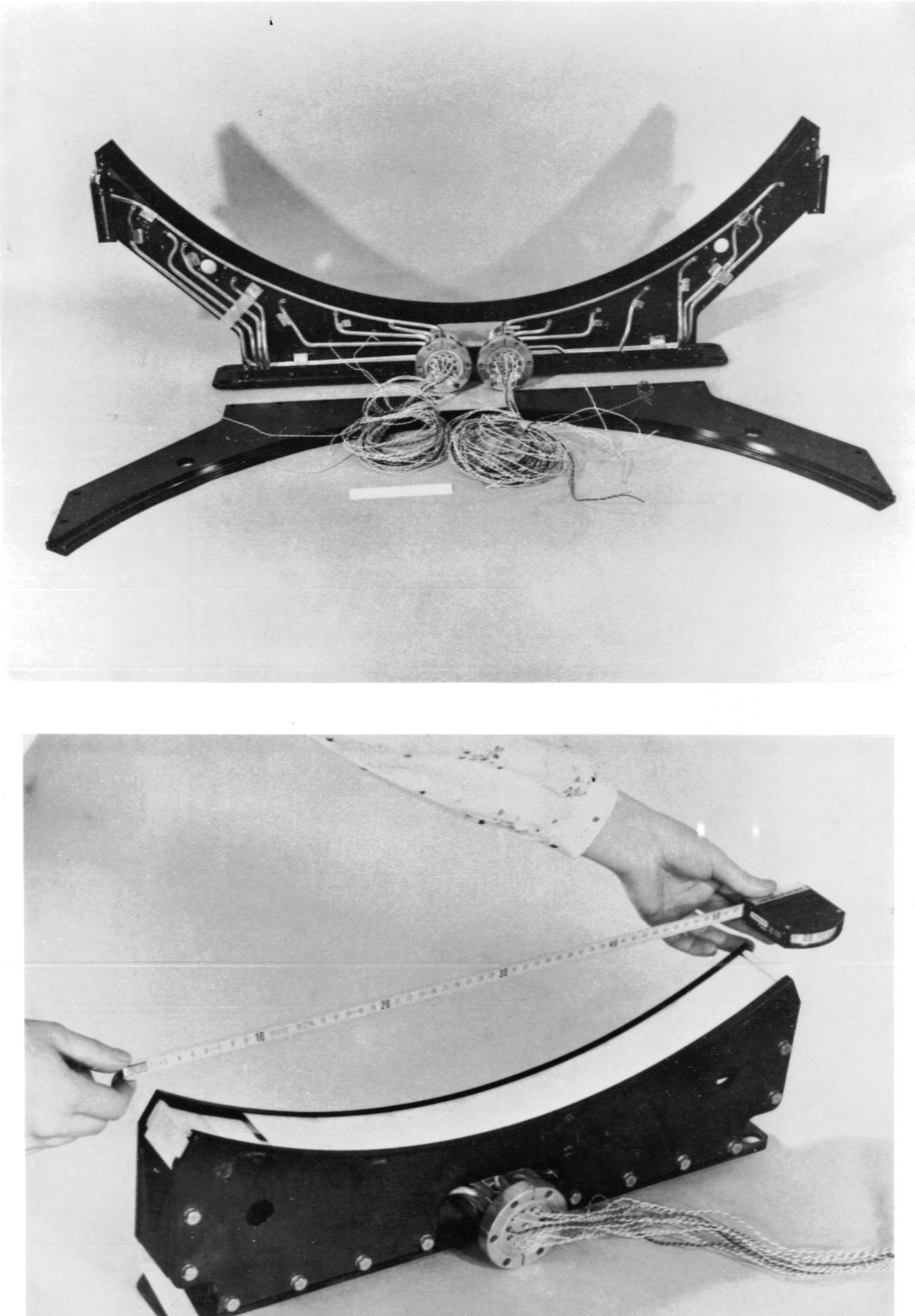


FIG.5: PHOTOGRAPH OF THE MAGNETIC PROBE SUPPORT.

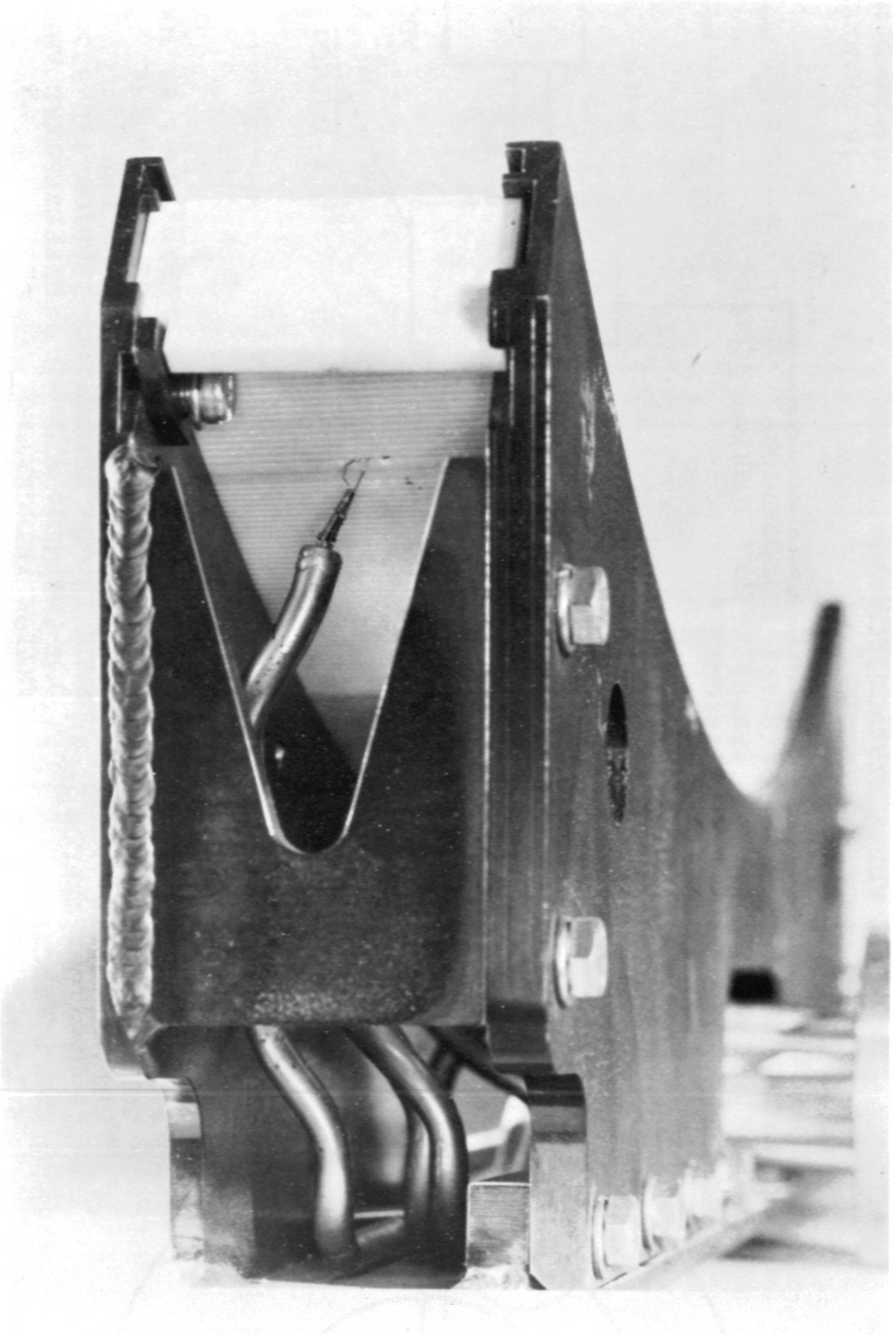
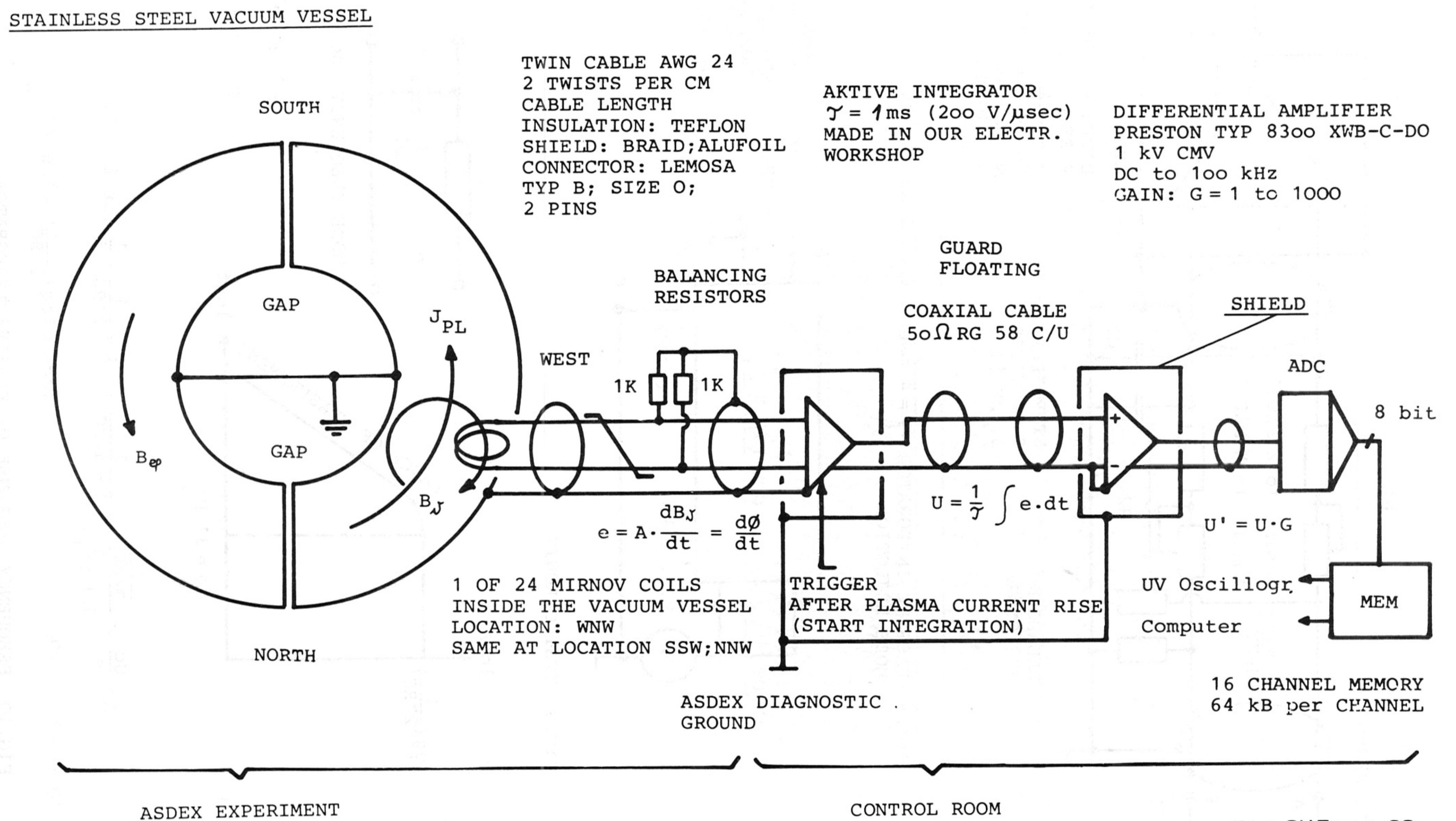


FIG.6: PHOTOGRAPH OF THE MOUNTED MAGNETIC PROBE

FIG.7: ELECTRICAL CIRCUIT OF THE MAGNEITC PROBES.



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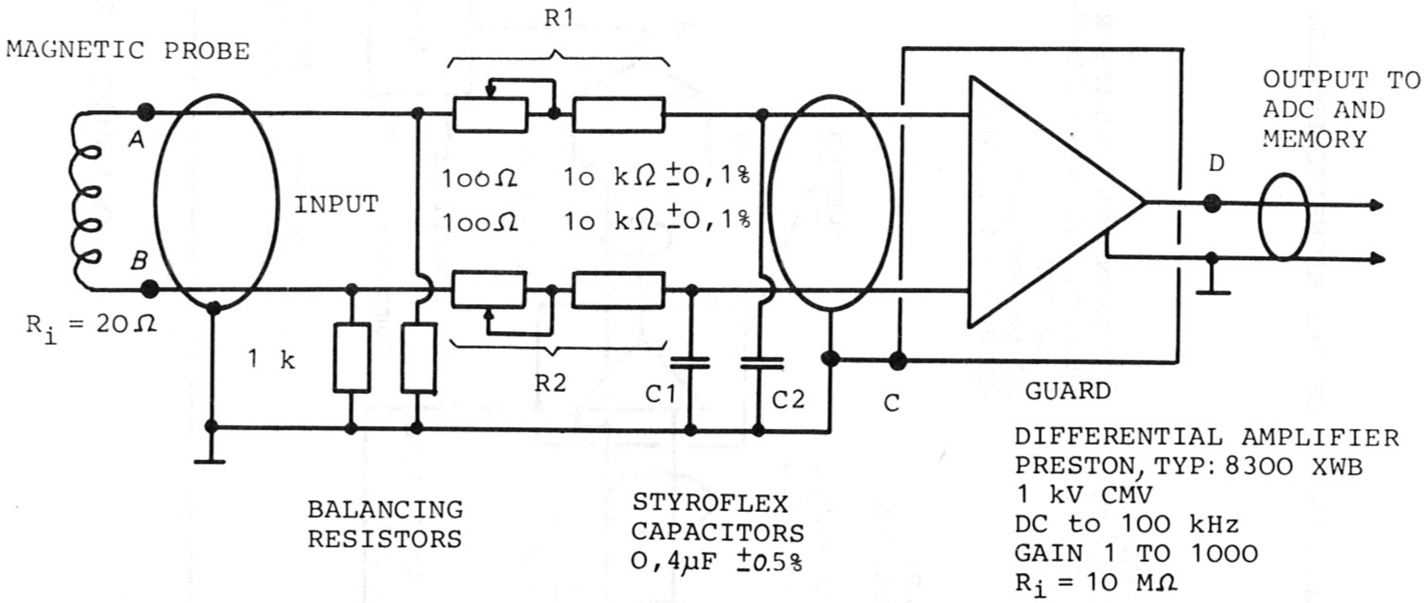


FIG.8 PASSIVE INTEGRATOR (τ = 4 msec) WITH HIGH COMMON MODE REJECTION

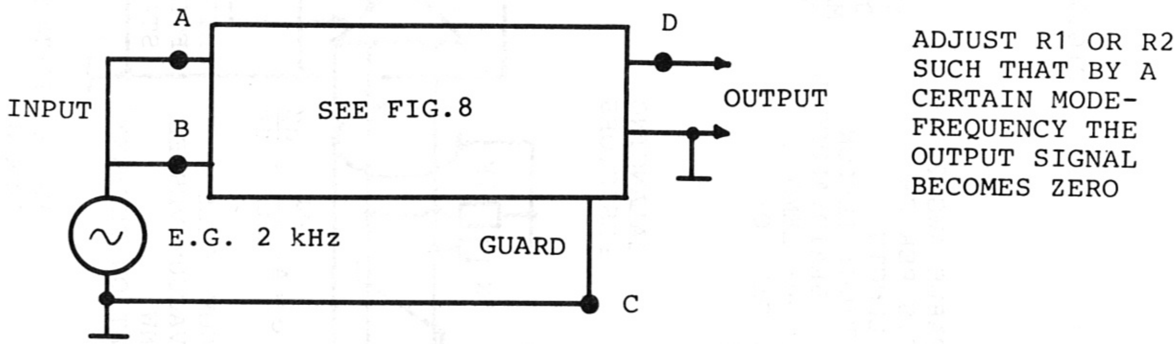
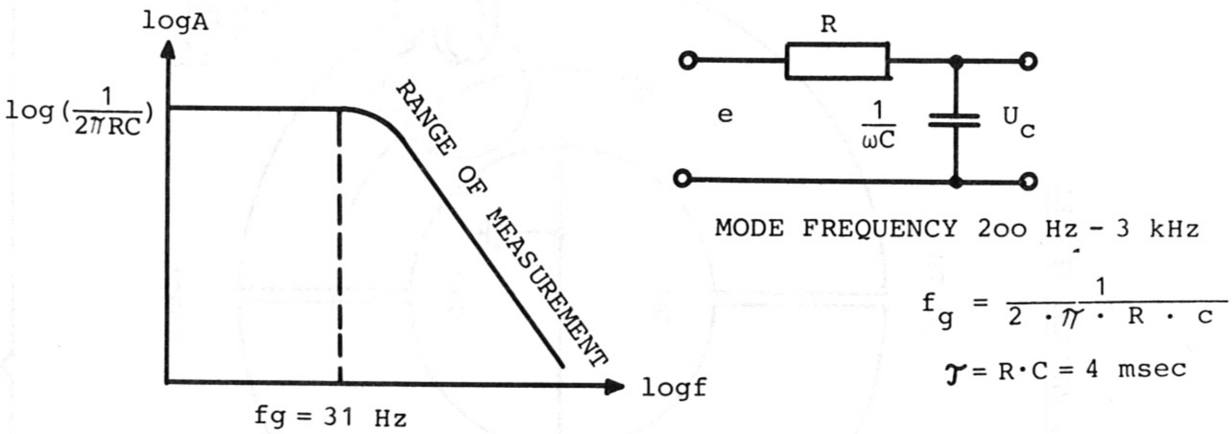


FIG.9 TEST CIRCUIT



$$A = \frac{U_c}{e} = \frac{\frac{1}{j\omega RC}}{R + \frac{1}{j\omega RC}} = \frac{1}{1 + j\omega RC} \; ; \quad A = \frac{1}{2\pi RC} \cdot \frac{1}{f} \text{ for } f \gg fg$$

$$\log A = \log\left(\frac{1}{2\pi RC}\right) - \log f$$

FIG.10 FREQUENCY RESPONSE OF PASSIVE INTEGRATOR

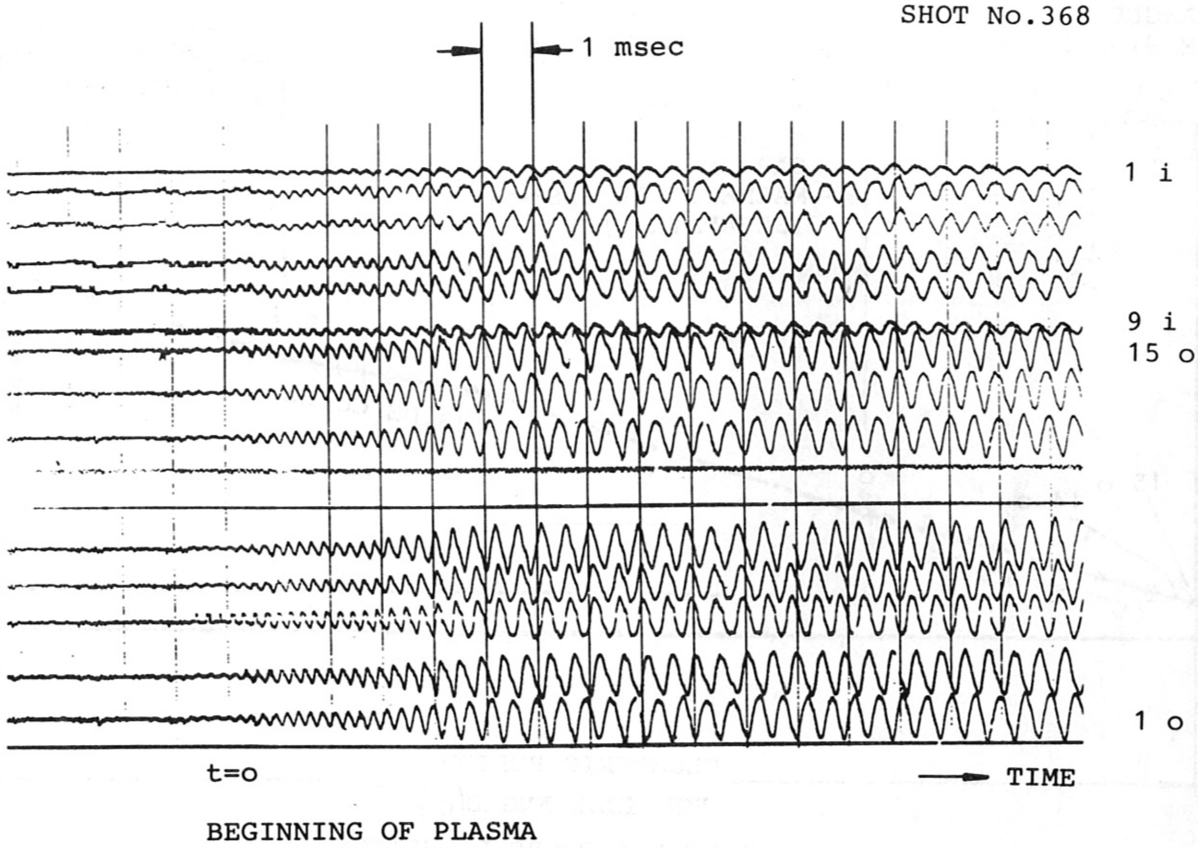


Fig.11: MAGNETIC PROBE SIGNALS

3 PERIODS BEFORE DISRUPTION
(SHOT No. 373)

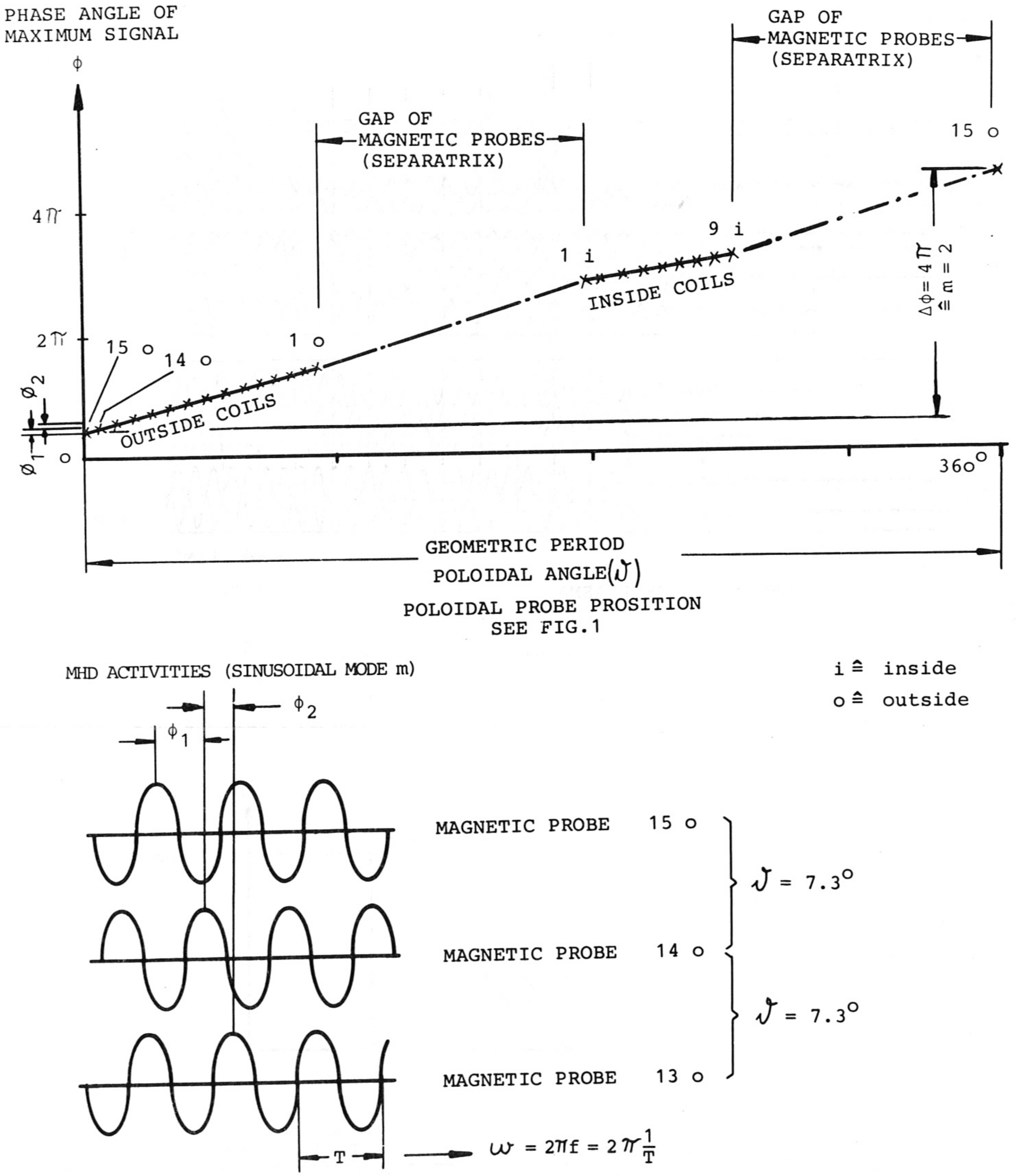


FIG.12: EXPERIMENTAL TEST RESULTS

MHD ACTIVITIES SINUSOIDAL MODE

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