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RF COUPLER TECHNOLOGY FOR FUSION APPLICATIONS*

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ABSTRACT

Radio frequency (rf) oscillations at critical frequencies have successfully provided a means to convey power to fusion plasmas due to the electrical-magnetic properties of the plasma. While large rf systems to couple power to the plasma have been designed, built, and tested, the main link to the plasma, the coupler, is still in an evolutionary stage of development. Design and fabrication of optimal antennas for fusion applications are complicated by incomplete characterizations of the harsh plasma environment and of coupling mechanisms. A brief description of rf coupler technology required for plasma conditions is presented along with an assessment of the status and goals of coupler development.

BACKGROUND

The need for auxiliary rf heating arose when ohmic heating alone was found to be insufficient for obtaining fusion. Early experiments on the B-65[1] and Model C[2] devices clearly demonstrated that rf energy could heat a plasma by means of ion cyclotron resonance heating (ICRH). Optimistic confidence in plasma theory led researchers to use "Stix coils," shown in Fig. 1, to couple the power. Up to 2 MW was coupled by these antennas, but heating was unexpectedly low due to poor energy confinement in the Model C experiment. Subsequent changes in plasma confinement devices would render these antennas impractical.

Subsequently, Becker et al.[3] demonstrated that electron cyclotron resonance heating (ECRH) could heat and ionize plasmas. Also, Golant et al.[4] showed that a third mechanism, lower hybrid resonance heating (LHRH), might have plasma applications. As with ICRH, changes in the confining devices necessitated changes in the launching apparatus.

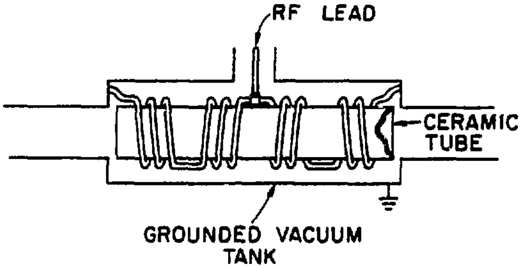

Fig. 1. Stix coil and shield box for ion cyclotron resonance experiments. Redrawn with permission after T. H. Stix and R. W. Palladino, *Phys. Fluids*, 1, 446 (1958).

Through the course of experiments, a number of rf applications and potential applications have become evident. Although they are functions of the particular confinement device, a general roster is given in Fig. 2. The main applications are plasma heating to ignition, plasma current drive for sustaining confinement, and plasma generation.

The appropriate frequency, power, and antenna configuration are functions of the confinement device parameters. In particular, the wave resonance, electron density, magnetic

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FREQUENCY RANGE \ rf APPLICATION	BULK HEATING*	CURRENT DRIVE*	PLASMA GENERATION*	STARTUP*	PROFILE CONTROL	IMPURITY CONTROL
ICRF	■	●	○	■	○	○
LHRF	●	■	○	○	–	○
ECRF	●	●	■	●	●	○

*MAJOR APPLICATION OF rf

DEFINITIONS

■ : SERIOUS CANDIDATE FOR ENGINEERING TEST REACTOR HIGHEST PRIORITY
● IMPORTANT RESEARCH ITEM FOR ADVANCED TOROIDAL PROGRAM
○ REQUIRES ASSESSMENT BUT NO EXTENSIVE R&D IS WORTHWHILE UNLESS INITIAL RESULTS ARE EXCEPTIONAL
– NOT OF INTEREST

Fig. 2. Assessment of rf applications.

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field, and physical size of the machine impose constraints (Table 1). For magnetic fields of 1-3 T and densities of $\sim 3 \times 10^{13}$ cm^{-3}, typical frequencies are 15-45 MHz for ICRH, 0.8-4.6 GHz for LHRH, and 28-60 GHz for ECRH. The low frequency of ICRH and the 1- to 2-m size of confinement devices make loop antennas more practical for present machines. Waveguide ICRH launchers would have to be $\sim$3 m long, thus limiting the heating method until both the frequency and the machine size increase by a factor of 2. At present, LHRH and ECRH are not constrained to having loop antennas because the higher frequency permits waveguide antennas.

One final constraint is the required power. Transport of particle energy favors a large machine volume V. The Lawson criterion specifies the ultimate required temperature T_i, density n, and confinement time τ_E. For present experiments the power, $P_{rf} \sim [nk\Delta(T_i + T_e)V]/\tau_E$, is on the order of 1-5 MW. For LHRH and ECRH, this necessitates using several waveguides or waveguide arrays.

STATUS AND FUTURE REQUIREMENTS

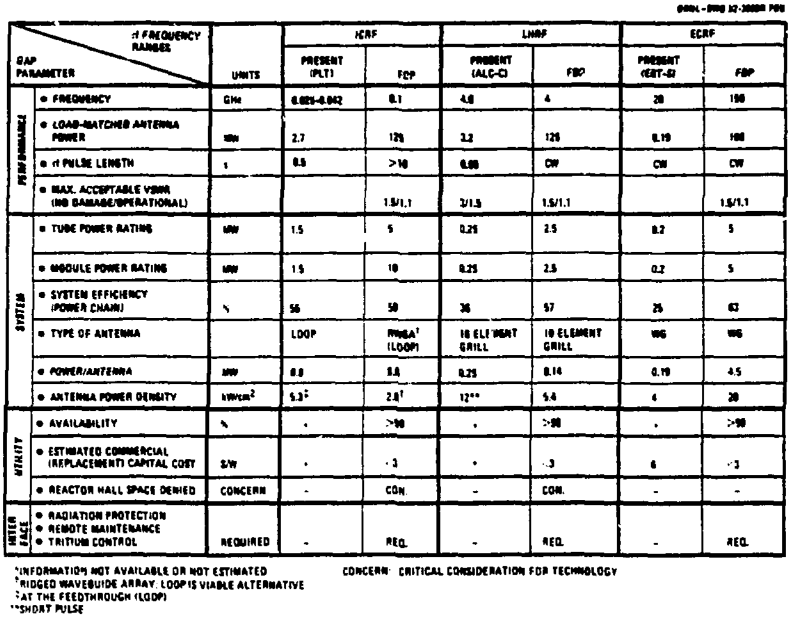
The status of antenna performance is characterized by three state-of-the-art experiments, as shown in Fig. 3. The total power is on the order of 3 MW for ICRH and LHRH. ECRH power is somewhat lower (200 kW) due to the difficulty of obtaining rf power. Since different problems are peculiar to each frequency regime, each range is described. At this time, ICRH experiments in the Princeton Large Torus (PLT)[5] are characterized by large antennas (Fig. 4). The antenna assembly has a Faraday shield to reduce undesired electrostatic rf fields and to protect the antenna from the plasma environment. The short rf pulse (0.05-0.5 s) permits inertial cooling. In order to minimize impurity injection, various materials (such as titanium, titanium carbide, or stainless steel) have been exposed to the plasma. The antenna itself has a characteristic real impedance of $\sim$1-5 Ω. This impedance mismatch ripples back through the current feeds to an impedance-matching network. The coaxial current feeds must be able to handle the high currents and voltages associated with the mismatch. Despite the low impedance and high antenna current, approximately 800 kW at 25 MHz has been coupled through a single antenna in the plasma.

Experiments at 4.6 GHz on Alcator-C[6] characterize the LHRH antenna performance. Since current drive requires a wave number spectrum with a net toroidal direction, the array of waveguide antennas requires phase controllability (Fig. 5). The waveguides (using the TE_{10} mode) have the same phase in a column and different phases in adjacent columns. The

Table 1. RF heating applications, frequencies, and characteristics

	Application	Frequency[a]	Polarization at plasma boundary	Additional constraints
ICRH	Heating	$(1\text{-}3)f_{ci},\ f_{ci} = \frac{q_i B}{2\pi m_i}$	$B_{rf} \parallel B$, fast wave	
LHRH	Current drive	$(1\text{-}3)f_{lh}$ $f_{lh} = \left(\frac{1}{\frac{nq_i^2}{4\pi^2 m_i \epsilon_0} + f_{ci}^2} + \frac{1}{f_{ci} f_{ce}}\right)^{-1/2}$	$E_{rf} \parallel B$	Must control $N_\parallel$ spectrum and direction
ECRH	Heating, plasma generation	$(1\text{-}2)f_{ce},\ f_{ce} = \frac{q_e B}{2\pi m_e}$	$E_{rf} \parallel B$ (0 mode) $E_{rf} \perp B$ (X mode)	X mode — high field launch and density cutoff

[a] q_i = ion charge, q_e = electron charge, m_i = ion mass, m_e = electron mass, B = confining magnetic field, ϵ_0 = permittivity constant, f_{ci} = ion cyclotron frequency, f_{lh} = lower hybrid frequency, f_{ce} = electron cyclotron frequency.



	GAP PARAMETER \ rf FREQUENCY RANGES	UNITS	ICRF		LHRF		ECRF	
			PRESENT (PLT)	FDP	PRESENT (ALC-C)	FDP	PRESENT (EBT-S)	FDP
PERFORMANCE	• FREQUENCY	GHz	0.025-0.042	0.1	4.6	4	28	150
	• LOAD-MATCHED ANTENNA POWER	MW	2.7	125	2.2	125	0.19	100
	• rf PULSE LENGTH	s	0.5	>10	0.08	CW	CW	CW
	• MAX. ACCEPTABLE VSWR (NO DAMAGE/OPERATIONAL)			1.5/1.1	3/1.5	1.5/1.1		1.5/1.1
SYSTEM	• TUBE POWER RATING	MW	1.5	5	0.25	2.5	0.2	5
	• MODULE POWER RATING	MW	1.5	10	0.25	2.5	0.2	5
	• SYSTEM EFFICIENCY (POWER CHAIN)	%	56	50	36	57	25	63
	• TYPE OF ANTENNA		LOOP	RWGA† (LOOP)	16 ELEMENT GRILL	10 ELEMENT GRILL	WG	WG
	• POWER/ANTENNA	MW	0.8	8.8	0.25	0.14	0.19	4.5
	• ANTENNA POWER DENSITY	kW/cm²	5.3‡	2.8†	12**	5.4	4	20
UTILITY	• AVAILABILITY	%	*	>90	*	>90	*	>90
	• ESTIMATED COMMERCIAL (REPLACEMENT) CAPITAL COST	$/W	*	<3	*	<3	6	<3
	• REACTOR HALL SPACE DENIED	CONCERN	-	CON.	-	CON.	-	-
INTERFACE	• RADIATION PROTECTION • REMOTE MAINTENANCE • TRITIUM CONTROL	REQUIRED	-	REQ.	-	REQ.	-	REQ.

*INFORMATION NOT AVAILABLE OR NOT ESTIMATED
†RIDGED WAVEGUIDE ARRAY; LOOP IS VIABLE ALTERNATIVE
‡AT THE FEEDTHROUGH (LOOP)
**SHORT PULSE

CONCERN: CRITICAL CONSIDERATION FOR TECHNOLOGY

Fig. 3. The technology gap between operating devices and FDP, presented in terms of key system characteristics.

antennas are made with stainless steel and are actively cooled despite the short pulse length. Coupling is best when the antennas are very close to the plasma (∼1 cm); once again, impurities arising from the antenna are a matter of important studies. The combination of an electron cyclotron resonance and the impurities inside the waveguide can also lead to arcing. The power density through each antenna is approximately 10 kW/cm², with each waveguide carrying a maximum of 65 kW. The VSWR observed on the antennas is approximately (1.5-3):1; this provides a possible cause for the sometimes-observed breakdown on the beryllium oxide windows. The breakdown may also limit the power density, although it is probably already sufficient.

Electron heating and ring formation experiments on ELMO Bumpy Torus-Scale (EBT-S)[7] are partially indicative of the status of ECRH antennas. The 28-GHz, 200-kW EBT-S system is designed for continuous wave (cw) operation. The low electron density of 1-2 × 10^{12} cm^{-3} still mandates active cooling. Since wave polarization is not extremely important for plasma breakdown and ring formation, the antennas are merely an aperture in the aluminum vacuum walls. Thus, EBT-S has coped with cw operation but has not truly controlled polarization. For heating experiments on tokamaks, such as Doublet III[8] or the Impurity Study Experiment (ISX-B),[9] the polarization is important. On ISX-B, 300 kW at 35 GHz is coupled through the plasma from the high field side by converting a TE_{01} mode in a 6-cm (2.375-in.) circular waveguide to linear polarization with a Wengenroth reflector.

A summary of problems in present couplers is given in Table 2. One difficulty common to all three regimes is that the optimum configuration of the antenna is not known. Resolution of this issue is a major goal of both the confinement program and the development and technology (D&T) program. The other serious problem, which will only become worse in the future, is the suitability of antenna assemblies for long pulse operation. Cooling for dielectric windows and for elements that contact the plasma has not had to be designed to handle thermal stress because of the short duration of the rf heating. However, 0.5-s discharges approach the thermal equilibrium times, so that the full impact of high

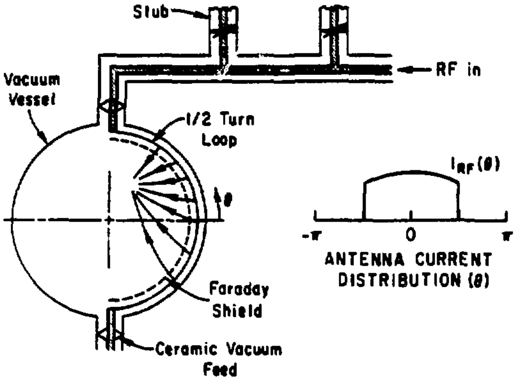


Fig. 4. The half-turn ICRH loop antennas inside the PLT vacuum chamber.

power is starting to be felt by these components.

The next generation of confinement devices will pose a new set of technological requirements. Figure 3 compares some technology parameters required for the Fusion Demonstration Plant (FDP) and the status today. There is a quantum leap in total power and pulse length. The impact of the change in frequency on the rf coupler is not known because there is little experience with couplers in this plasma environment at the new frequency. The plasmas will have tritium, a clear health hazard. For the International Tokamak Reactor (INTOR),[10] a 160-g inventory must be contained well enough to keep personnel exposure below 0.5 rem/year. The thermal loading is expected to be ∿300 W/cm^2. Also, since there will be an abundance of neutrons, coupler assemblies must be remotely maintainable.

Fig. 5. Waveguide grill used in Alcator-C LHRH experiments at MIT.

Table 2. Present rf coupler technology issues

ICRF

- VOLTAGE STANDOFF (ANTENNA COMPONENTS AND FEEDTHROUGHS)
- FARADAY SHIELD
  - UNDERSTANDING OF HOW IT WORKS
  - AMOUNT AND DISTRIBUTION OF COOLING
  - CONTROL OF *IMPURITY AND NEUTRALS INFLUX TO* THE PLASMA
  - DEVELOPMENT OF MATERIALS WITH ADEQUATE THERMAL/ELECTRICAL CONDUCTIVITY
- MATCHING NETWORK
  - MAINTENANCE OF MATCHING NETWORK IN THE PRESENCE OF HIGH CIRCULATING CURRENTS AND VOLTAGES
  - *FEASIBILITY OF NEW* TECHNIQUES FOR IMPEDANCE MATCHING (E.G., DISTRIBUTED CAPACITANCE)
- SELECTION OF BEST ANTENNA CONFIGURATIONS (E.G., REQUIRE PREDICTIVE CODES FOR ANTENNA-PLASMA COUPLING)
- SYSTEM COOLING FOR STEADY-STATE POWER OPERATIONS
- MICROWAVE SHIELDING OF FEEDTHROUGHS
- SUFFICIENT BANDWIDTH FOR PROPER EXPANSION OF THE PHYSICS DATABASE IS OFTEN PROHIBITIVELY EXPENSIVE

LHRF

- ELIMINATION OF BREAKDOWN IN THE GRILL
- ELIMINATION OF BREAKDOWN AT THE VACUUM WINDOW BY USING LONG CONDITIONING TIMES OR COATINGS
- DEVELOPMENT OF CIRCULATORS CAPABLE OF HANDLING HIGHER POWER
- DEVELOPMENT OF VACUUM WINDOWS CAPABLE OF HANDLING HIGHER POWER
- LAUNCHING STRUCTURES FOR CURRENT DRIVE OR HEATING ARE ADEQUATE, BUT OPTIMUM CONFIGURATIONS ARE UNKNOWN DUE TO THE *INCOMPLETE PHYSICS DATABASE*

ECRF

- MODE SELECTION AND CONTROL
  - SELECTION AND PRODUCTION OF DESIRED POLARIZATION IN ANTENNA
- WINDOW BREAKAGE AT HIGH POWER
- RELIABILITY OF COMPONENTS IN STEADY-STATE MODE
- ANTENNA DIRECTIVITY

Before the dramatic conditions of FDP must be faced, plans for a 20-MW ICRH experiment on Doublet III and for a 30-MW experiment on the Tokamak Fusion Test Reactor (TFTR) upgrade, TFTR-U, will require coupler development to begin coping with the cooling problem. Since TFTR is expected to be "hot," remote maintenance is a requirement. In addition, 10 MW of LHRH power may be used on TFTR-U for current drive. For ECRH, 2 MW at 60 GHz will be used on Doublet III, and ∿1 MW at 56 GHz will be used on the Mirror Fusion Test Facility (MFTF) upgrade, MFTF-B. In each machine, coupler optimization, long pulse (∿10-s) operation, and a hotter plasma environment must be dealt with technologically.

SUMMARY

Coupler technology for plasma applications is in a state of change: it is on the verge of demanding serious engineering for material, electrical, and structural aspects.

Reactor-relevant cw antennas will require new developments. Experience gained from both near-term experiments and off-line development facilities is expected to further elucidate the nature and restrictions of plasma-compatible rf couplers.

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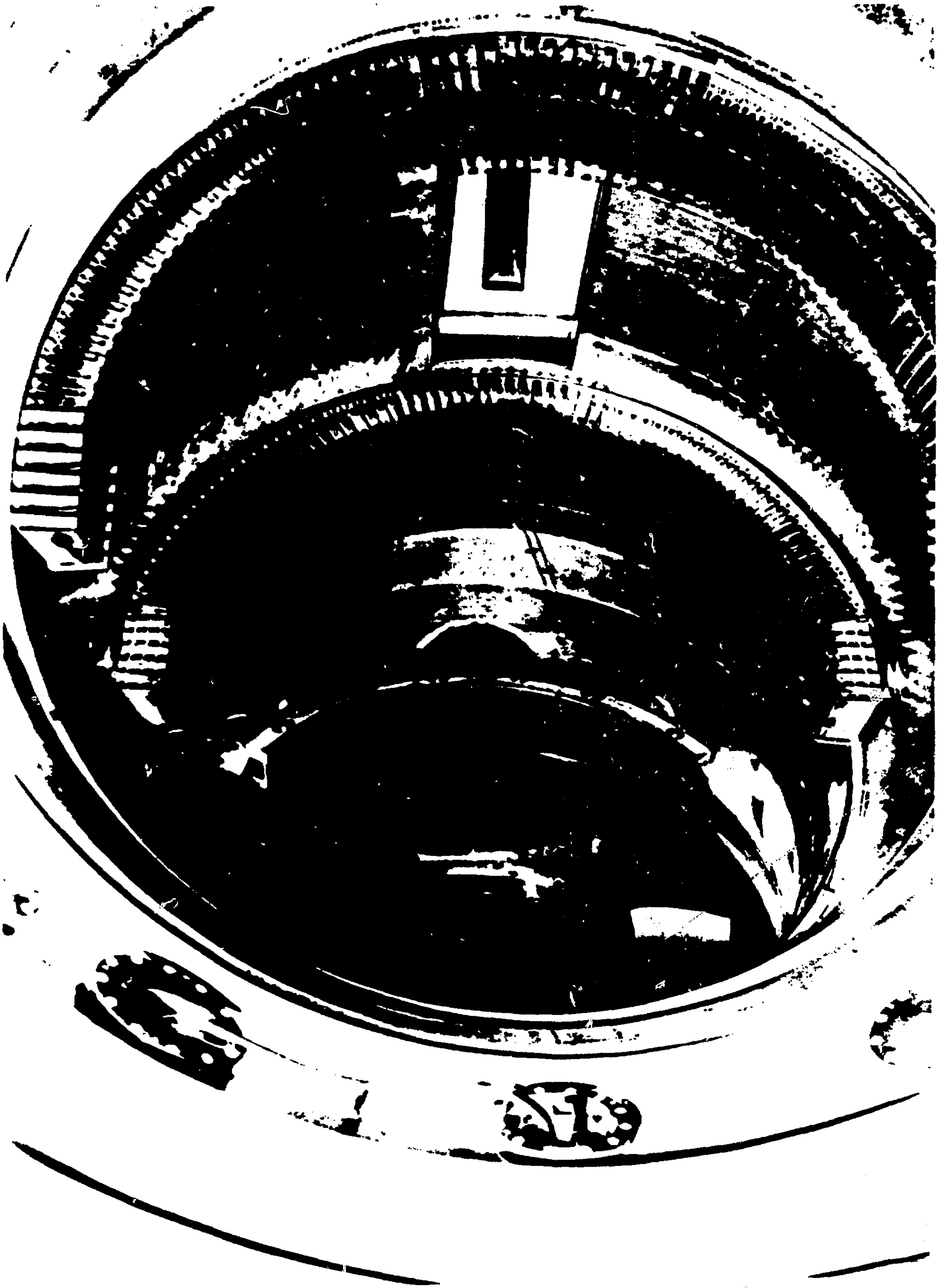

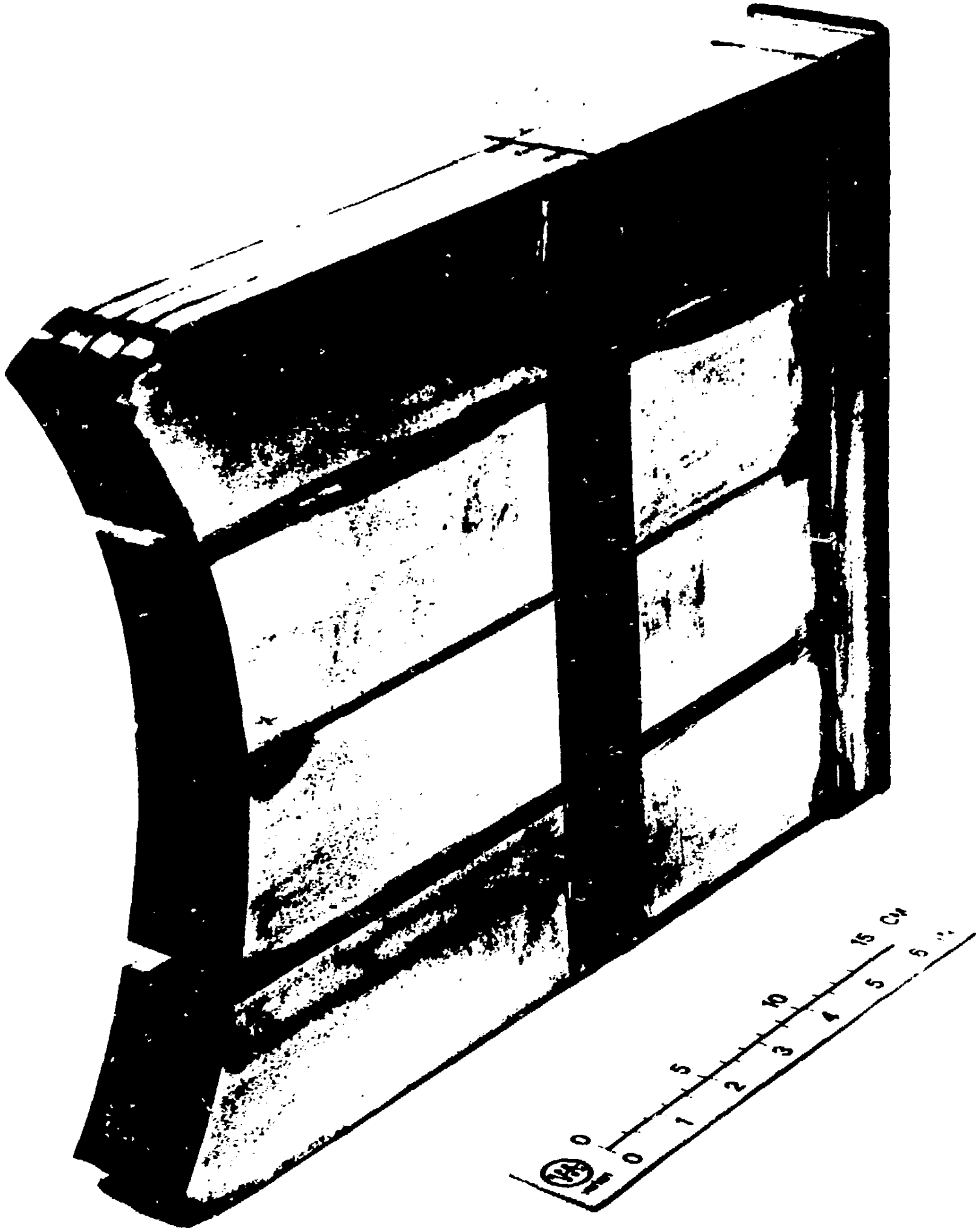
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