

## **RF Superconductivity at Interatom**

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### **I Introduction**

Since more than ten years Interatom is working in the field of rf superconductivity mainly by developing and fabricating superconducting accelerator cavities and complete accelerator modules for nuclear and high energy physics and for free electron laser (FEL) application.

The RF superconducting work ist part of the Accelerator and Magnet Technology Department which is committed to

**layout, design, construction and testing of**

- . accelerator components and**
- . magnet systems**

**with focus on**

- . normal and superconducting accelerator units**
- . normal and superconducting magnet systems**
- . ultra high vacuum and rf systems**
- . beam transport lines**
- . advanced accelerator concepts like**
  - synchrotron radiation sources**
  - free electron lasers**
- . high temperature superconductivity/rf test systems**

Our team incorporates the necessary engineering resources and it has developed mutual relationships with national and international research and development groups.

The manufacturing department is equipped for all relevant materials, mechanical processes and treatments, inspection and quality assurance procedures. Emphasis is laid on precision manufacturing and assembly, of joining techniques incl. electron beam welding, laser welding and high temperature vacuum brazing processes.

## II Superconducting accelerator projects

Interatom has built about 50 niobium cavities and several s.c. accelerator modules mainly for national and international research institutes [table 1]. Examples of those projects are given in the following.

Until today for CEBAF we built 4 five cell 1.5 GHz cavities of the Cornell type, prepared and assembled them to 2 hermetically sealed 'cavity pairs' (Fig 1) and performed cryogenic rf tests. With acceleration fields between 8.8 and 12.1 MV/m at cavity Q values above  $2 \times 10^9$  at 2.1 K [3, 9] the results were well in excess of the required values ( $E_a \geq 5$  MV/m,  $Q_0 \geq 2.4 \times 10^9$ ).

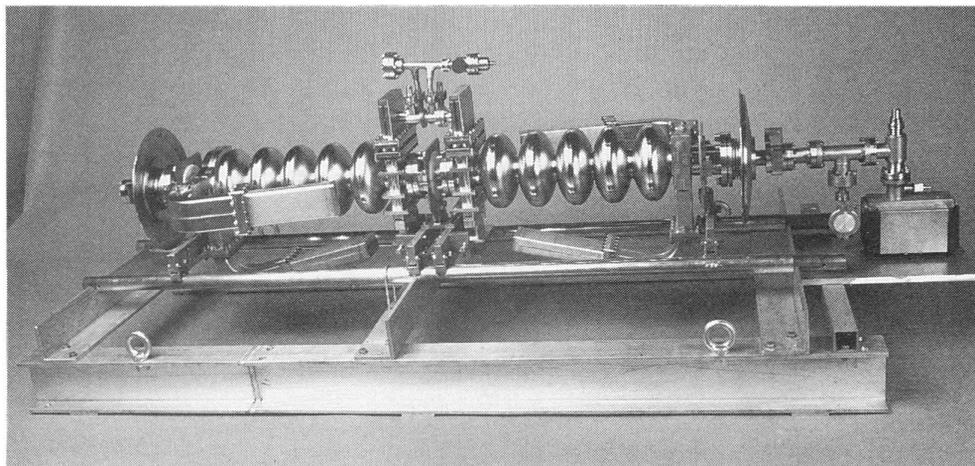


Fig. 1: Accelerating module for CEBAF consisting of two hermetically sealed five cell cavities readily mounted for installation in the beam line cryostat

In the meanwhile both pairs have been transported to CEBAF (Fig. 2) without degradation of performance and have been mounted into the first CEBAF cryomodule (housing 8 cavities) ready for test in autumn 1989.

Quantity	Cells per Structure	Frequency	Customer	Qo at 5 MV / m	Ea (MV / m)	Comment
1	Helix	40 MHz	CEA/F	$> 2.5 \times 10^9$	12.1; 10.4; 9.4; 8.8	hermetically sealed "cavity pair" cavity and cryostat, completely accembled
4	5	1.5 GHz	CEBAF	$2 \times 10^9$	5.4; 8.5	
2	4	350 MHz	CERN	$> 3 \times 10^9$	12.3	RRR 120
5	1	3 GHz	CERN	$> 3 \times 10^9$	7.4 (typ. 4)	RR 120 (< 40)
1	5	3 GHz	Darmstadt	$> 10^9$	8.9	Nb/Cu by explosion bonding, pipe cooled
11	20	3 GHz	Darmstadt			
1	1	500 MHz	DESY	$10^9$	5.7; 6.7	RRR < 40, T = 3.7 and 2.7 K
1	1	1 GHz	DESY			still in fabrication
1	2	1 GHz	DESY	$> 3 \times 10^9$	10.2	RRR > 150
1	5	1 GHz	DESY	$> 3 \times 10^9$	9 + 12.6	still in fabrication, Nb/Cu pipe cooled
2	9	1 GHz	DESY			RRR > 150
4	4	500 MHz	INFN			
1	1	3 GHz	LANL			
1	1	402 MHz	LANL			
2	1	1.5 GHz	Saclay			
1	1	1.5 GHz	Saclay			
3	1	9.5 GHz	Siemens			
1	2	500 MHz	TRW			
1	1	1 GHz	Wuppertal	$> 3 \times 10^9$	12	RRR = 288
2	1	1.5 GHz	Wuppertal	$> 3 \times 10^9$	12 - 25	RRR > 90
4	1	3 GHz	Wuppertal	$> 3 \times 10^9$	5.6	RRR < 40
1	3	3 GHz	Wuppertal	$> 3 \times 10^9$	4	RRR < 40
2	5	3 GHz	Wuppertal			
1	20	3 GHz	Wuppertal			
1	32	8 GHz	Wuppertal			
1	1	23 GHz	Wuppertal			
1	1	86 GHz	Wuppertal			

**Table 1:** Interatom fabricated superconducting accelerating cavities/modules (delivered or under contract) and rf performance



Fig. 2:  
Transportation of a  
completely tested  
superconducting  
accelerator module  
for CEBAF/USA

The manufacture of the series of the 360 CEBAF-cavities has just been started.

For CERN two superconducting accelerator modules each consisting of a 350 MHz niobium 4 cell cavity, couplers and a cryostat have been manufactured and assembled in 1988 (Fig. 3, 4). The obtained accelerating fields are 5.4 and 8.5 MV/m, respectively [7]. Details of this project are given in [2]. These two units are now assembled with 2 other modules from CERN for a beam test in the near future.

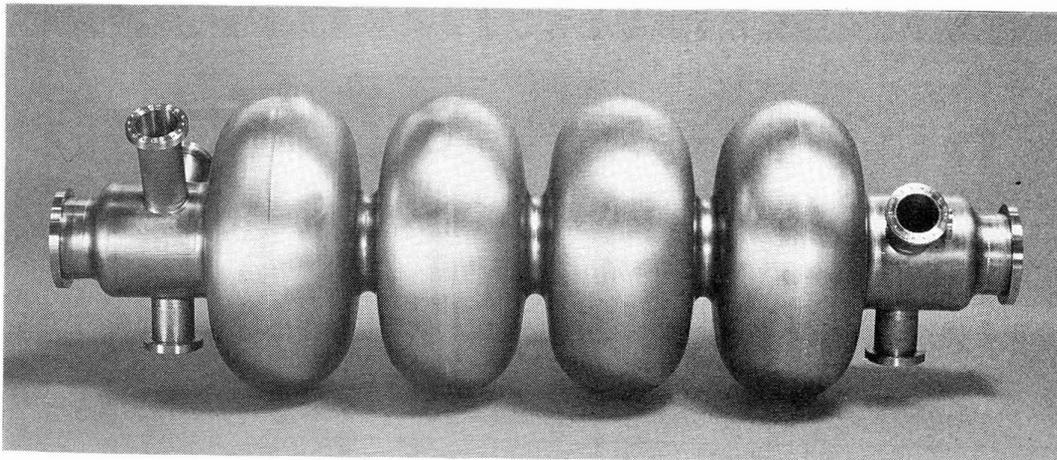


Fig. 3: Superconducting 350 MHz cavity for LEP/CERN

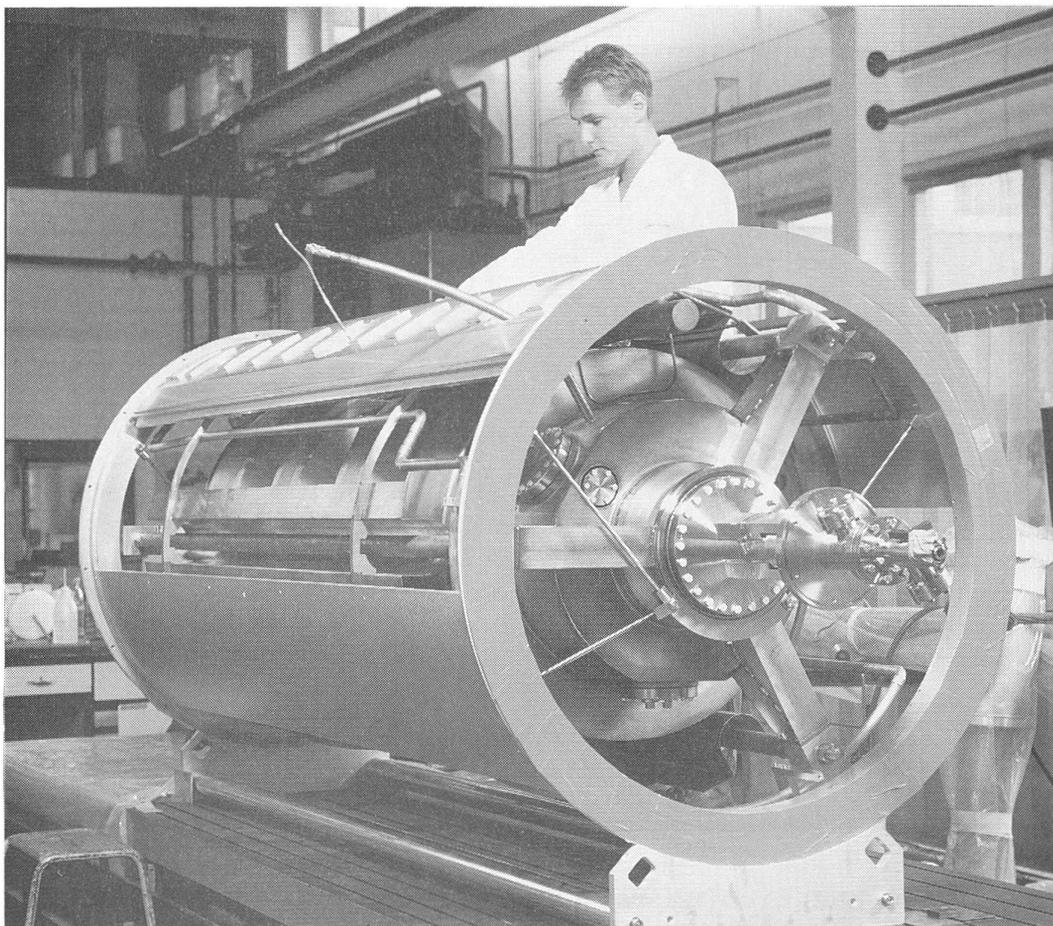


Fig. 4: Integration of a 350 MHz superconducting LEP cavity into the cryostat

Four fully equipped and tested 500 MHz modules are presently in production for LISA, the free electron laser driver at INFN [11]. The accelerating structures (Fig. 5) and almost all cryostat parts have been fabricated. The cryogenic and rf test of the first accelerator unit is scheduled for the beginning of 1990. The design of the module is schematically shown in figure 7.

In cooperation with DESY a pipe cooled niobium/copper 500 MHz cavity has been developed using the explosion bonding technique [6] (Fig. 6). An accelerating field of 8.9 MV/m was obtained in the first experiment. With this experiment the pipe cooling concept as a potential alternative to bath cooling was demonstrated.

Based on this technique now a 402 MHz Nb/Cu pipe cooled module (cavity and cryostat) for a low energy pion momentum compactor at LANL is being fabricated [12].

For TRW a superconducting 500 MHz accelerating unit is in production. Special higher order mode couplers have been developed (Fig. 8) in order to fulfill the requirements for FEL application.

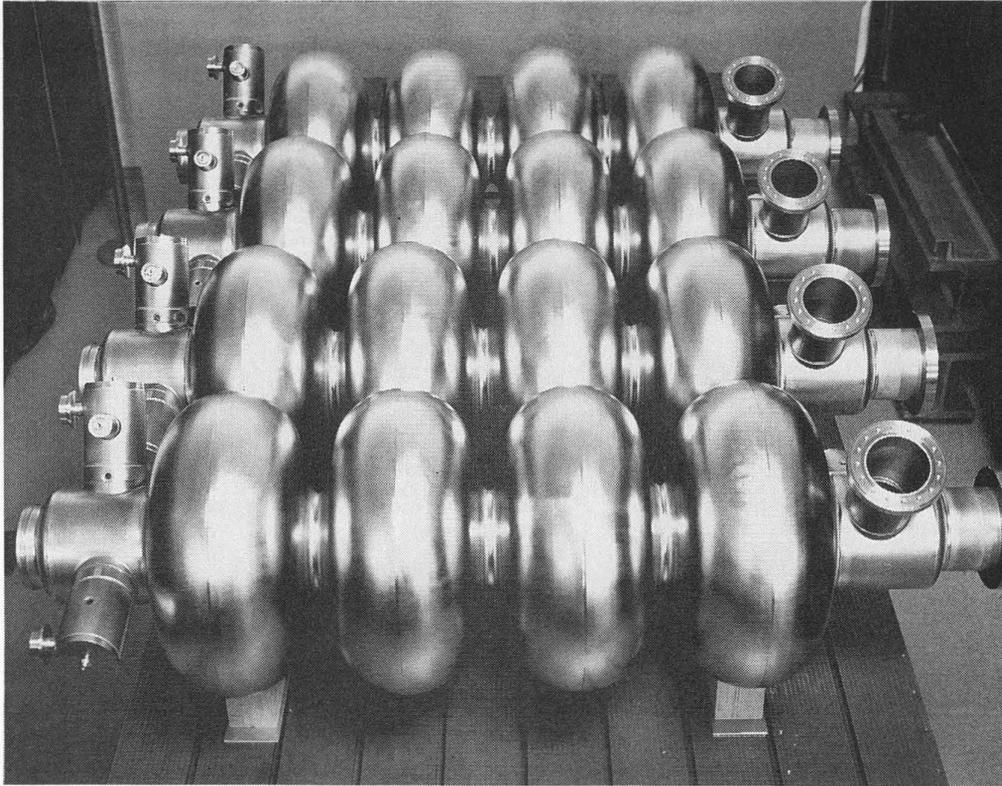


Fig. 5: 500 MHz niobium cavities for the FEL driver LISA at INFN/Frascati with higher order mode couplers and fundamental mode coupler part

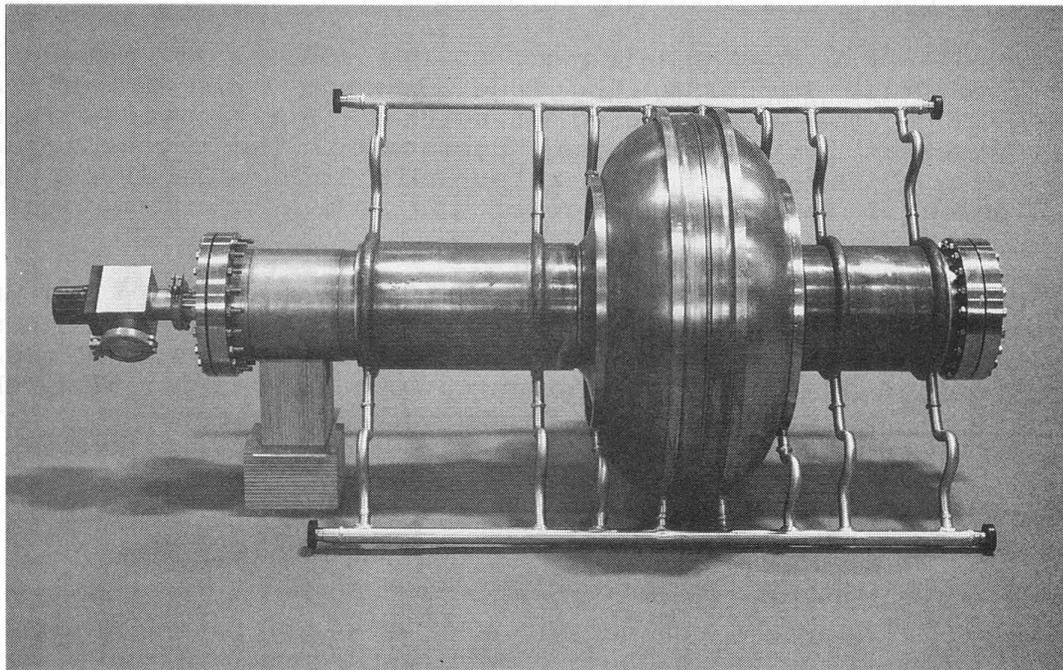
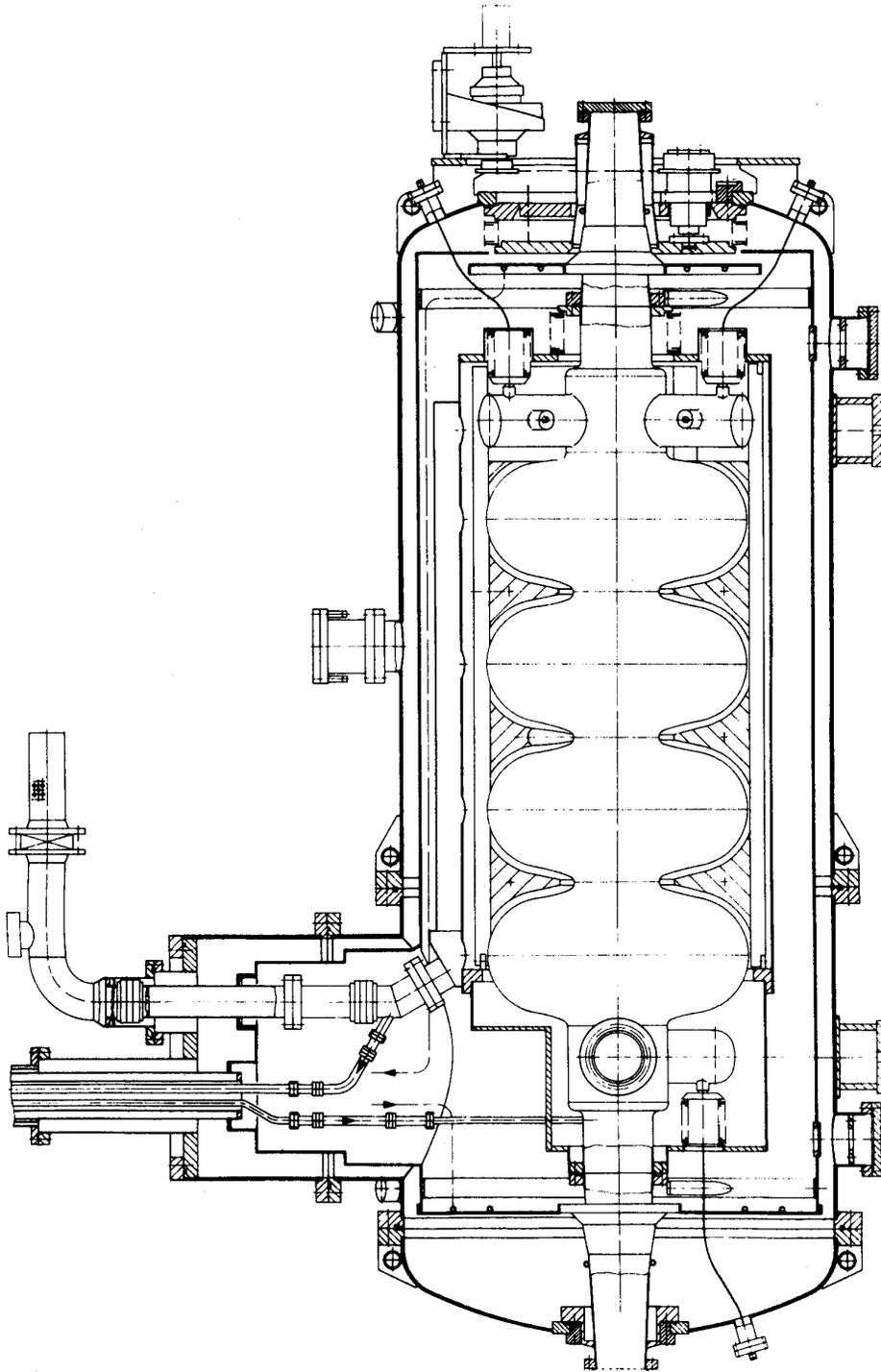


Fig. 6: Pipe cooled 500 MHz superconducting niobium/copper cavity



**Fig. 7:** Design of the superconducting 500 MHz  
INFN/Frascati accelerator module

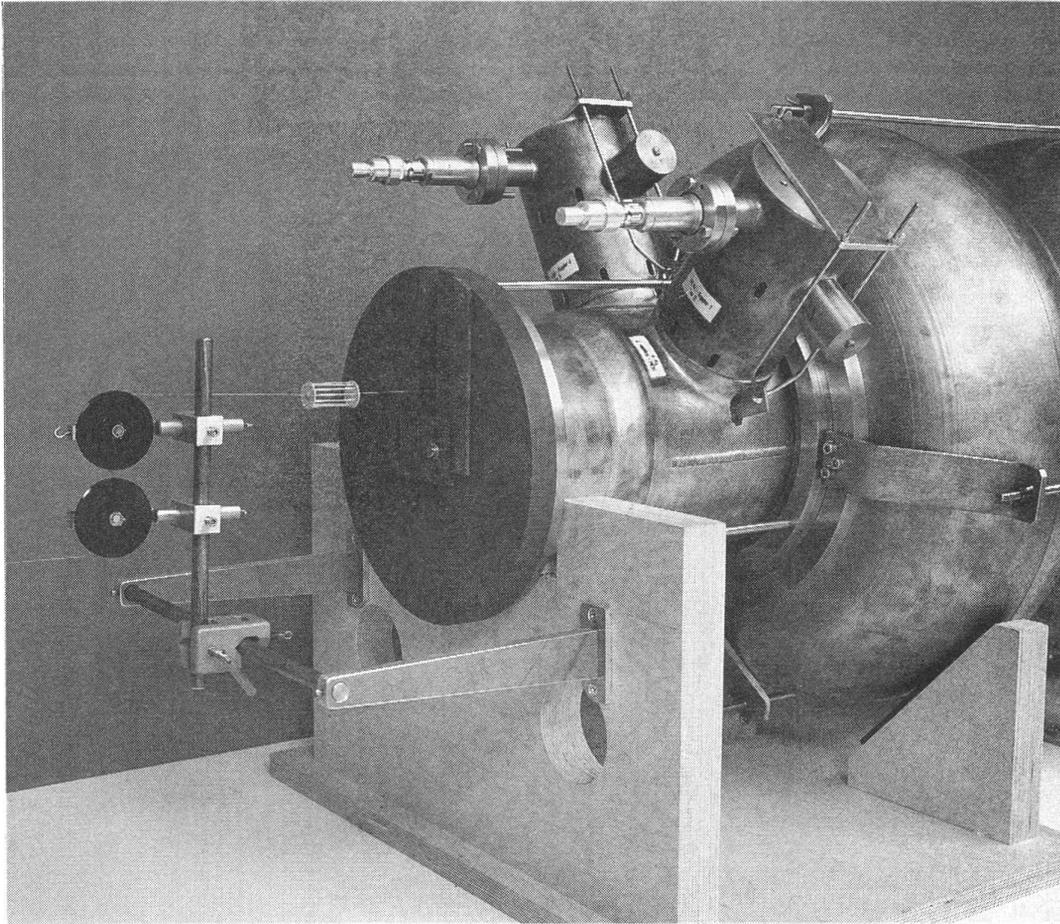


Fig. 8: Development of higher order mode couplers of a 500 MHz two cell cavity for FEL application

### III The story of a superconducting accelerator module

#### 1. *Layout and Design*

Depending on the technical requirements specified by our customer, Interatom is performing the following layout and design steps are carried out:

- . General layout of the complete system in respect to cavity frequency, accelerating field, cavity Q, rf input power, higher order mode damping, number of cells per cavity, number of cavities per cryostat, cryostat performance and interfaces to the customer's facilities.

- . Calculation and optimisation of the rf performance and the mechanical stability of the s.c. cavity. This is performed by using computer codes like SAFESHELL, URMEL and URMEL T [10].
- . Design and optimisation of the fundamental mode (FM) input coupler and the higher order mode (HOM) couplers (e.g. Fig. 8).
- . Evaluation of the tuning range and design of the coarse and (if necessary) fine and fast tuning systems
- . Detailed design of the complete cryostat and its interfaces to the facilities of the customer (e.g. Fig. 7).

## 2. Fabrication

About 50 niobium cavities with frequencies between 350 MHz and 86 GHz have been manufactured as of today [table 1]. In general the accelerating cavities are fabricated of niobium sheet material by using the following main steps.

- . Inspection and control of niobium sheet material in respect to surface appearance (impurities, scratches, laminations), crystallographic performance and yield strength.
- . Shaping of the half cells by deep drawing (e.g. CEBAF, [3]) or numerically controlled spinning (e.g. CERN [2], Fig. 3, INFN, Fig. 5)
- . Shaping of beampipe and coupler parts by bending, deep drawing, extrusion or machining from bulk material (Fig. 9)
- . EB welding of cavity parts from outside and from inside if necessary
- . Appropriate surface preparation by buffered chemical etching (BCP, HF-HNO<sub>3</sub>-H<sub>3</sub>PO<sub>4</sub> of 1:1:2 to 1:1:6 volume parts)
- . High temperature brazing of niobium stainless steel transition joints (e.g. CERN, INFN, Fig. 10) based on a procedure developed by CERN [4]

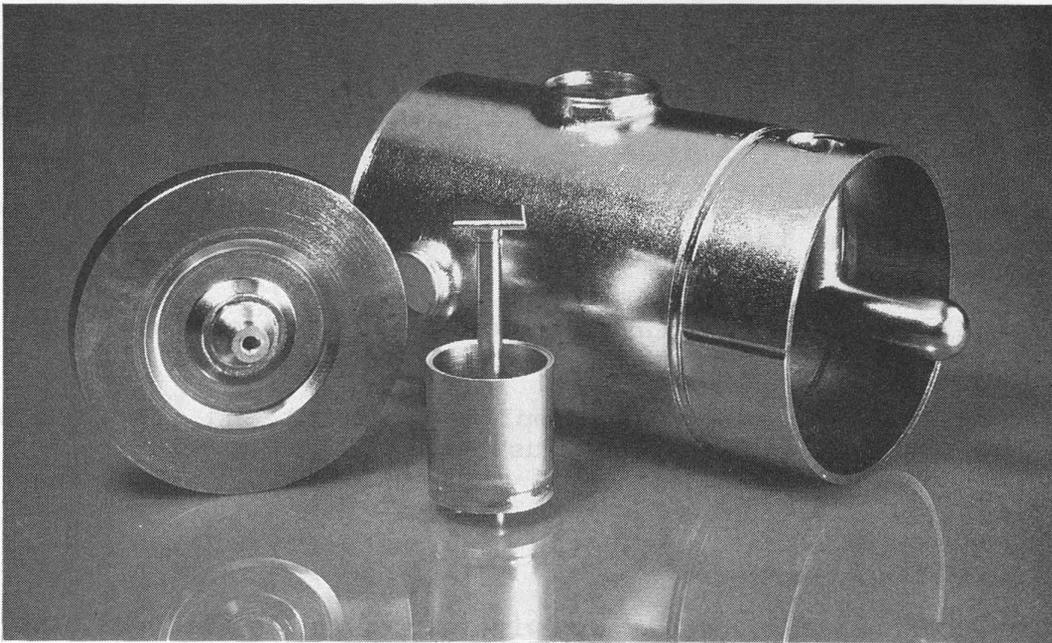


Fig. 9: Niobium components of a HOM coupler



Fig. 10: Brazed niobium/stainless steel transition joints (cooperation with CERN/Geneva)

- . An attractive alternative to the conventionally bath cooled niobium sheet cavities are pipe cooled resonators made from composite materials. Based on the development of a pipe cooled niobium/copper 500 MHz cavity together with DESY [6] (Fig. 6) now a 402 MHz s.c. cavity for LANL using this technique is being manufactured. The Nb/Cu composite is done by explosion bonding 3 mm Cu sheets with 2.5 mm Nb sheets (Fig. 11).

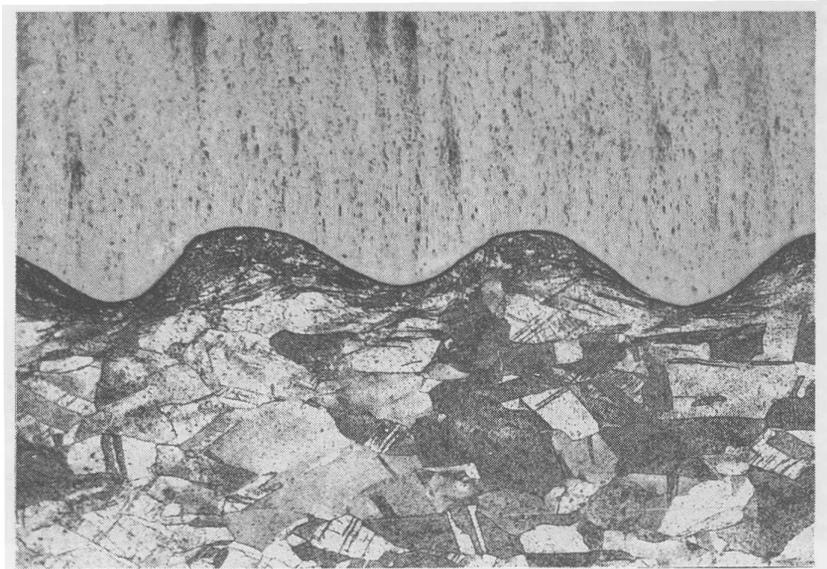


Fig. 11: Cross sectional view of an explosion bonded niobium/copper (above/below) composite (magnification factor = 200)

All fabrication steps are carefully followed by the quality control department.

### 3. *Optimisation of rf performance*

To achieve the required cavity frequency and field flatness, the cavity fabrication is 'guided' by frequency measurements and adjustments of the single cells.

After the fabrication has been finished the frequency and field profile are adjusted by inelastically tuning the single cells of the complete cavity (Fig. 12, 13). Furthermore the rf performance of the FM and HOM couplers are optimised in respect to coupler Q and appropriate damping of special higher order modes.

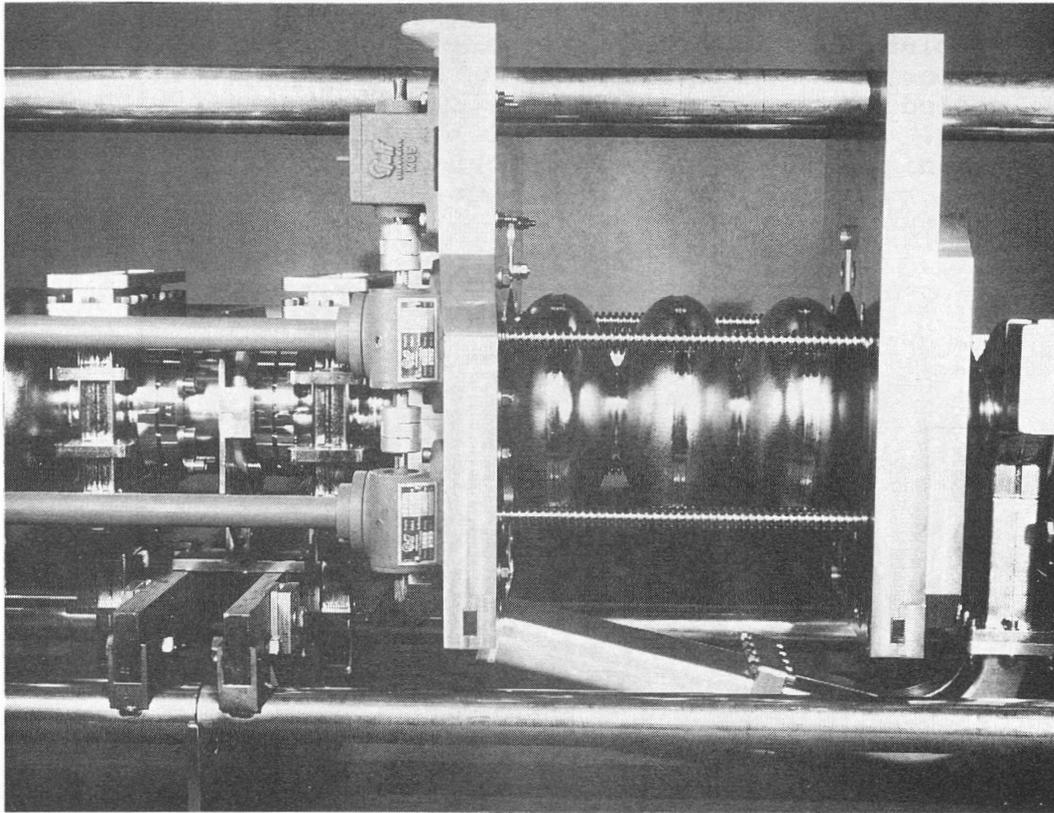


Fig. 12: Tuning of a 1.5 GHz CEBAF five cell cavity for adjustment of frequency and field flatness

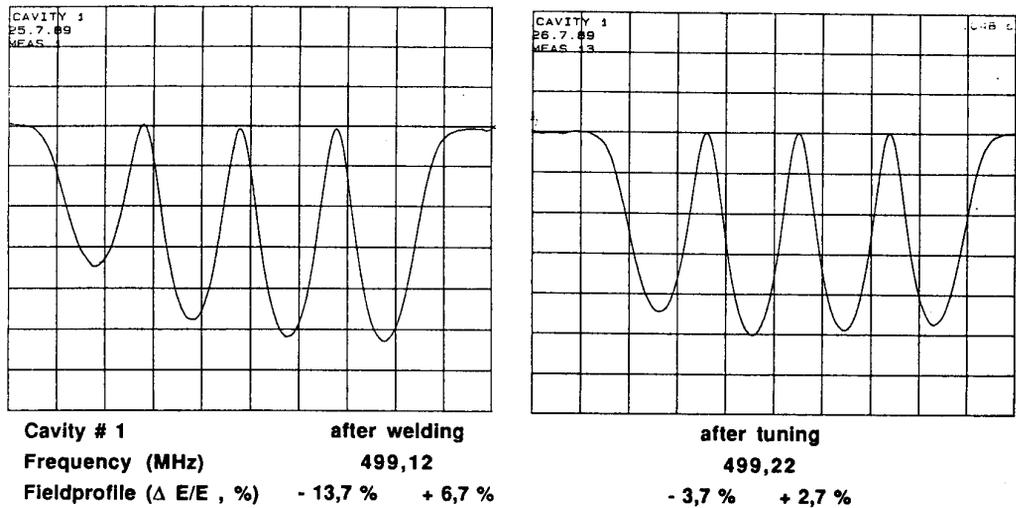


Fig. 13: Measured field profiles of a 500 MHz four cell INFN cavity before and after the tuning procedure

#### 4. *Integration*

Thereafter a final chemical polish (BCP 1:1:2 to 1:1:6) of the cavity is performed. The assembly with all necessary cryostat components and the subsequent evacuation and leak test is carried out under class 10 clean room conditions (Fig. 14).

In the last step the evacuated cavity is assembled into the cryostat (Fig. 4).

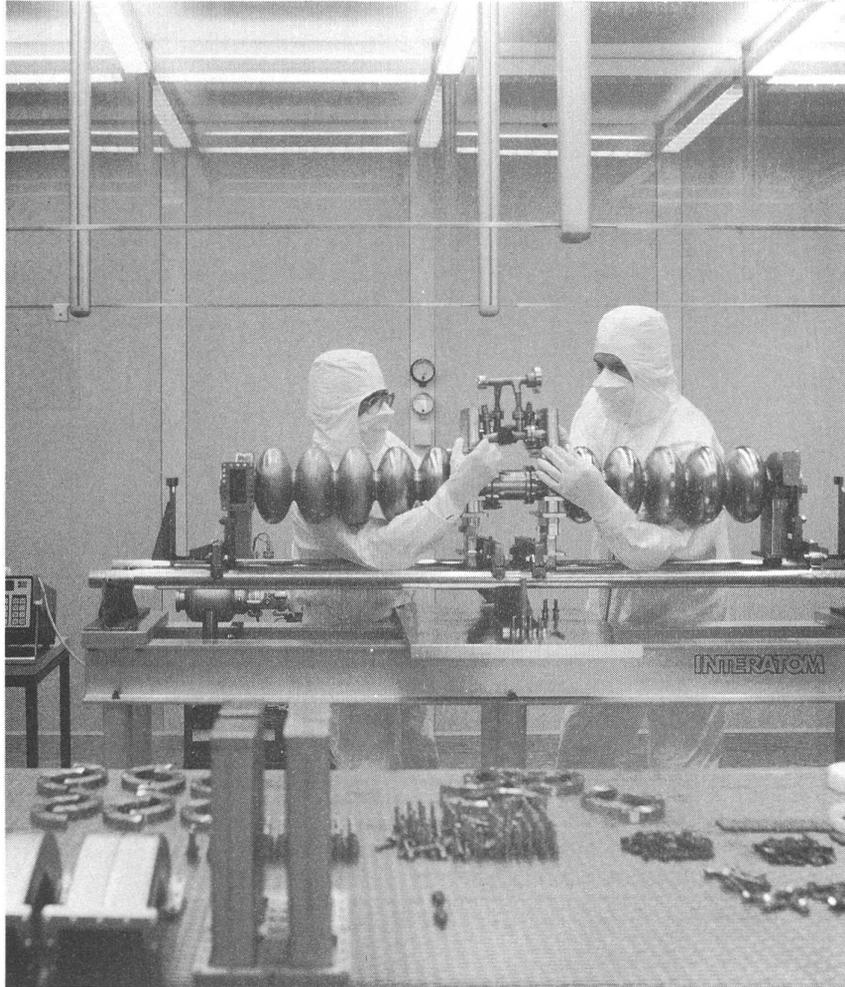


Fig. 14: Assembly of a CEBAF cavity pair under class 10 clean room conditions

#### 5. *Test and commissioning*

At room temperature all cavity and cryostat subsystems are controlled and tested for proper performance.

In some cases the customer asks for performance tests at liquid helium temperature.

In 1988 4 cavities have been assembled to 2 cavity pairs (Fig. 1) and rf tested for CEBAF in cooperation with the University of Wuppertal [3]. These tests included the well known thermometry technique (Fig. 15) performed in subcooled LHe 2.2 K.

For the INFN project cryogenic performance tests with input powers up to 25 kW are foreseen.

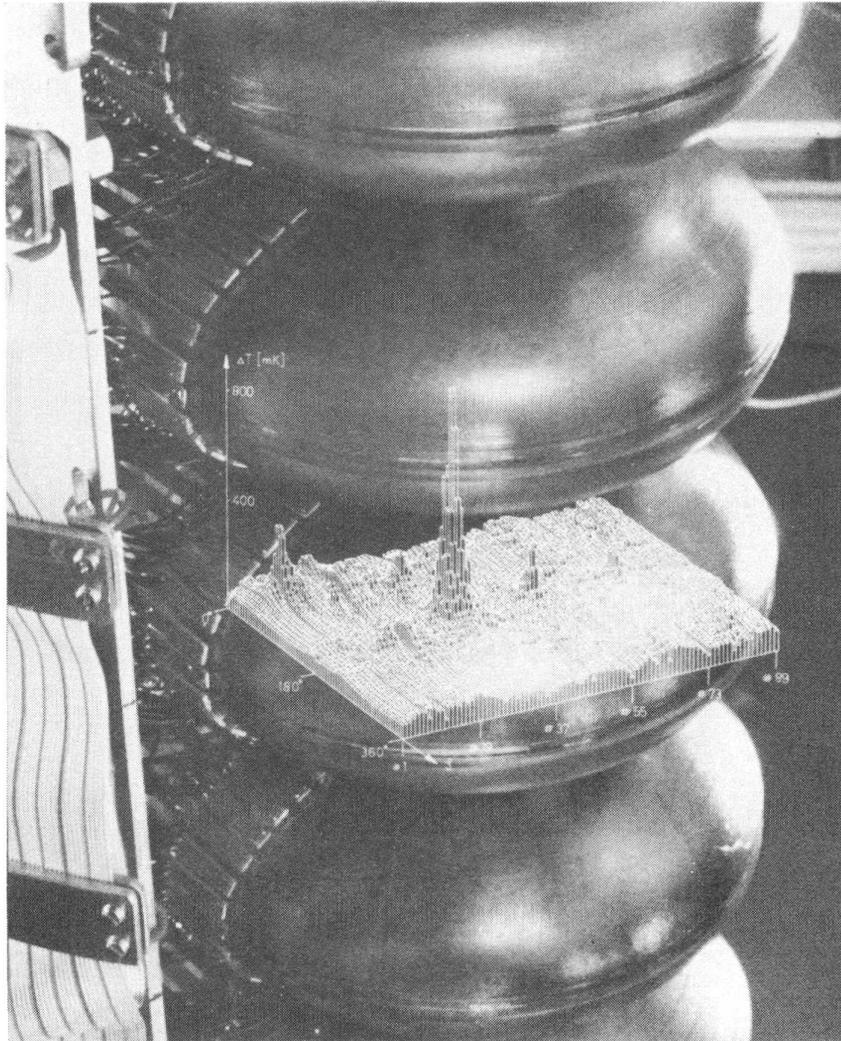


Fig. 15: Thermometry system for taking temperature maps (faded in the center) of the CEBAF five cell niobium cavities

## 6. *Transportation*

From the experience with the CEBAF, DESY and CERN projects it can be concluded that transportation of finally prepared and clean room assembled cavities or modules by air plane by truck is of no problem if special care is taken.

The transportations have been carried out with cavities both in an evacuated, actively pumped (CEBAF, first cavity pair (Fig. 2)), and not actively pumped state (CEBAF, second cavity pair) and under slightly overpressured N<sub>2</sub> atmosphere (CERN, DESY).

In all cases there was no hint of any rf performance degradation due to transportation.

## IV R + D work at Interatom

### 1. *Advanced superconducting accelerator components*

For future large accelerator applications it is mandatory for cost reasons to improve the rf and cryogenic performance of the superconducting accelerator modules as well as to optimise the design, the manufacturing and the assembly techniques.

So on one hand we are working on improved concepts for cryostats and rf components and on the other hand on the improvement of the superconducting material. The latter is done in close cooperation with the University of Wuppertal.

- Nb, Nb<sub>3</sub>Sn and Nb/Cu:

For accelerating structures made of pure niobium the thermal conductivity of low temperature can be improved by a factor of 3 - 4 by postpurification in titanium atmosphere at temperatures around 1300°C [13]. Applying this technique on a 1.5 GHz CEBAF five cell accelerating structure the accelerating field could be increased from 6.3 MV/m to 12.1 MV/m (Fig. 16). The thermal conductivity at 4.2 K measured on coprocessed samples went up from 31 W/m/K to 95 W/m/K [3].

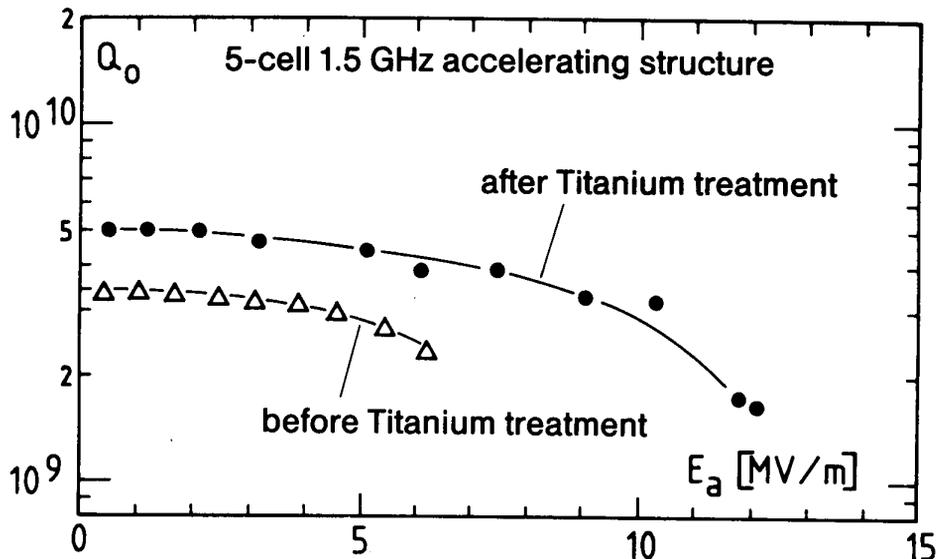


Fig. 16: Cavity Q as a function of accelerating field for a 1.5 GHz five cell structure before and after postpurification by titanium treatment at 1300°C

Because of its relatively high transition temperature of  $T_C = 18.1$  K cavities with  $Nb_3Sn$  surface promise much lower rf losses and higher accelerating fields as compared to niobium with a  $T_C$  of 9.2 K [14].

In cooperation with the University of Wuppertal a special vapor diffusion technique was developed for depositing a  $Nb_3Sn$  layer on the inner surface of a niobium cavity while from outside the cavity is exposed to a titanium atmosphere in order to keep or even increase the RRR value of the niobium. Using this technique an accelerating field of 9.9 MV/m was achieved in a 3 GHz cavity at 4.2 K in the first experiment [15].

A new and very attractive technique is the sputter coating of niobium on copper cavities. This procedure was developed by CERN [16]. Today a similar or even better performance in accelerating field and Q value compared to niobium sheet cavities has been obtained at CERN [16].

Since this technique requires copper cavities with a very clean and smooth surface we are developing a fabrication technique for complete cavities without any welding in the cell region.

This can be performed by electroforming as we already demonstrated by producing a 1.5 GHz single cell accelerating structure. An additional advantage of this technique is the possibility of implementing appropriate cooling channels in the same step.

In cooperation with the University of Wuppertal, DESY and CEBAF the development of a superconducting injector for the production of a microbunched electron beam with high brightness, low energy spread and potentially high beam power is underway [17].

In figure 17 the UHV chamber for the preparation of photo emission layers is shown.

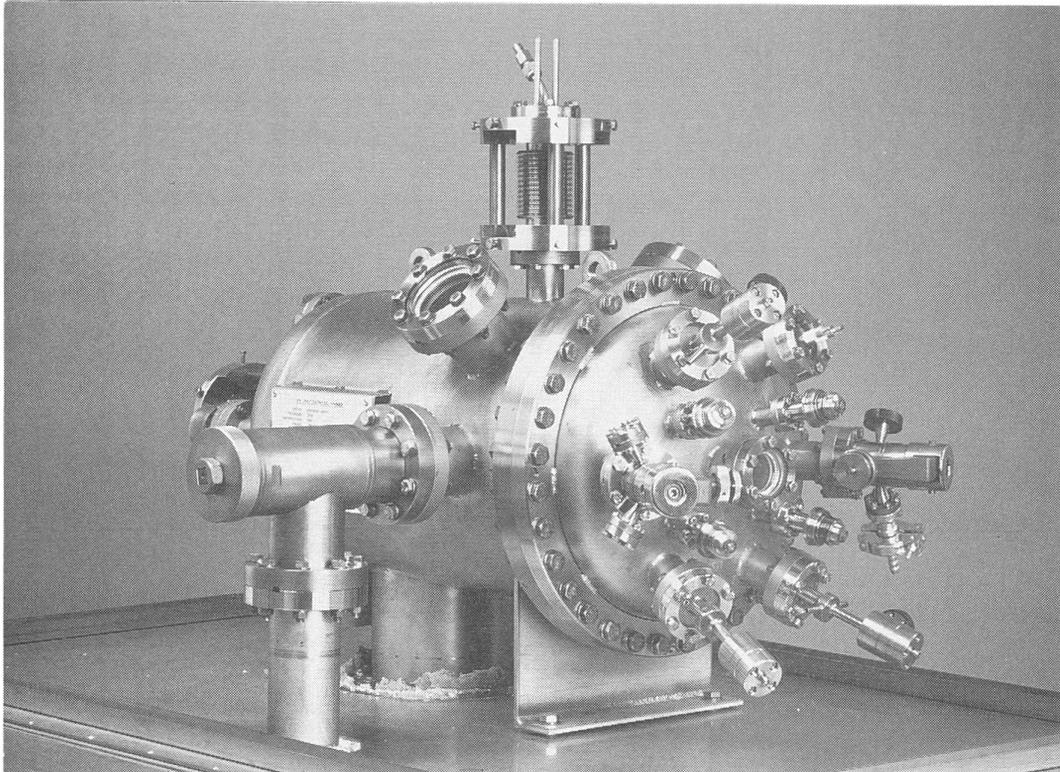


Fig. 17: Ultra high vacuum chamber equipped with evaporation sources and diagnostics for the preparation of photocathodes

## 2. *High temperature superconducting materials and rf test systems*

The new high temperature superconductors (HTS) with transition temperatures above 90 K could possibly play an important role for future rf applications at LN<sub>2</sub> temperature if an appropriate coating technique for the ceramic like material can be developed.

Multidisciplinary collaborations have been established with the Siemens research laboratory and with the University of Wuppertal for the development of coating techniques on appropriate substrates as well as especially on rf characterisation techniques.

Additional to high quality thin films formed on  $\text{SrTiO}_3$ , MgO or  $\text{LaAlO}_3$  substrates by laser ablation [18] or sputtering a coating technique was developed which enables the deposition of HTS material on large and curved silver substrates [19] (Fig. 18).

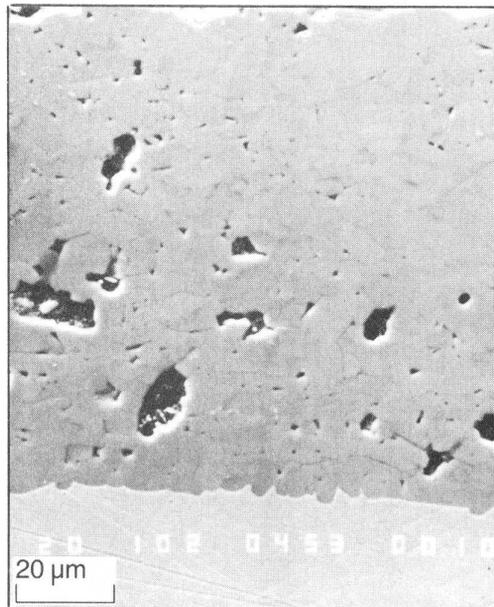


Fig. 18: Cross sectional view of an YBCO layer electrophoretically deposited on a silver substrate (SEM photograph)

For the measurement of the surface impedance of the new materials as a function of rf field level, temperature and frequency, rf test systems have been built up at 3 GHz, 22 GHz and 86 GHz (Fig. 19 and 20).

In figure 21 the surface resistance of different HTS samples is shown in comparison with the metallic superconductor Nb.

A detailed status of the rf performance of the HTS material is given by G. Müller in this workshop.

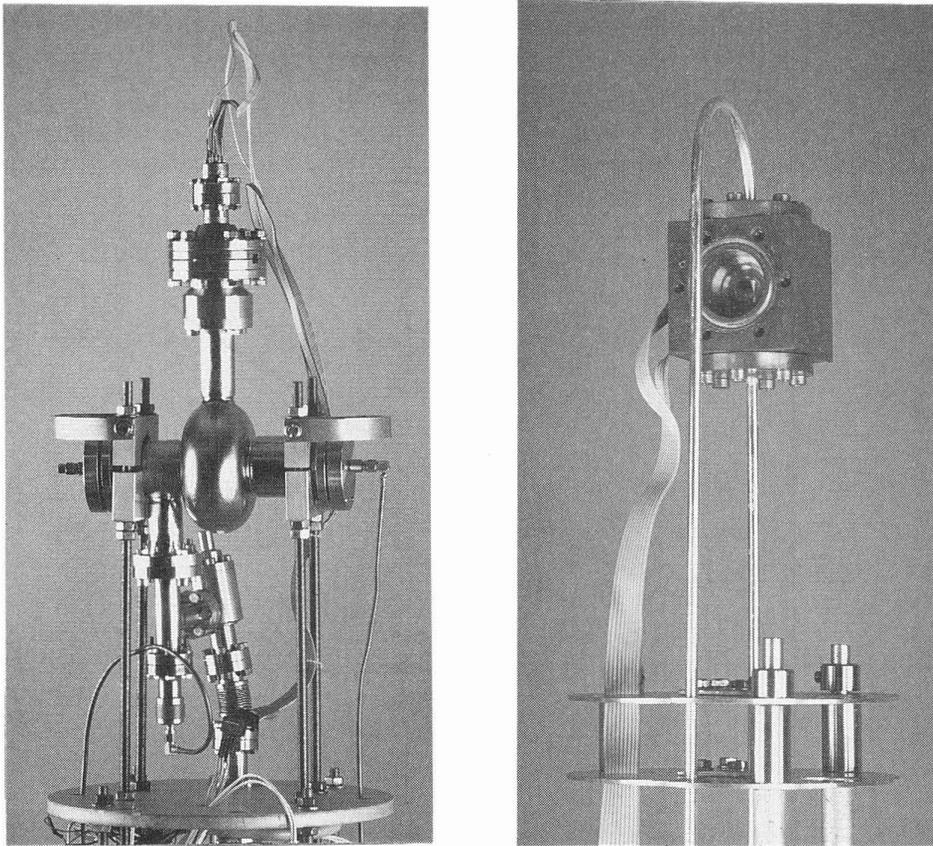


Fig. 19: Rf test systems for HTS samples at 3 GHz and 86 GHz (right). The HTS probe is either used as an endplate of a pill box cavity (right) or is put inside a superconducting cavity (left) on the top of a sapphire rod the temperature of which can be varied between 4 and 300 K.

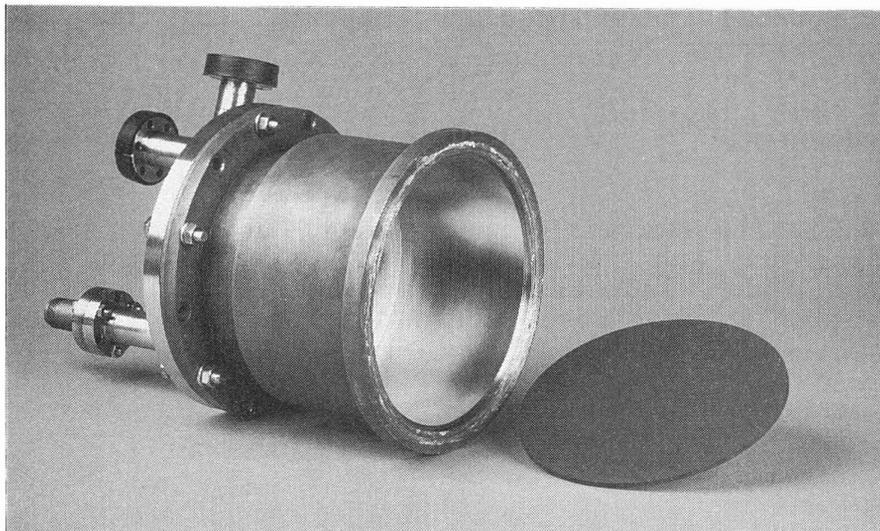


Fig. 20: Test of an electrophoretically coated 125 mm diameter HTS plate in a 3.5 GHz TE mode cavity

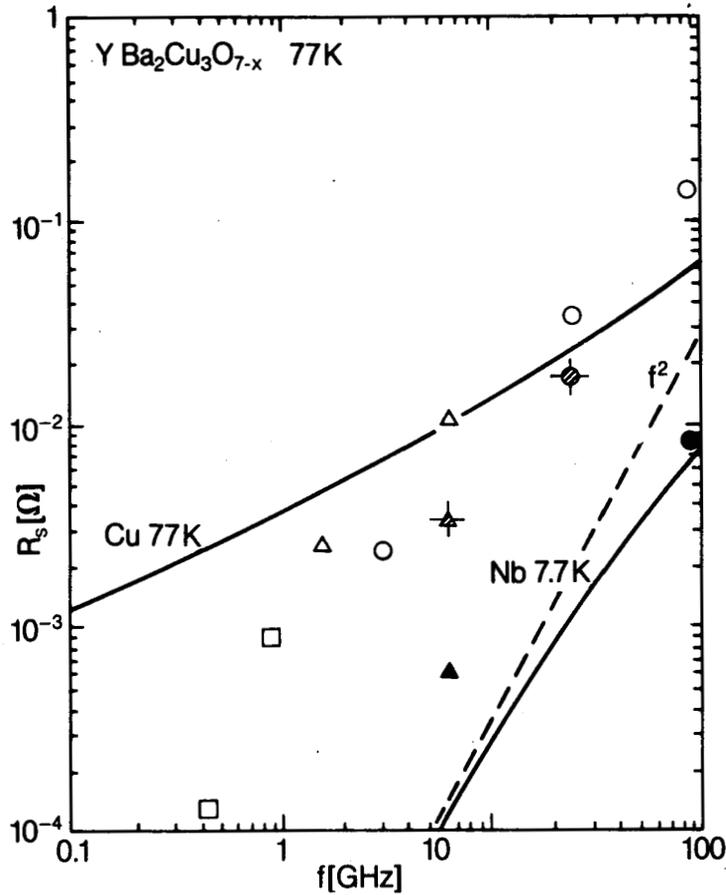


Fig. 21: Frequency dependance of the rf surface resistance at 77 K for c-axis textured layers (shaded), polycrystalline bulk (open) and single cristalline thin film samples of YBCO measured at Argonne (squares), Cornell (triangles) and Wuppertal (circles) (see reference 20).

## V Acknowledgements

We would like to express our gratitude to all our partners in the national and international Universities, research institutes and industrial companies for tje enjoying collaboration in this most interesting technology.

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