Laboratory Report

DESY

Deutsches Elektronen-Synchrotron, Notkestrasse 85,
22603 Hamburg, Germany

D. Proch, B. Dwersteg, G. Kreps, A. Matheisen, W.-D. Möller,
D. Renken, J. Sekutowicz, W. Singer.

1. Abstract

Two major activities have been carried out at DESY since the last SRF workshop in Hamburg, 1991:

-Operation of the superconducting cavity system in HERA
-Design and installation work for the TESLA Test Facility (TTF).

The last two days of this workshop were especially devoted to the TESLA project. Detailed information was given by several talks. Therefore only a general overview over the TESLA activities is given here.

2. The HERA Superconducting RF System.

2.1 Description of the system

The HERA e^- storage ring is equipped with 84 normalconducting (nc) and 16 superconducting (sc) resonators. The resonance frequency for both types of cavities is 500 MHz. The RF power is generated by 800 KW klystrons, grouped to a pair before guiding the RF-power by rectangular wave guides (WR1800) down to the tunnel. The superconducting cavities are powered by a combined system of 9 directional couplers and 6 magic Ts (see Fig. 1). The coupling factor (nominal Q_{ext}=3*10^5) and the relative phase can be adjusted at each cavity by a three plunger tuner. In

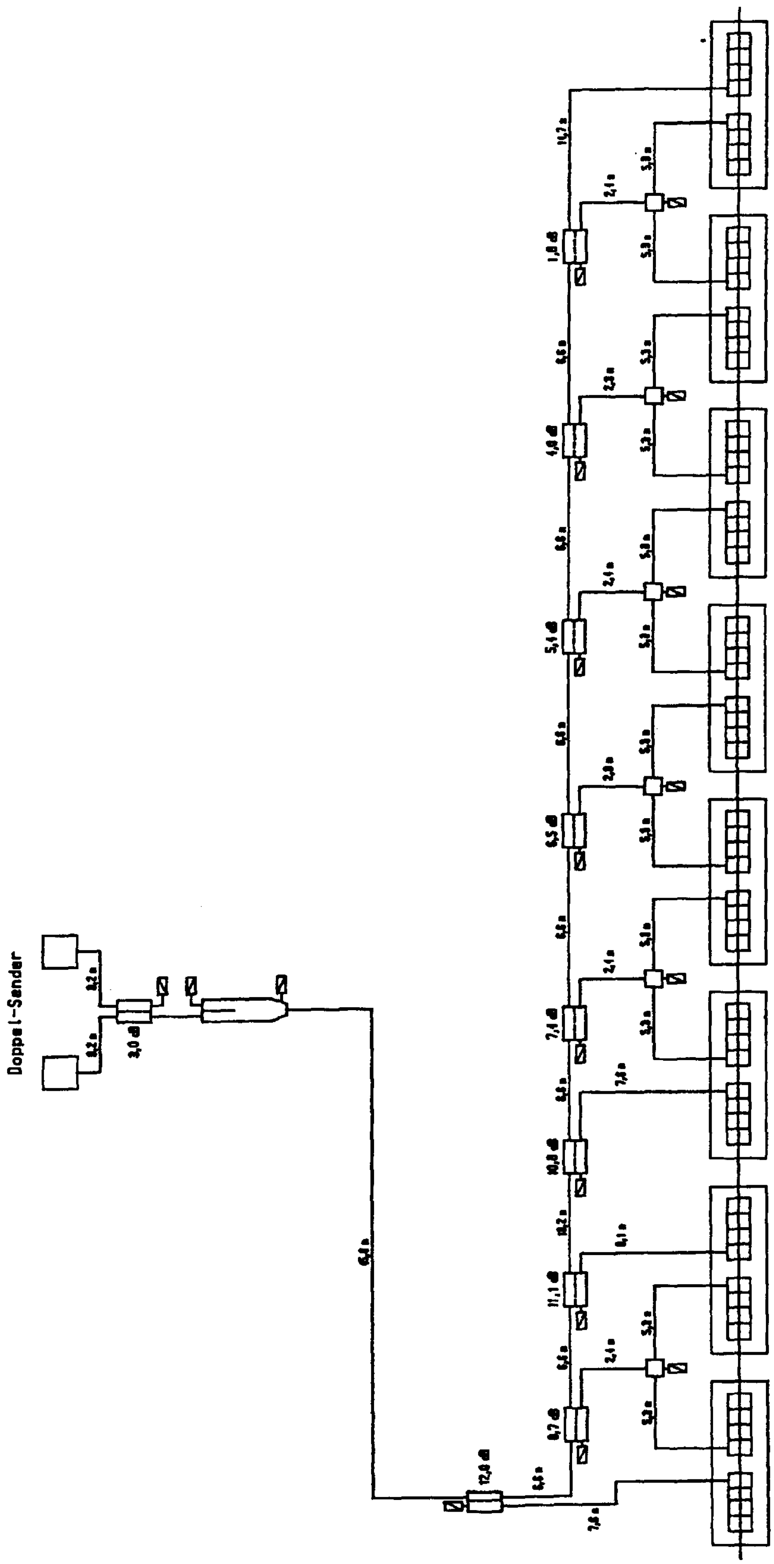


Fig. 1 High power RF distribution in HERA

order to operate HERA at 28 GeV an energy loss equivalent to 100 MV per turn has to be compensated.
The 16 sc cavities are contained in 8 cryostats. One valve box supplies one cryostat with LHe at 4.3 K and GHe at 40/80 K. The cryogenic power of 1 kW at 4.3 K is delivered by the central HERA plant.
Several control-, interlock and data-logging systems are installed to operate the sc RF:

- Slow cavity tuner: No fast tuner is needed because of the large bandwidth of 1.7 kHz
- Vector sum control: The power of the klystron is regulated to keep the vector sum of all 16 cavities constant. This system was put into operation in the second half of 1993.
- Cryogenic control: The level of LHe, the temperature of the input coupler heat exchanger and the shield circuit are controlled by adjusting the individual mass flow. This is part of the control system for the HERA refrigerator.
- Interlocks: Various readings are used to interlock the klystron power and the beam current. For details see table 1. A quench of a cavity is detected by a pressure increase (above 1.1 bar) in the LHe circuit.
- Data-logging: Operating conditions (level, pressure and mass flow in the Helium circuit, insulation- and beam vacuum, cavity voltage, klystron power, beam current) and interlock events are recorded by several computer systems.

Signals per cavity	**klystron off**	**beam dump**
3 HOM coupler, temperature	•	•
input coupler: infrared sensor	•	o
input coupler: e^- detector	•	o
input coupler: light detector	•	o
input coupler: spark detector	•	o
input coupler: cooling air	•	o
quench detector: pressure in LHe	•	•
vacuum ok	•	o
cryogenics ok	•	o

Table 1 Interlock circuit for SRF in HERA (•: active; o: optional)

2.2 Milestones

The sc cavity system was installed and put into operation during the year 1991. Beam current of typical 3 mA was accumulated. The sc cavity system was successfully used to raise the HERA energy up to the design value of 30 GeV. Furthermore the additional circumferential voltage of the sc cavities was helpful during the first measurements of polarized beams in HERA.

Milestones

June 91	**increase HERA e^- energy from 28 to 30.4 GeV by adding <u>12</u> sc cavities to 84 nc cavities**
July, Oct.-Dec.	**nc& sc cavities: increase overvoltage factor during e^- polarization measurements, machine shifts : measure injection efficiency for nc, sc.,nc&sc cavities**
Apr.92 -Nov.92	**operate all <u>16</u> sc cavities, max $\langle E_{acc} \rangle$ = 4 MV/m (= 76 MV) limited by global heating of one cavity i_{beam} < 10 mA**
March93 -now	**luminosity runs i_{beam} < 20 mA**

in total :16000 hours of operation

(256000 cavity hours)

19 warm up/cool down cycles

max i_{beam} = 40 mA

Table 2 Milestones of SRF in HERA

During 1992 regular operation of HERA with typical currents up to 12 mA was experienced. Because of the only moderate beam loading the sc cavities were operated at constant forward power of 300 kW, resulting in a circumferential voltage of 50 MV. This has to be compared with the 100 MV produced by the nc cavities.
In 1993 the HERA beam current at luminosity runs was raised to 20 mA. Since September of this year the cavity vector-sum control was operated to keep the cavity voltage constant under various beam-loading conditions.
During machine shifts near to the end of 1993 beam currents of typical 30 mA and a maximum value of 40 mA could be reached.

In total 16000 hours of operation (256000 cavity hours) were accumulated until the end of 1993. Table 2 gives an overview on the milestones.

2.3 Operating experience

Since installation in HERA the 16 cavities were warmed up/cooled down 19 times. One cryostat showed a small leak between LHe and beam vacuum. This leak showed up after the first cool down and did not change until now. At room temperature this leak was too small to be detected. At cold the beam-vacuum at this cryostat remained stable at 10^-7 mbar. Therefore no attempt was undertaken to repair this leak.
The standard procedure for cool down is: slow gradient until 150 K (all cavities together) and then fast gradient down to 4.3 K. (each cavity individually for increased speed). This procedure is recorded in Fig. 2. It is done to minimize the deterioration of the Q-value due to the Hydrogen disease. All cavities have been chemically polished during the fabrication at a temperature of 30 °C or even higher. Fig. 3 shows the resultant increase of Hydrogen.
A measurement of the individual Q-value of each cavity (nominal 2*10^9) is difficult because of the strong input coupler loading. The calibrated LHe mass flow of the whole system can be measured with and without RF drive. In order to cancel short time fluctuations of the mass-flow the measurement has to average over several hours. This method has been used to determine the total RF-loss and thus an average Q value. At 3 MV/m an average Q-value of $0.9 \bullet 10^9$ has been concluded. With another method the transient behavior of the pressure in the LHe bath of each individual cavity was measured during pulsing the RF drive. The slope of the pressure increase was calibrated by heaters in the LHe. This method is accurate enough to compare the relative Q-values of the 16 cavities. The result indicated a ratio of 1.5 between lowest and highest Q-value.

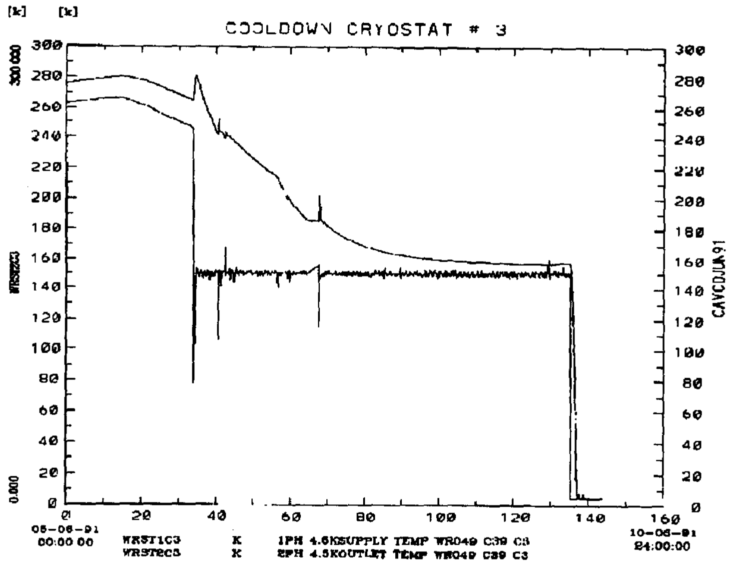


Fig. 2 Cool down of the superconducting cavities in HERA (vertical scale 300 K; horizontal scale 160 h). Lower (upper) curve is the temperature of the forward (return) GHe flow.

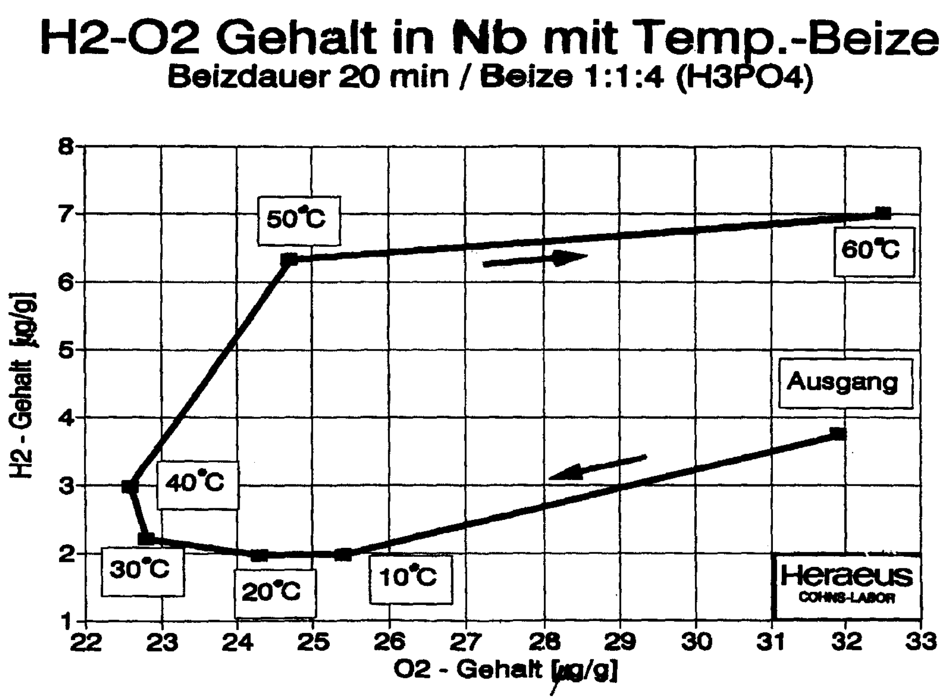


Fig. 3 H_2 and O_2 pick up during BCP (1:1:4; 20 min) as function of temperature.

2.3.1 Modes of operation

The loss in a superconducting cavity is determined by the beam loading. The wall losses of typically some 10 W can be neglected in this respect. For no or only small beam loading the cavity voltage scales with the square root of the klystron power whereas the beam power scales linear with the cavity voltage. As result the beam current for matched conditions changes with forward power although the coupling (Q_{ext} value) is constant. If the cavity tuner compensates the reactive part of the beam induced voltage, the cavity vector sum simplifies into a scalar sum:

$$U_c = U_{c,I_b=0} - U_{beam} = \sqrt{4(\frac{r}{q})Q_{ext}\frac{P_{Klyst}}{16}} - I_b(\frac{r}{q})Q_{ext}\cos(\phi)$$

(r/q): shunt impedance, Q_{ext}: external coupling, P_{klyst}: klystron power, I_b: beam current, ϕ: synchrotron phase

During 1992 the beam current was 10 mA (begin of lumi run), the klystron power was fixed to 300 kW (for all 16 cavities) and the average value of Qext was 3*10^5. The resultant cavity voltage and reflected cavity power is plotted vs. beam current in Fig. 4 (with a fixed synchrotron phase angle of 45°). The equivalent values for the normalconducting cavities are shown in Fig. 5. It can be seen that the superconducting cavities were operated in a very efficient way. Table 3 compares the operating cost of the mixed sc- and nc cavity system with a pure nc system.

At higher beam current the cavity voltage drops too much so that a amplitude control is needed. All 16 cavity voltage vectors are added up for reference of the klystron output power control. The resultant cavity voltage and reflected power vs. beam current is displayed in Fig. 6. Limits are a maximum cavity gradient of 4 MV/m and a maximum forward cavity power of 100 kW. The 4 MV/m is chosen to have a safety margin against the onset of thermal instability (due to enhanced losses by the hydrogen disease). The restriction of 100 kW per input coupler assures a safe operation of the present window design. The cavity vector sum control was put into operation in September 93.
The maximum forward power was 550 kW, limited by interlock trips in the high power wave guide distribution system. During the latest machine studies beam currents around 30 mA were injected and accelerated. The highest recorded beam current was 40 mA. The maximum transferred beam power by the sc cavity system was 430 kW.

Power/Money saving by sc cavities in 1992

	U(MV)	Pklys.(MW)	Pac (MW)
NC	81.3	3.4	5.66
SC	55.7	0.25	0.42
		(500 W)	0.15
Tot.	137		6.23
NC	137	9.65	16.05
SC	- -	- -	- -
Tot.	137	9.65	16.05

Power saving: 16.09 − 6.23 = 9.86

Money saving:

4000 h x 9860 KW x 0.15DM/KWh = 5.9 MDM

saving of klystron replacement not included

Table 3 Comparison of operating costs. Upper table: mixed SC and NC system, lower table: pure SC system

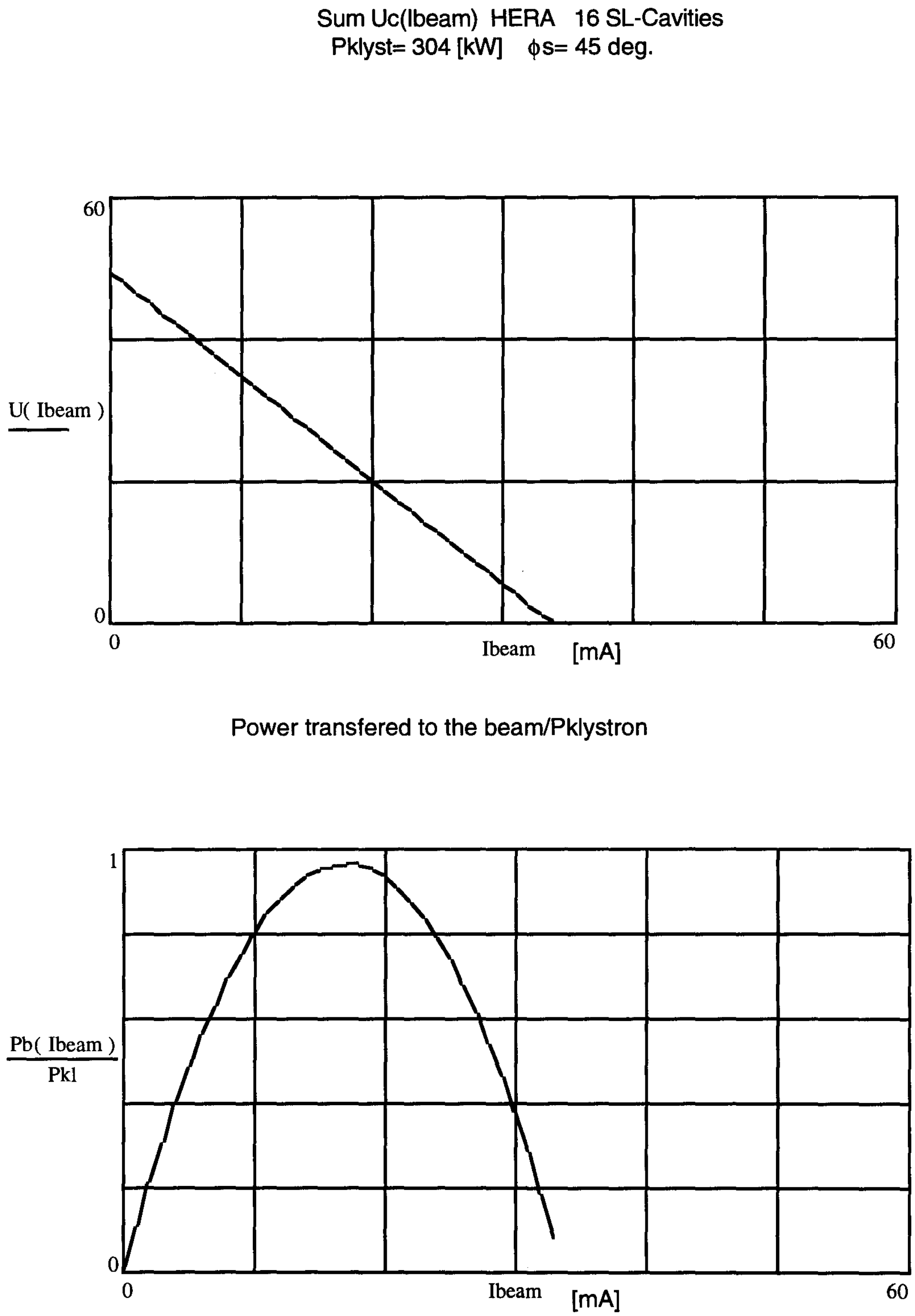
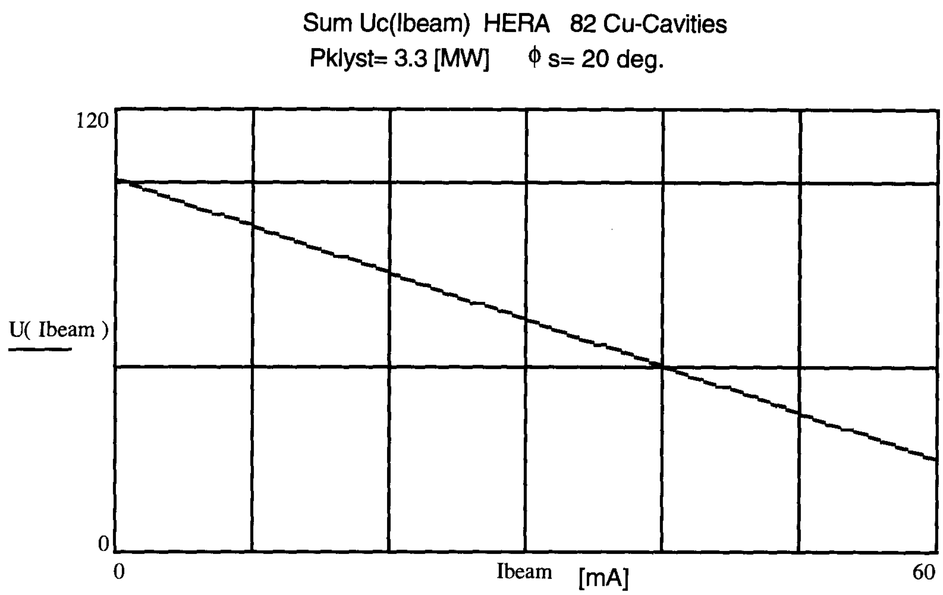


Fig. 4 Cavity voltage U_C (upper graph) and transfered beam power (lower graph) of SRF vs beam current in HERA. Forward power is constant at 300 kW



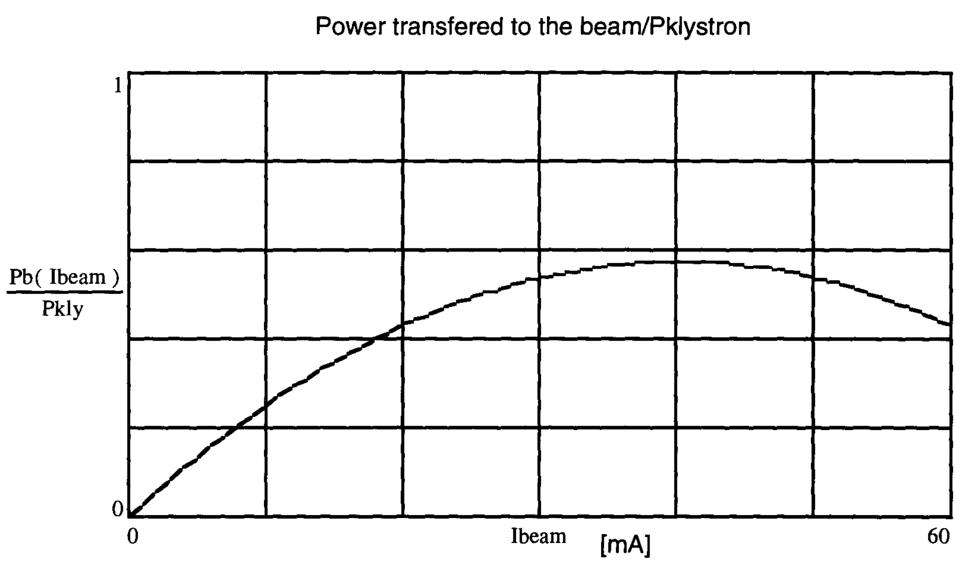
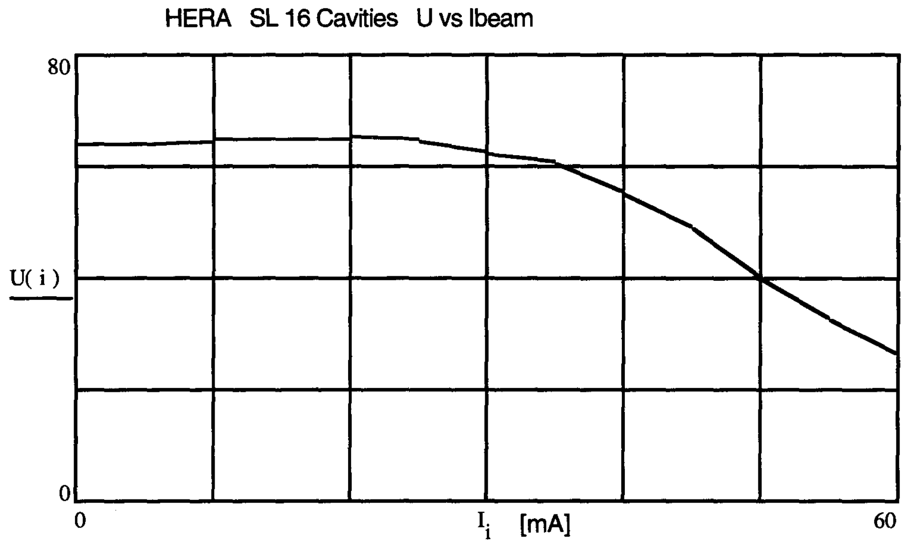


Fig. 5 Cavity voltage U_C (upper graph) and transfered beam power (lower graph) of NC cavities in HERA. Forward power is constant at 3.3. MW



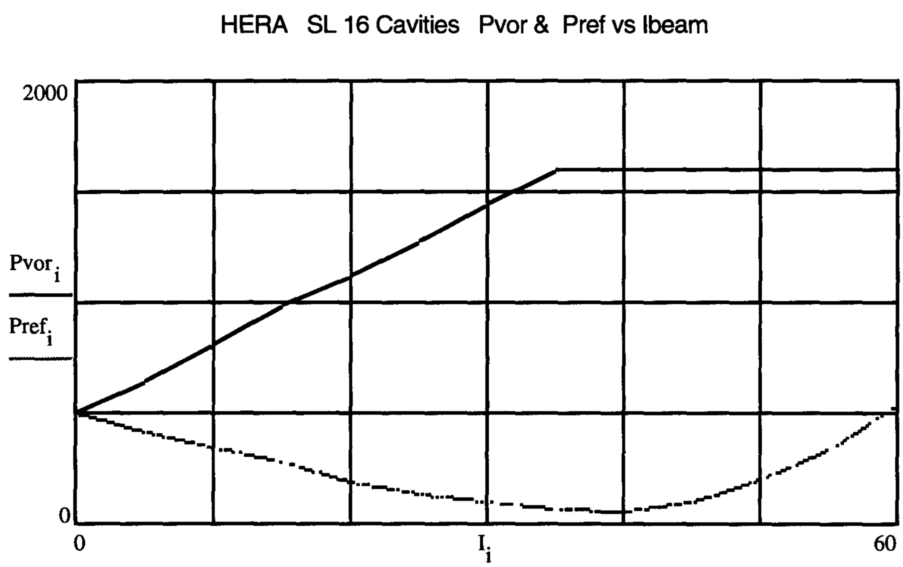


Fig. 6 Operating conditions for SRF in HERA with active vector voltage control. Limits are: max E_{acc} 4 MV/m, max P_{cavity} = 100 kW. Upper graph: cavity voltage; lower graph: upper curve forward power, lower curve reflected power

2.3.2 Reliability, trip events

Working conditions and component behavior is monitored to ensure a safe operation of the sc system:

- input coupler (e-detector, spark detector, window temperature, cooling air)
- HOM coupler (temperature at feed through)
- vacuum (beam-, insulation vacuum)
- quench detector
- absorber power (in main RF line)
- cryogenic OK.

Table 1 summarizes the interlock philosophy. In case of an interlock interrupt the leading event is recorded. In addition a fast event recorder can be used to document the evolution of an interlock process. Fig. 7 shows an example of multipacting in an input coupler:

- The e- detector measures an electron current in the coupler of cavity 11.
- RF-power is absorbed by this process because the reflected RF power decreases although the cavity voltage drops down.
- The forward RF-power stays constant as can be seen by the constant voltage in cavity 10.

The amount of absorbed RF power by the multipacting process can be estimated to 7 kW. Finally the e^- detector trips the klystron power after 200 msec. The time constant of the measured electron current is slowed down by a low pass filter in the electronics.

In most cases the trip of the sc voltage also results in loss of the beam. This cannot be explained by the missing circumferential voltage. Most likely this is due to the uncompensated (unpowered) cavity impedance of 2 GΩ.
After every cool down the sc system has to be processed to overcome the multipacting barriers in the input coupler. The most efficient way to do this is operation with short, high power pulses. The typical procedure is to increase the power from 100 kW to 800 kW at pulse length from 100 μsec to 3 msec. After a cool down this has to be done for about 12 h. Some multipacting barriers might reappear after 6 weeks of operation. A short pulse conditioning of about 1 h is sufficient to clean the coupler again.

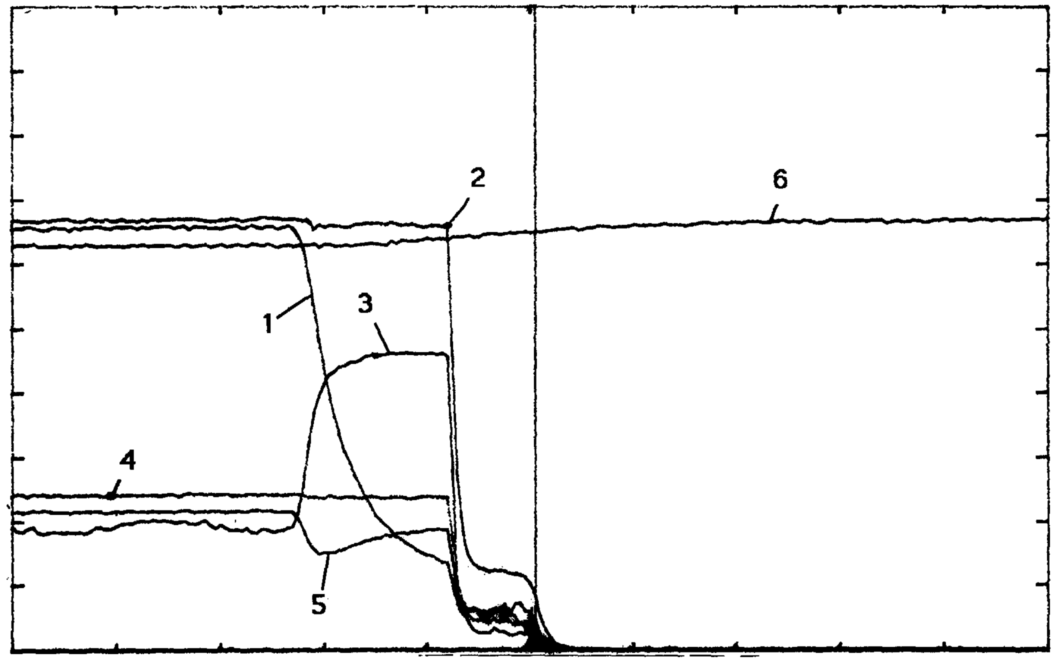


Fig. 7 Recorded multipacting event in input coupler of cavity 11:
1: voltage in cavity 11; 2: voltage in cavity 10; 3: electron current in probe at input coupler 11; 4: reflected power cavity 10; 5: reflected power cavity 11; 6: Helium pressure in cryostat for cavities 10 and 11.

After debugging the new sc system operation was reliable. Fig. 8 shows typical conditions of operation. Here the beam on time, the sc RF on time and the beam off time after a sc system trip are plotted. The sc system was operated by the regular shift crew, only in very few cases experts from the sc group had to be called.
All feedthroughs of the 48 HOM coupler cables are temperature monitored to detect heating by excessive RF power or by a bad contact. Two types of HOM couplers are installed: 32 TE couplers and 16 TM couplers. The predicted HOM power at nominal current of 60 mA and 210 bunches is typically 100 W at fundamental frequency and 1 W at HOM frequencies for the TE (TM) coupler. Several power measurements have been done at 10 mA, 20 mA and 30 mA. for different bunch numbers. After appropriate scaling the agreement between measurement and calculation is within 30 %. During the three years of operation the HOM interlock did not trip at all. Only recently at the machine study runs (end of 1993) one TE-HOM connector showed heating up to 50 °C. The measured RF power of this coupler (about 30 W) was the same as the other TE couplers which showed no heating. It is expected that there is a non typical feed through problem. The feed through and cable connector will be carefully inspected in the forthcoming shutdown.

All magic Ts and directional couplers are loaded by 50 kW absorbers. In a completely balanced system, .i.e. all cavities show the same reflection coefficient, these absorbers are not loaded but all reflected power is transferred to the main circulator load. In unbalanced conditions, however, considerable energy might be dumped in those absorbers. One unbalanced situation is created by operating the sc system with one cavity out of resonance. This happened due to malfunction of the tuner control. In the worst case 4 times the cavity forward power is dumped in one directional coupler absorber.

HERA Luminosity Runs with e-beam
(Superconducting Cavities Operation Time)
September 93

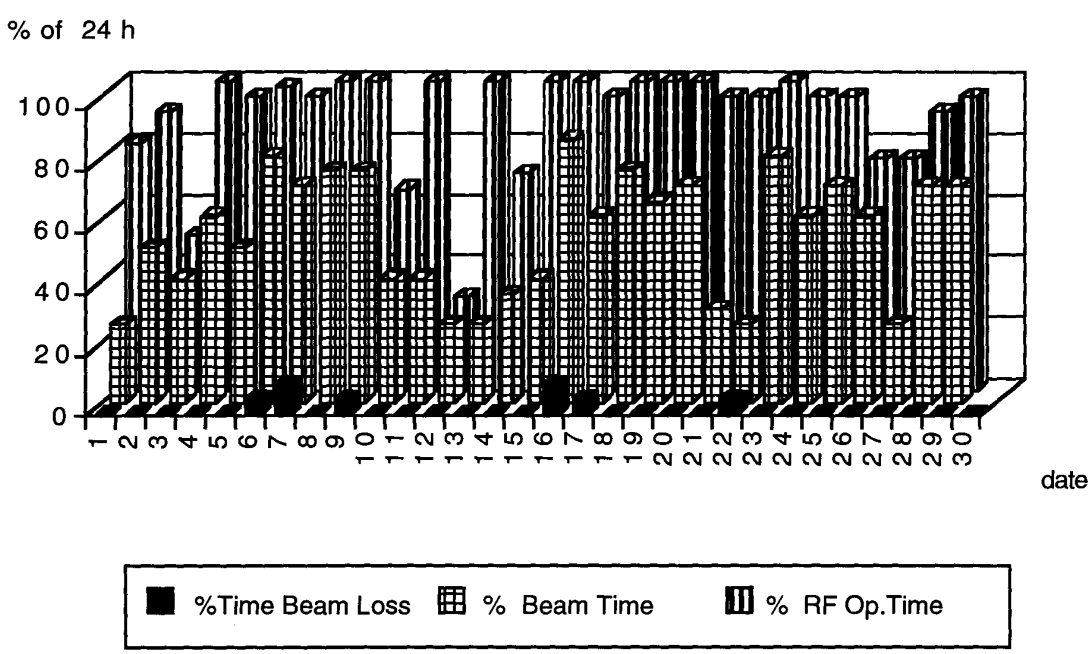


Fig. 8 Typical operating condition of HERA:
crossed line bar: beam on time
vertical line bars: SRF voltage on time
dark bars: beam off time due to interlock of SRF

Another dangerous condition might evolve during injection. Here a synchrotron phase angle of 176 degrees is established. In case of tuning or calibration errors one sc cavity might operate above 180 degrees thus producing RF-power which will be dissipated in the balance absorbers. It is assumed that this condition created interlock trips in the absorber line, especially at high current runs during machine studies.

2.3.3 Hydrogen on cold surfaces

Each cryostat (two cavities) is pumped by an Ion Getter Pump (100 l/sec). The intermediate vacuum chamber (2 m) has an integrated quadrupol pump which is activated when the magnet is energized. During cool down and RF processing only the Ion Getter Pump is active. Fig 9 shows the typical improvement of the beam vacuum during cool down. At cold the typical pressure is in the 10^9 region. It can be seen in Fig. 9 that after several days the vacuum deteriorates. At this stage the gate valves are closed so that the cryostats (including the interconnecting beam pipe at

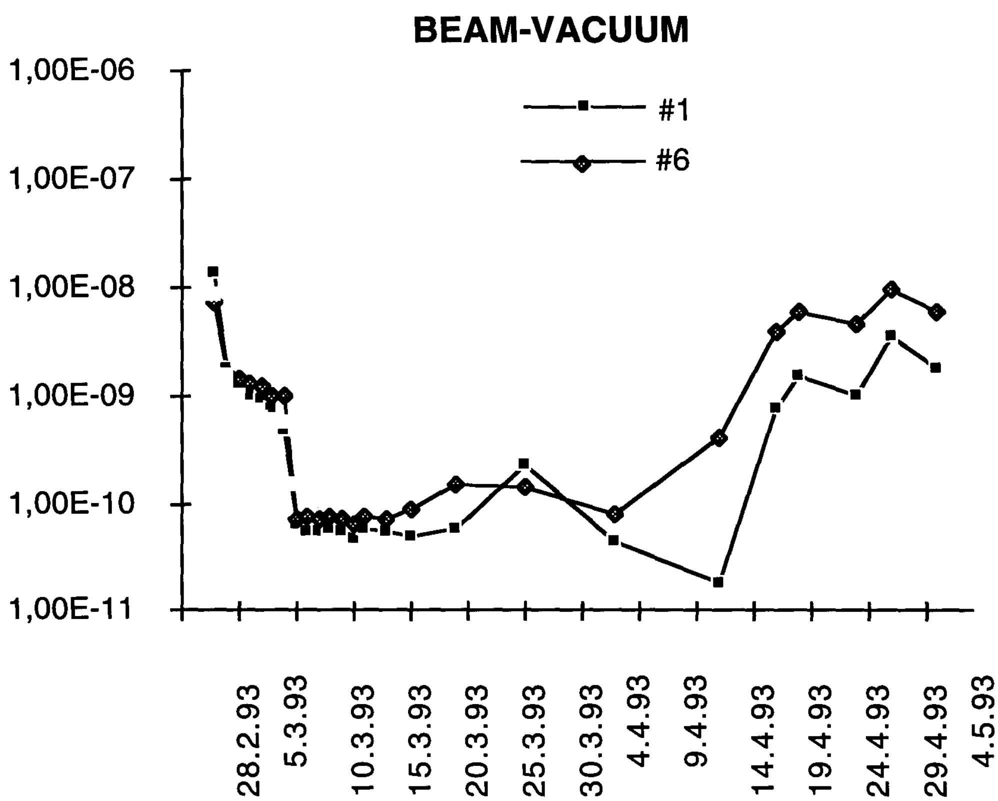


Fig. 9 Cavity vacuum during and after colldown. Both gate valves in the beam line are closed. The deterioration of the beam vacuum after cooldown is due to desorbed Hydrogen (see text).

room temperature) are insulated. With the exception of cryostat 3 (which has a small leak to LHe) only the partial pressure of H_2 is increased. This can be explained in the following way (see [1]):

- At 4.2 K a cold surface can absorb about one monolayer of H_2. After saturation the cold surface can no longer pump H_2.
- The warm part of the beam pipe (transition piece, interconnecting copper pipe) desorbs H_2, depending on heat treatment.
- With the given warm surface it can be shown, that a period of several days is needed to reach saturation condition of the cold surface.

By separating the warm beam pipe from the cold cavity it became clear, that the dominant Hydrogen production is at the copper beam pipe.
As consequence the vacuum at the cold cavities will not be superior to the room temperature parts of the storage ring if Hydrogen is the dominant residual gas. Furthermore a slight warm up of the cavities (due to refrigerator problems, e.g.) will cause a considerable pressure increase in the beam line vacuum because of desorption of a large amount of Hydrogen.

3. TESLA Activities

Several other papers will cover TESLA activities at DESY. Here only a short overview is given. It should be mentioned that most activities are carried out in collaboration with other national research centers or university groups. For details see report about TESLA [2] and on infrastructure [3].

3.1 Infrastructure

A new infrastructure is established at DESY to handle the 1.3 GHz 9-cell cavities:

- automized chemistry, including a high pressure water rinsing,
- clean rooms (class 10, 100, 10.000) to handle individual cavities as well as a complete string (8 cavities plus quadrupol),
- a high temperature furnace to fire cavities,
- two vertical and one horizontal test stations,
- klystron stations and
- a complete TESLA TEST Accelerator (injector, 32 cavity accelerator, diagnostics and beam station).

Fig. 10 shows the layout of the experimental hall. It is intended to commission the infrastructure (excluding the linac) in the beginning of 1994.

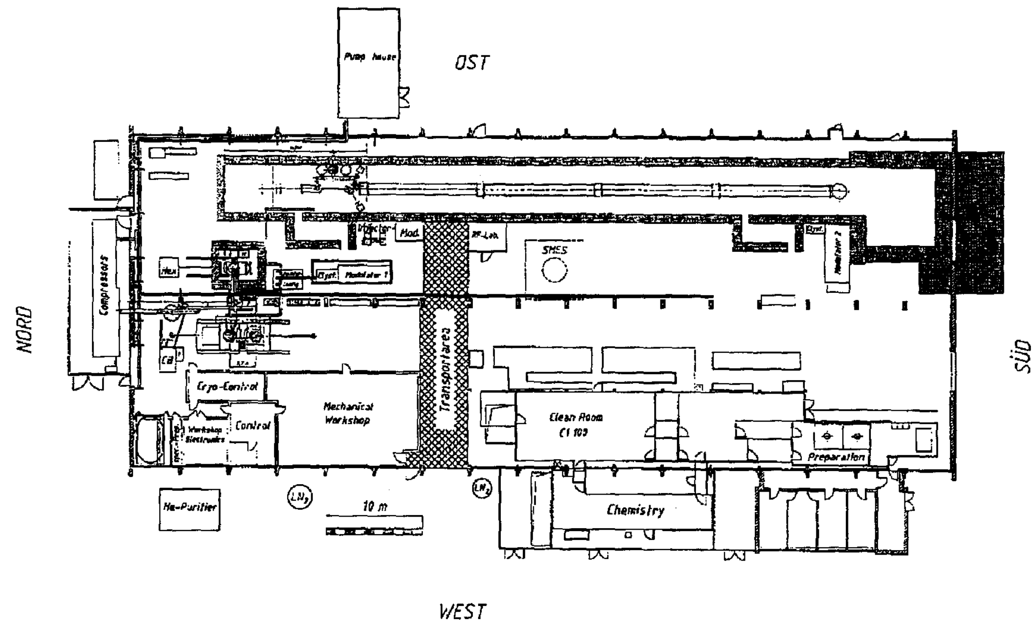


Fig. 10 Layout of the experimental hall for the TESLA Test Facility (TTF) at DESY. Upper part: linac, lower part left: cryogenics and test stands, lower part right: clean room, chemistry, vacuum furnace.

3.2 Procurement of cavities and couplers

The mechanical [4] and electric [5] layout of the TESLA cavity has been finished. Several prototypes (5 of Cu, 2 of Nb) have been build and tested. Fig. 11 shows the two Nb cavities. The stiffening rings at the iris are foreseen to compensate for the deformation due to the Lorentz force. The shape of the cavity is identical to the TESLA design. No input and HOM coupler is foreseen at those two resonators. They will be used to commission the infrastructure and to gain first experience with measurements at 1.8 K.

Two types of HOM couplers have been developed[6]. One design (see Fig. 12) follows the idea of a welded construction as being used for the 500 MHz HERA superconducting cavities. The other design (see fig. 13) is a flanged construction with a capacitive gap to close the electric path for the fundamental frequency. Both types of couplers have been tested at a superconducting single cell cavity at Saclay. The conclusion of the measurement is that the conduction cooling of both couplers is sufficient for the TESLA parameters (gradient of 25 MV/m at 2 msec and a rep.rate of 10 Hz) [7].

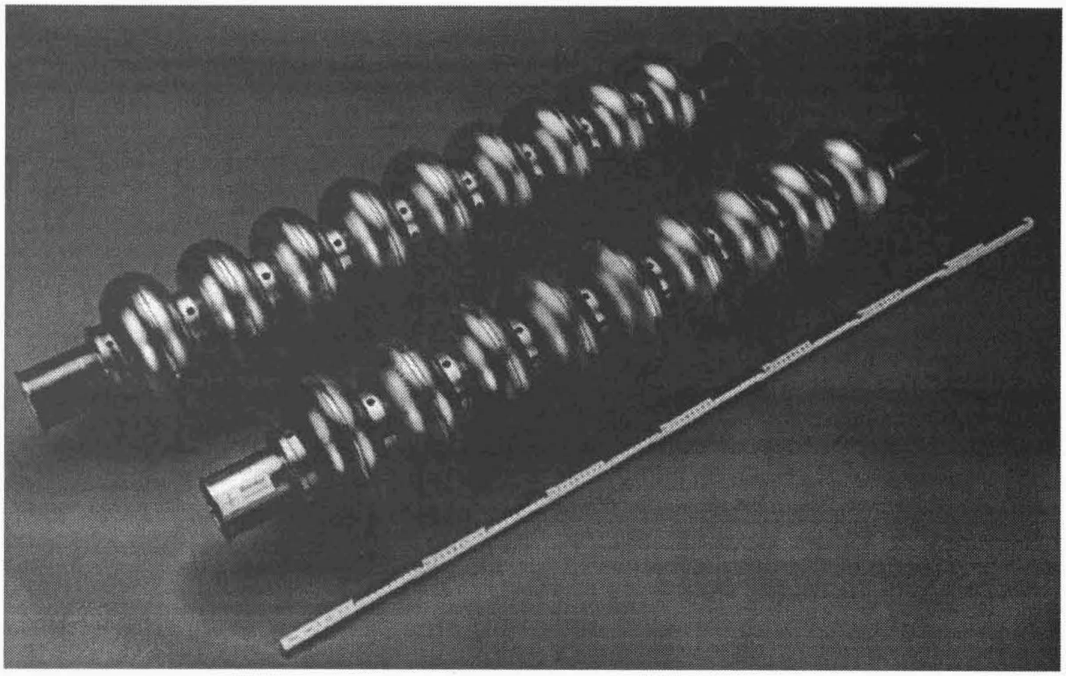


Fig. 11 The first two Nb TESLA cavities (no HOM- and input couplers)

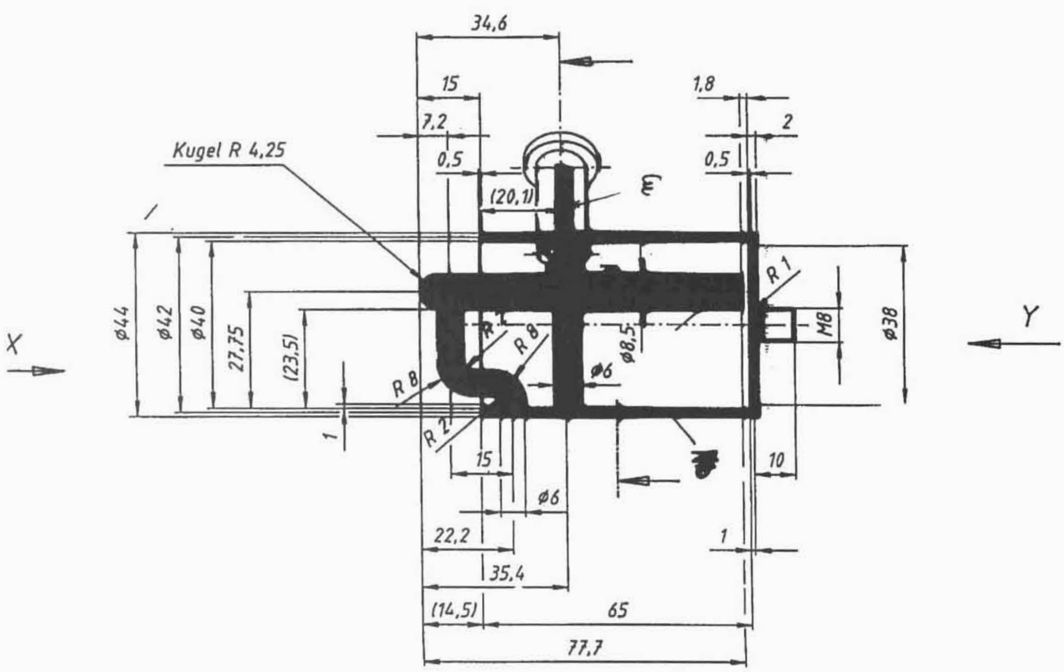


Fig. 12 Welded HOM coupler

At the time of the workshop the order for Niobium for the first 18 cavities has been placed and negotiation with several companies for fabrication of the cavities has been started.

Two types of input couplers are being developed for TESLA [8][9]. Both couplers have a cold window at 80 K and a second one at room temperature. The major difference of the cold window is the use of a conical ceramic versus a cylindrical one. Both designs will be tested at the stage of prototype.

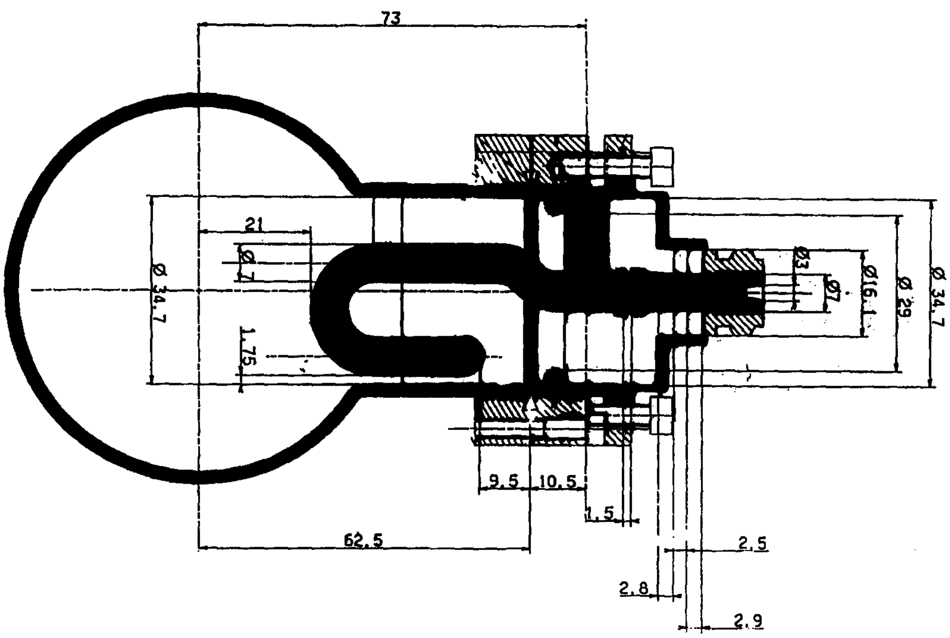


Fig. 13 Demountable HOM coupler

3.3 R&D effort

3.3.1 Nb material data

Only a few (and non consistent) data of mechanical material parameters of Noibium before, during and after firing at 1500 °C are available for RRR300 quality. Therefore an apparatus was built to measure yield strength and ductility in the temperature range from room temperature to 1500 °C. Fig. 14 shows the principal layout of the experiment. The Nb sample is heated by induction. A constant force is applied by a weight and the elongation is recorded. Fig. 15 shows a yield strength .2 % of 9 N/mm at 1375 K. In Fig. 16 it can be seen that fired Noibium starts to creep already at low values stress.

3.3.2 Dark current

Numerical investigation of the kinematics of dark current has been started. As first step, field emitted current from different cavity surface areas has been tracked through a set of 8 cavities. This is the distance between two quadrupols in the TTF arrangement. Fig. 17 shows first results and demonstrates that at E_{acc} = 15 MV/m field emitted current is captured by the RF field.

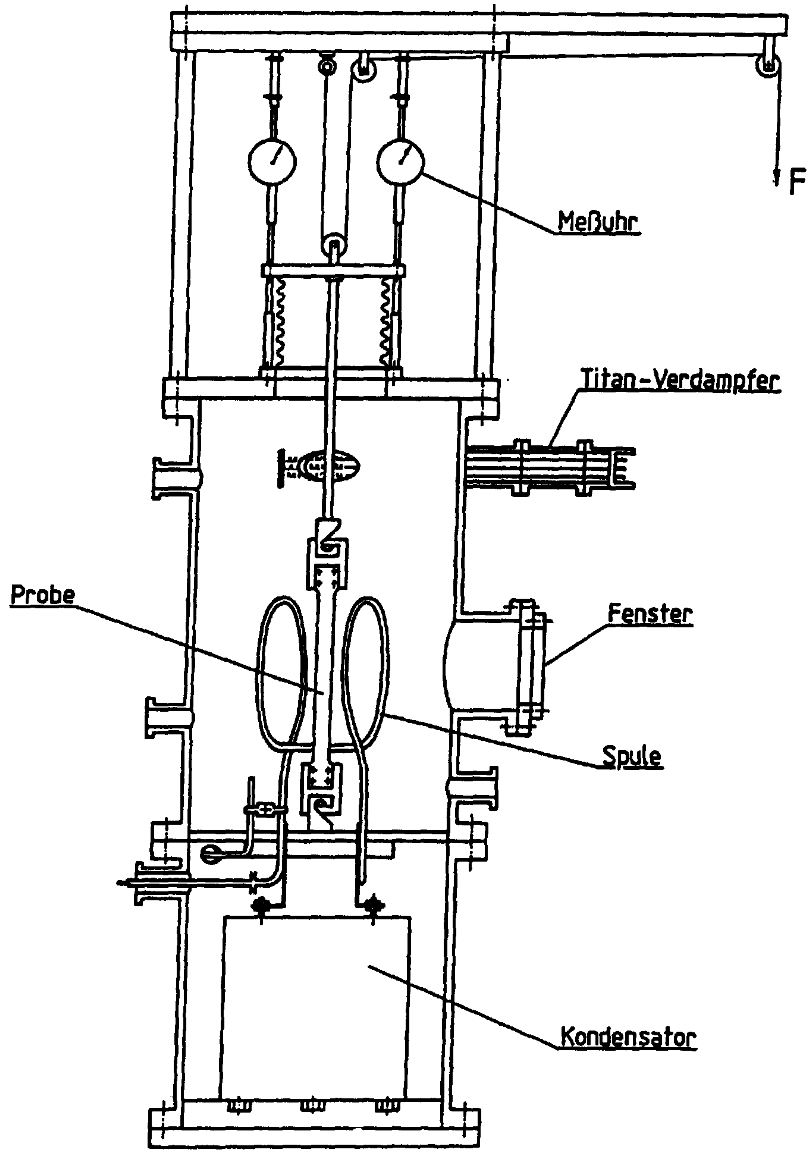


Fig. 14 Apparatur to measure yield strength of Nb at high temperatures (up to 1300 °C). The Nb sample is heated by induction.

3.3.3 Single cell experiment

In another experiment a single cell 1.3 GHz cavity will be equipped with 800 fixed resistors for fast temperature readout. It is the idea to investigate time dependent phenomena during field emission. Furthermore the 4 MW klystron will be used to drive the cavity surface fields above the theoretical limit.

3.3.4 Multipacting

In collaboration with the Rolf Nevanlinna Institute, Helsinki, a research effort was started to predict and describe multipacting phenomena in complex 3D RF structures. Multipacting has been observed, for example in input coupler lines for superconducting resonators. It is also assumed

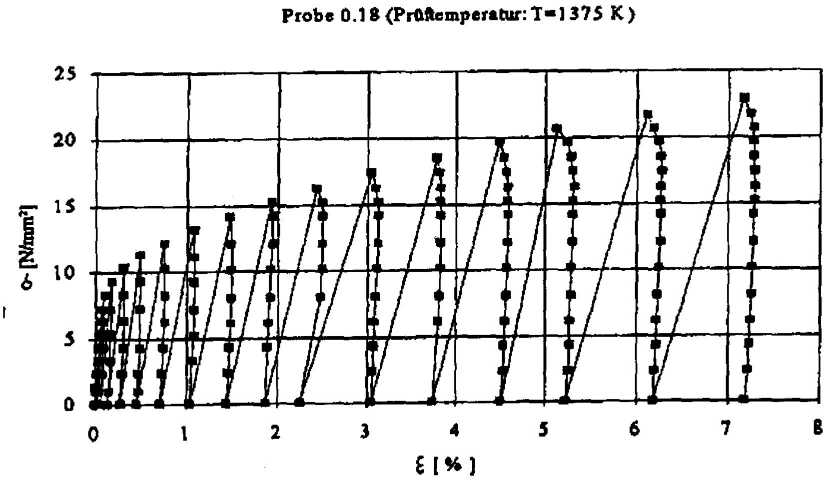


Fig. 15 Yield strength measurement of Nb at 1375 K. The resultant value for 2 % yield is 9.. N/mm.

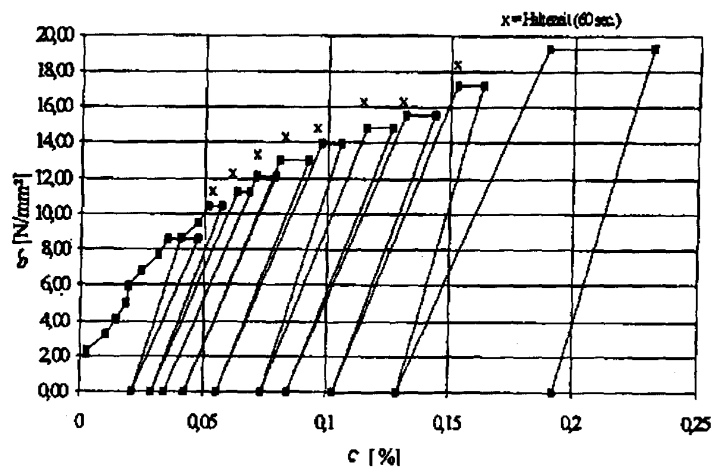


Fig. 16 Kreeps of Nb at room temperature (fired samples). The applied sorce is kept constant for 60 sec.

that multipacting might be involved in damage of RF windows. Therefore an analysis of this phenomenon is very worthwhile. As first step a trajectory program has been linked to standard 2D field solvers. One strategy applied to find multipacting is to search for conditions of enhanced impact power. This will be compared with the observed multipacting in coaxial lines. Later the 3D option will be added.

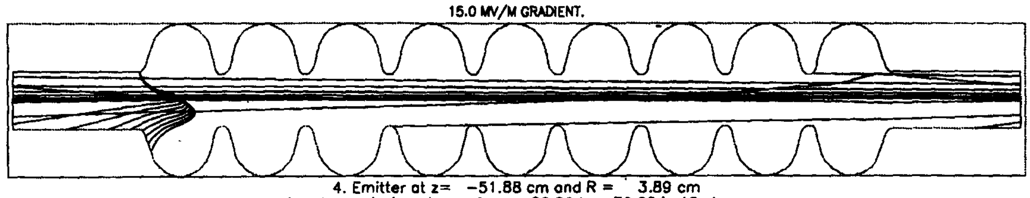


Fig 17 Result of tracking field emitted current. Electrons are emitted at the left iris. It can be seen that the field emitted current passes through all the other 7 cavities. There will be a set of 8 cavities between quadrupoles in TTF.

References

[1] D. Trines, TESLA Report 93-20
[2] H. Edwards, this conference
[3] M. Leenen, this conference
[4] H. Kaiser, this conference
[5] D. Proch, this conference
[6] J. Sekutowicz, this conference
[7] A. Mosnier, J. Sekutowicz, private communication
[8] B. Dwersteg, this conference
[9] M. Champion, this conference