SRF for Future Muon Colliders

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OUTLINE

- Describe 5 + 5 TeV Accelerator Layout and Required Performance
- Compare to existing design + performance (e.g. TESLA, TTF)
- Point out areas of R+D Necessary
- Give some estimate of costs!
- Quick Look at 50 TeV + 50 TeV Case
- Some Remarks about low Freq Front end.

MACHINE CONFIGURATION

CEBAF

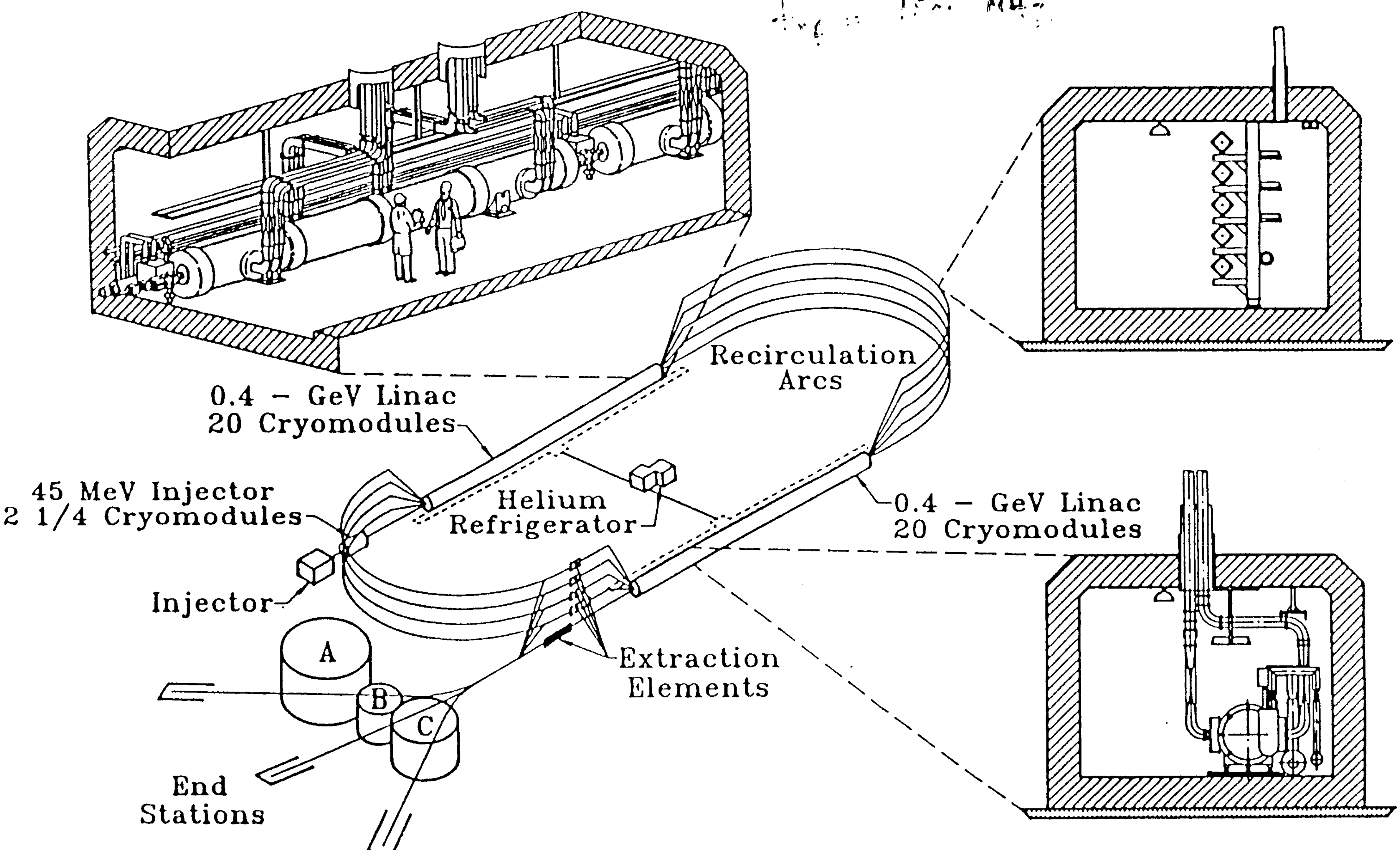
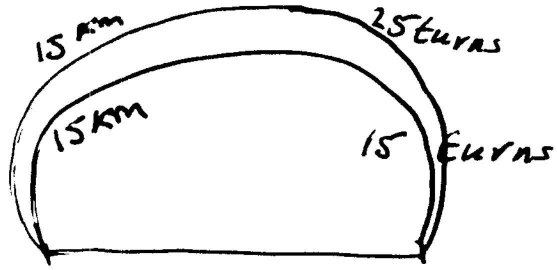


Figure 1

5 TeV + 5 TeV



and so on

Linac
2 Km = 50 GeV

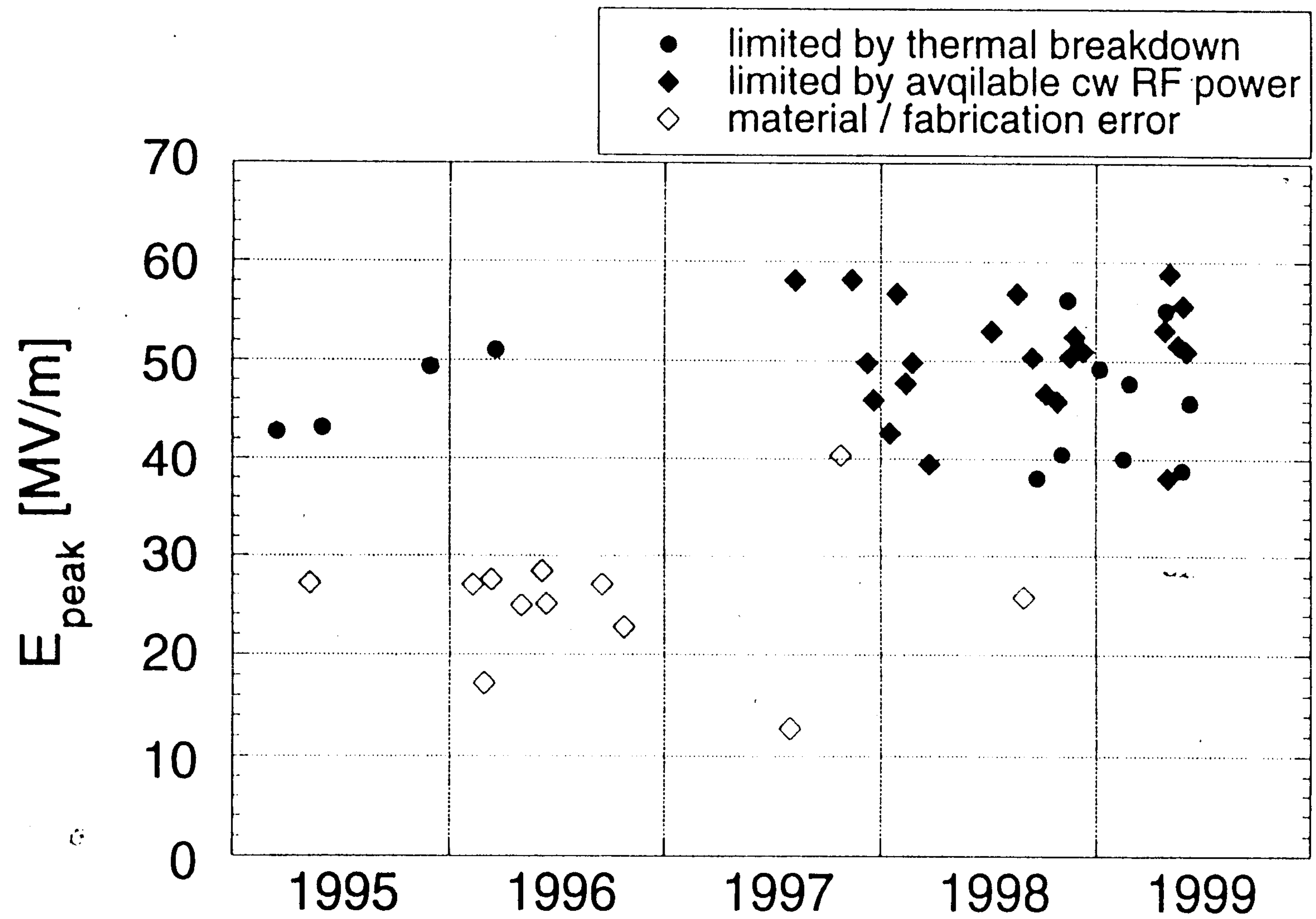
Total Number of turns = 15 + 25 + 20 + 21 + 9 = 90

Beam ON TIME = $90 \times \frac{15\,\text{Km}}{c} = 4.5 \times 10^{-3}$ sec

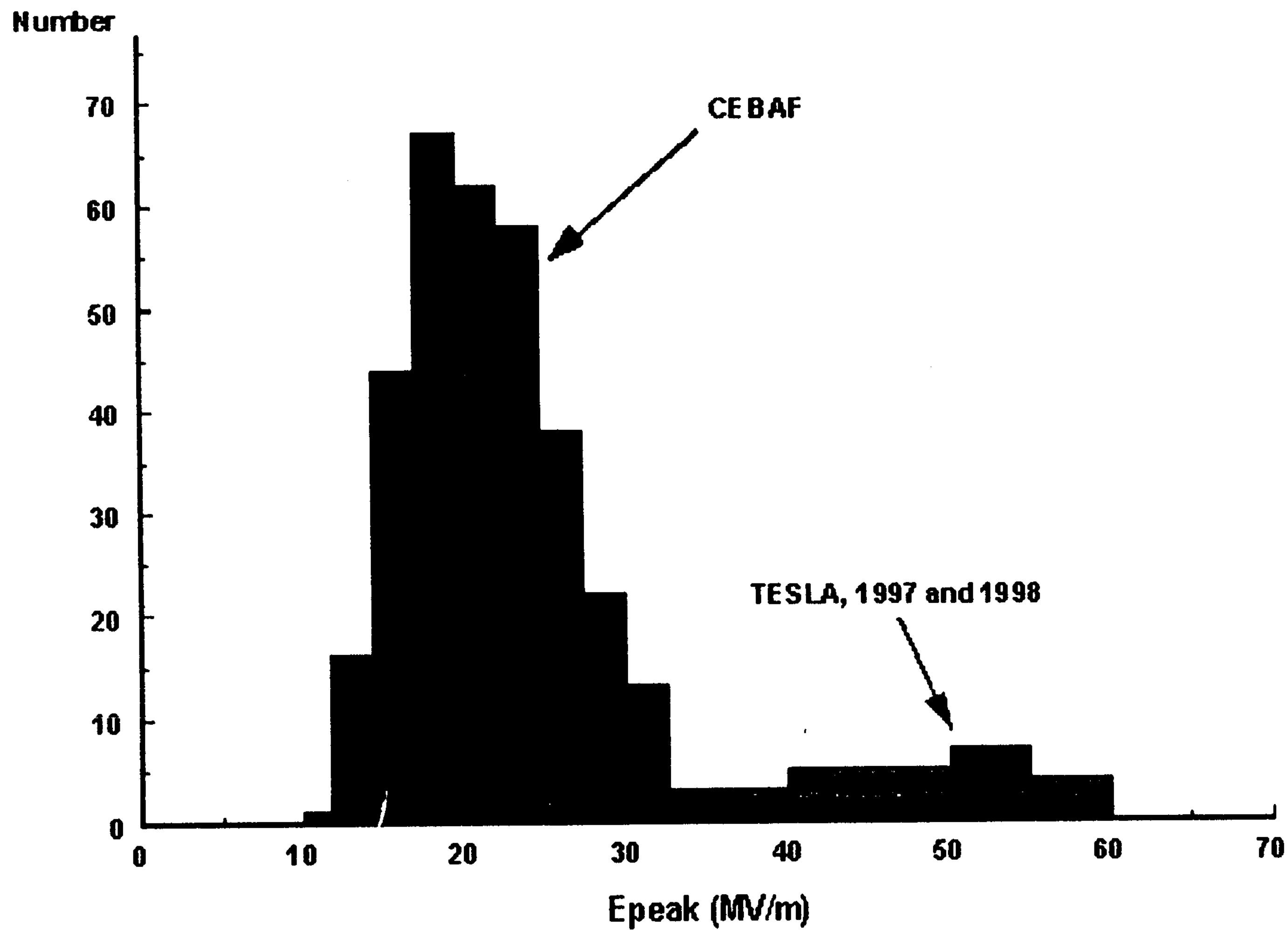
HEMC ($\mu^+\mu^-$)		**TESLA** (e^-)
5 TeV	Beam Energy	~~0.25 TeV~~
4.5 msec	Beam ON Time	800 × 1μsec = 0.8 ms
27 Hz	REP RATE	10 Hz
12.2%	Beam Duty Factor = Rep rate × $t_{beam\text{-}on}$	0.8%
3×10^{12}	No. of Particles /bunch	5×10^{10}
117 MW	Average Beam Power (Including HOM power)	16 MW
1.06 GW	Peak Beam Power	2 GW
1.3 GHz	RF Frequency	1.3 GHz


HOM Coupler

Maximum gradients reached in TESLA 9-cell cavities



Comparison of CEBAF and TESLA Peak Surface Electric Fields



TTF Performance

More than 60, 9-cell cavities built by industry
max gradients 29 MV/m

After some learning experience
Eacc = 20 - 29 MV/m,
Q0 > 5x10^9 in acceptance tests

16 cavities installed in 2 cryomodules
delivered 160 kW/m to 8 mA peak beam

!st cryododule
(included some cavities on learning curve)
<Eacc> = 16 MV/m

2nd Cryomodule (8 cavities)
<Eacc> = 20 MV/m, Q0 > 10^{10}, except one

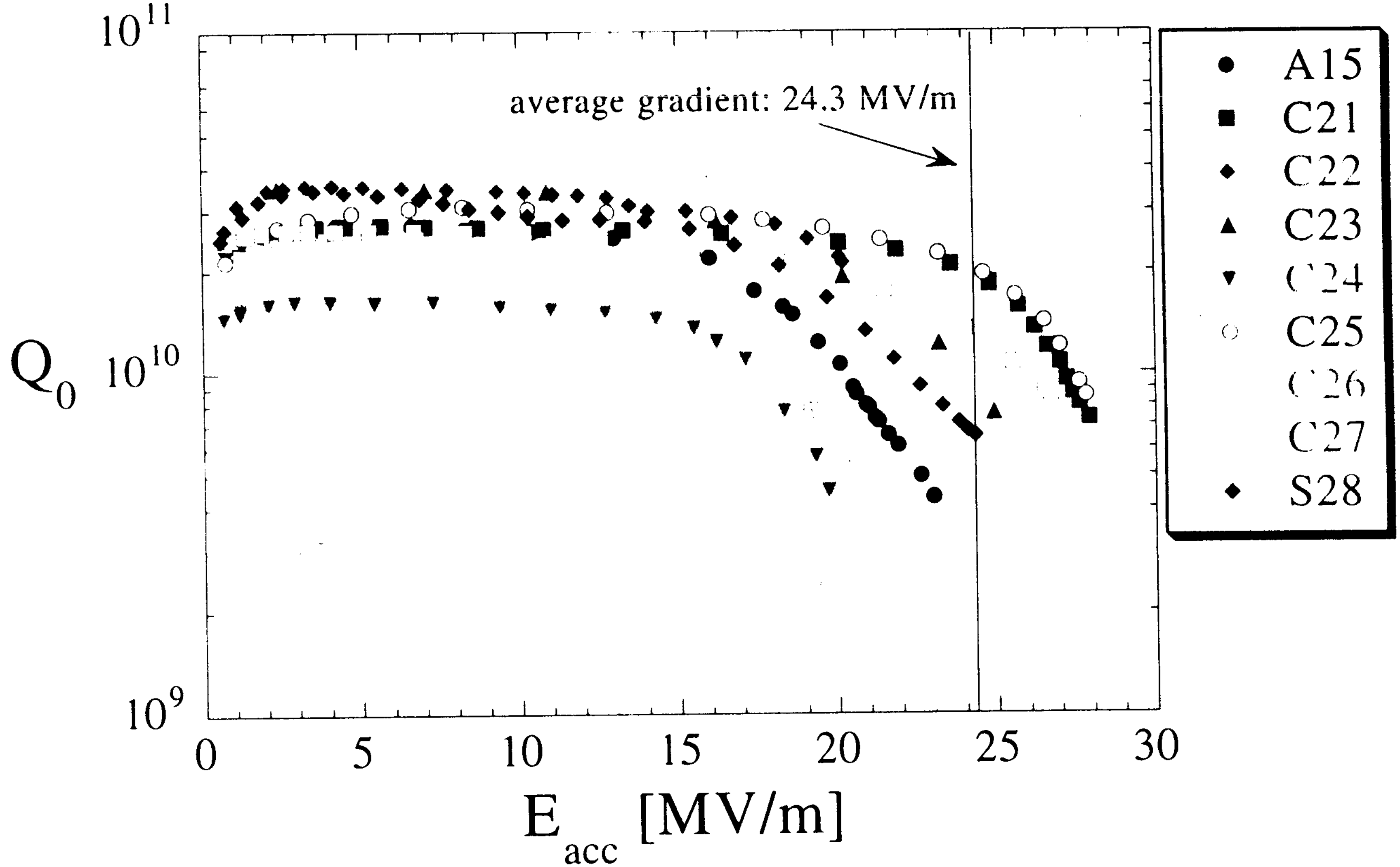
Pulsed operation demonstrated with beam
- 1 msec pulse length
- amplitude stability < 10^{-3}
- phase stability < 0.05 degrees

with feedback and feedforward

Best gradient in pulsed modes up to 33 MV/m

Static heat leak < 1 watt/m

Vertical test results of TTF cavities (A15,C21...C27: for module 2)



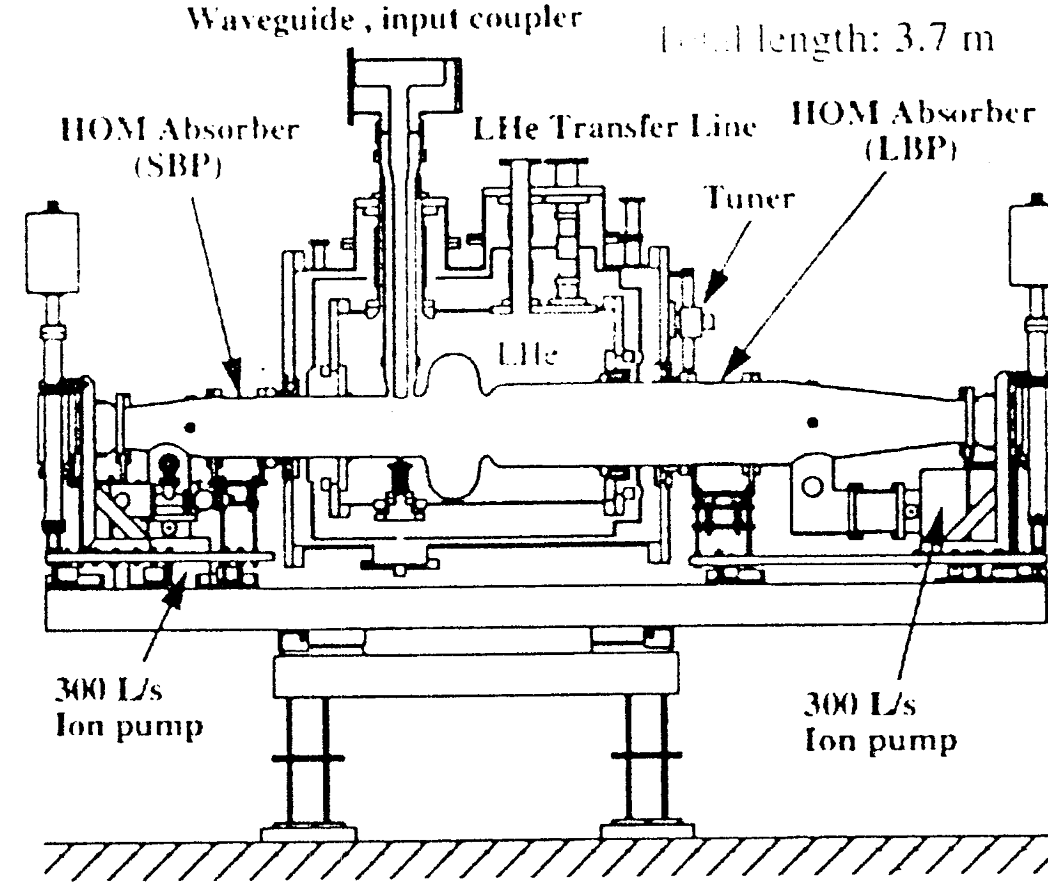


Figure 1: Superconducting cavity module for KEKB

Figure 2: A picture of four SCC modules in Nikko-D11 tunnel

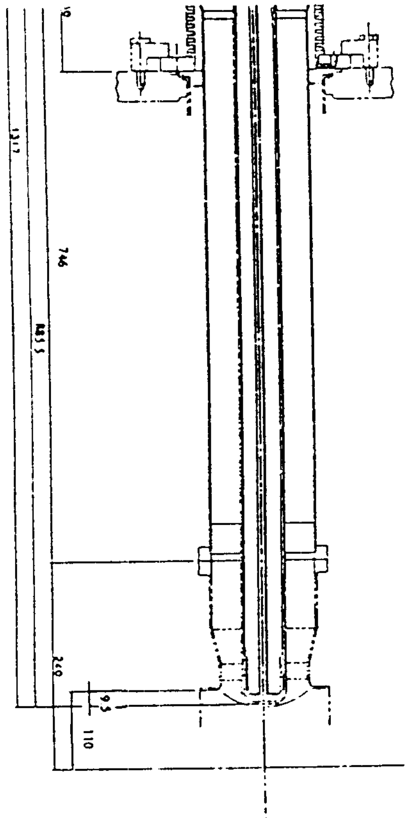


Fig. 1 Coaxial input coupler for KEKB SC cavities

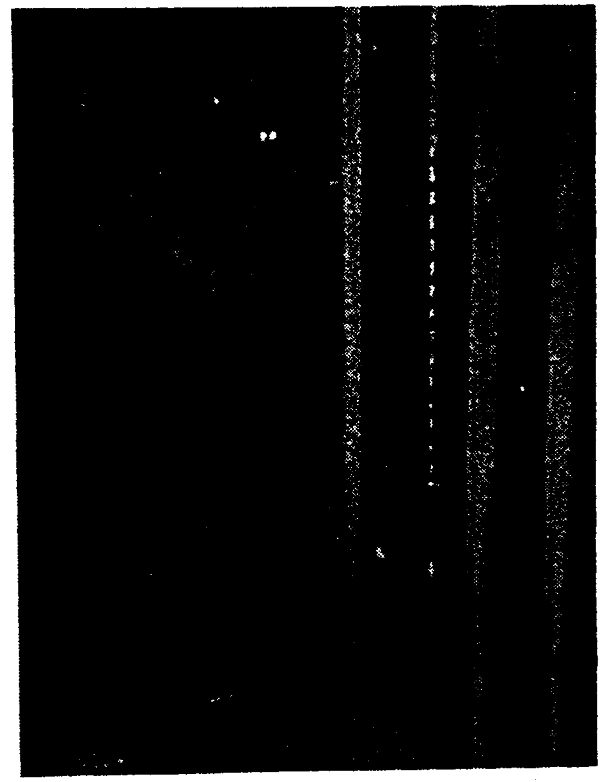
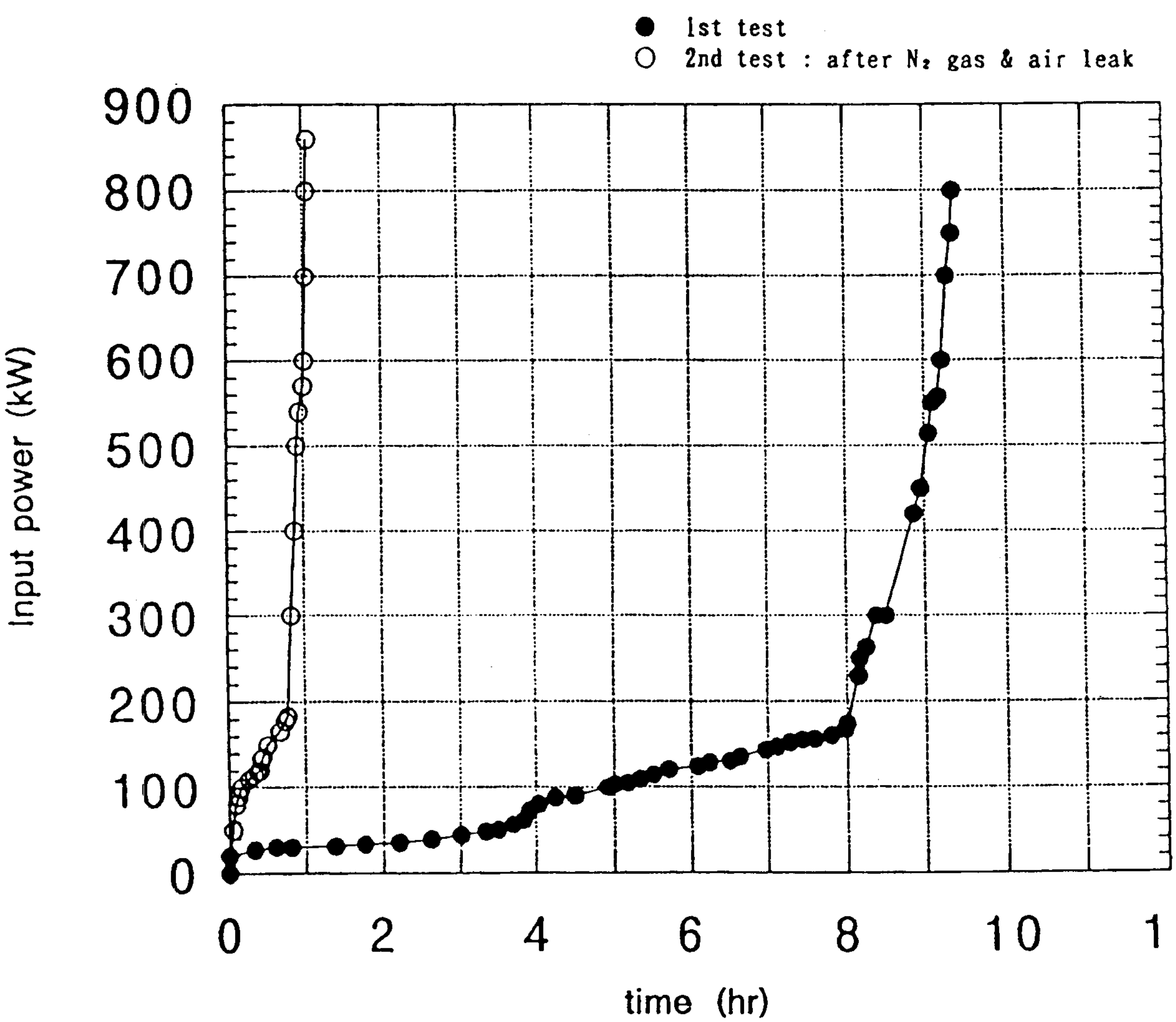


Photo.1 Coaxial input coupler wit

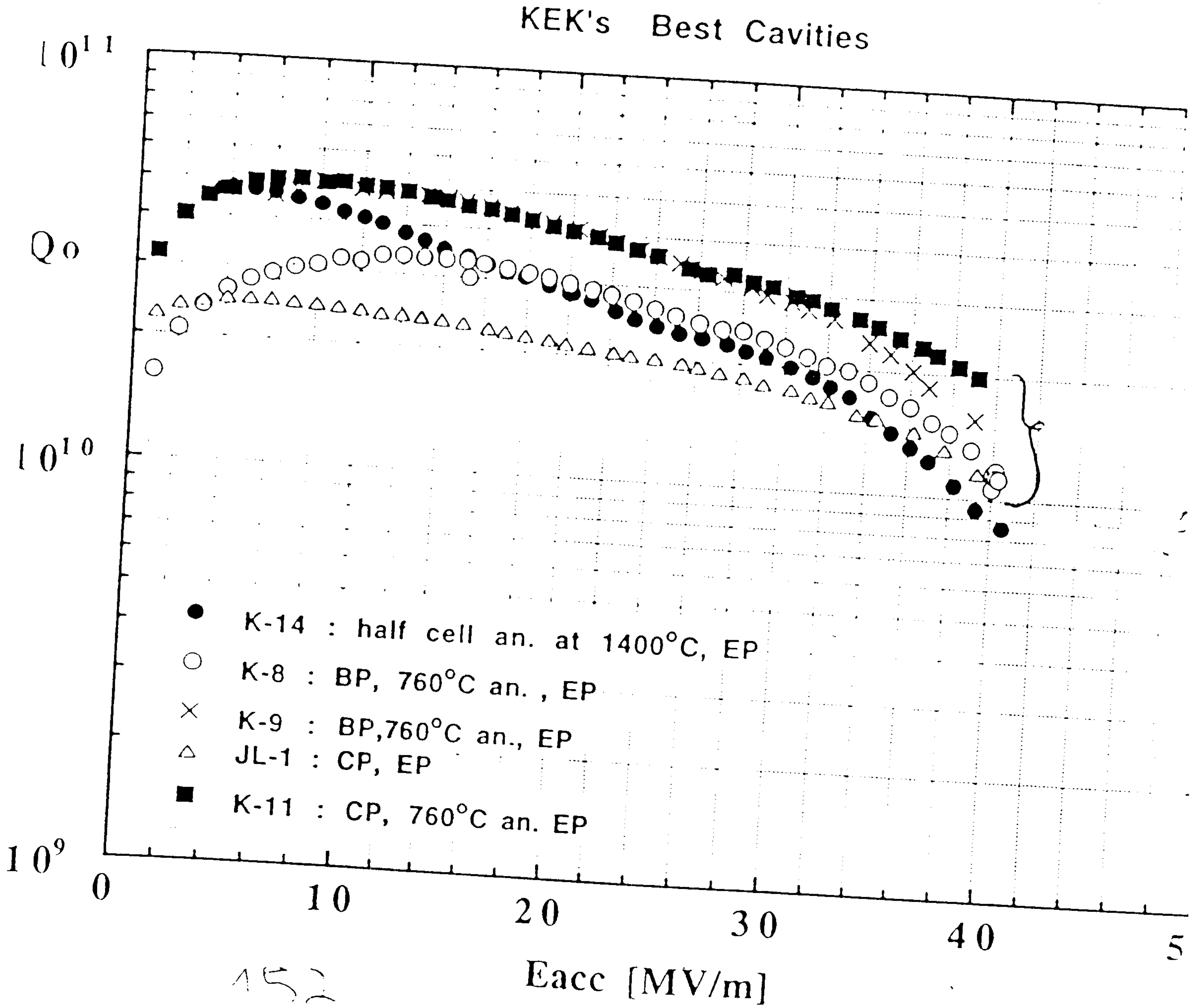


HEMC (5 TeV) $\mu^+\mu^-$		TESLA (e^-) 0.25 TeV
25 MV/m	Gradient (G)	25 MV/m
2 Km	Length	10 Km
540 KW/m	Peak RF Power/m	200 KW/m

TESLA TTF delivered 160 KW/m to beam

KEK-B delivered 380 KW/m to beam

1×10^6	Loaded Q_L (match to beam) $= \dfrac{G^2}{\left(\frac{R}{Q}\right)\frac{P_{pk}}{L}}$	3×10^6
180 μsec	Fill time $\frac{Q_L}{\omega}(2\ln 2)$	490 μsec
5 MW, 5 msec	Klystron	10 MW, 2 msec
235	Number of Klystrons	207
12.8%	RF Duty Factor (incl. fill + decay)	1.3%
15 KW	RF Dissipation into 2K Helium $\dfrac{G^2}{(R/Q)\,Q_0}\,D.F.\,L$	17 KW
1×10^{10}	Q_0	5×10^9



KEK's Best Cavities
Qo
10^11
10^10
10^9
0
10
20
30
40
5
Eacc [MV/m]
K-14 : half cell an. at 1400°C, EP
K-8 : BP, 760°C an. , EP
K-9 : BP,760°C an., EP
JL-1 : CP, EP
K-11 : CP, 760°C an. EP

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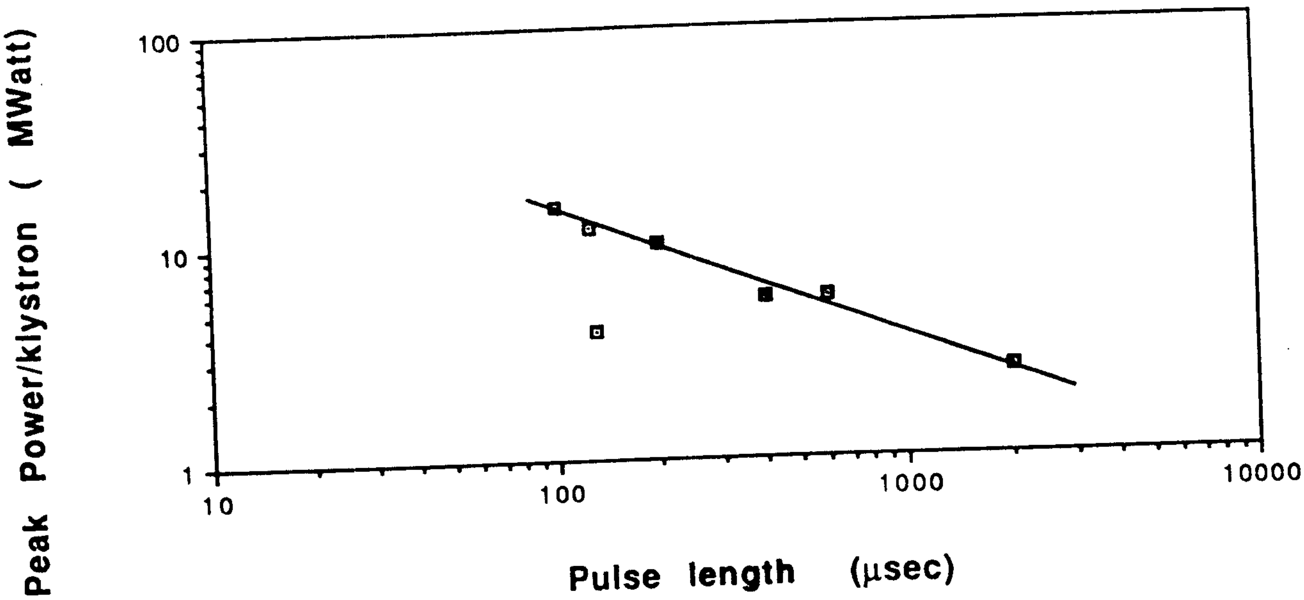
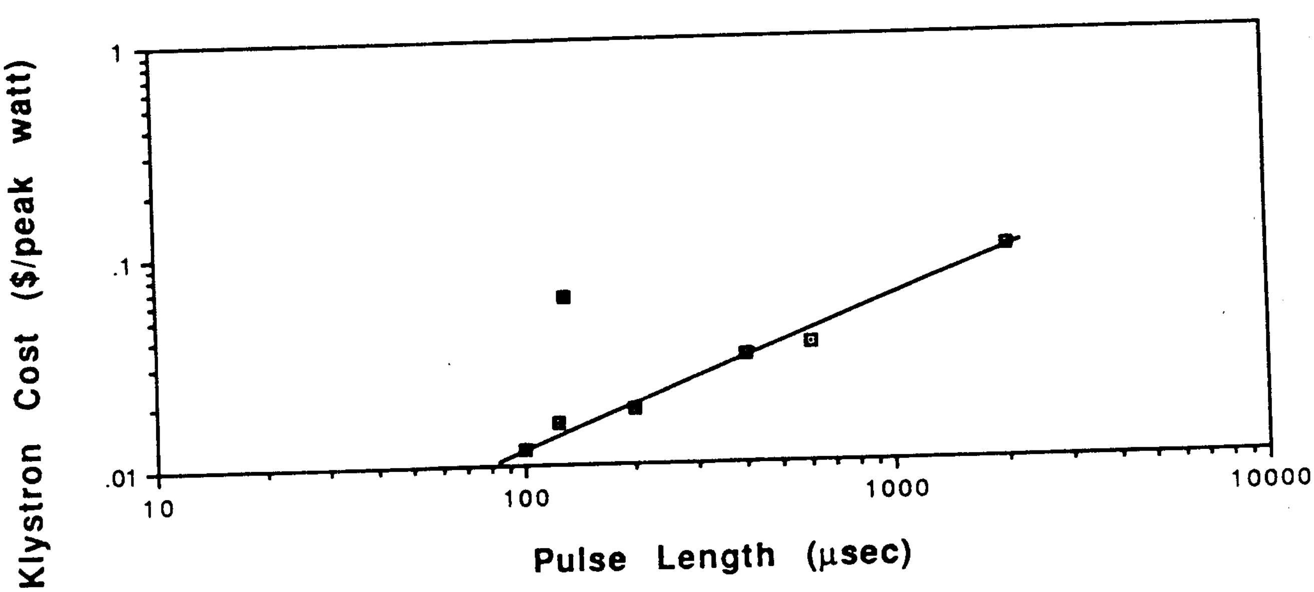
HEMC (5 TeV) $\mu^+\mu^-$		TESLA (e^-) 0.25 TeV
	Static Heat Leak	
4 KW	1 W/m x 2 L	20 KW
	He Distribution	
0.8 KW	0.2 W/m x 2 L	4 KW
20 KW	Total Cryo. Load	40 KW
51 M$	CAP COST (Cryo)	106 M$
245 M$ (Long Pulse)	CAP COST (RF)	190 M$
144 M$	LINAC 150 K$ $(0.8)^{\log L}$ TTF INDUSTRIAL STUDY	614 M$
440 M$	TOTAL CAPITAL	910 M$

Peak Power of klystrons (MWatts) depends on RF pulse length as shown

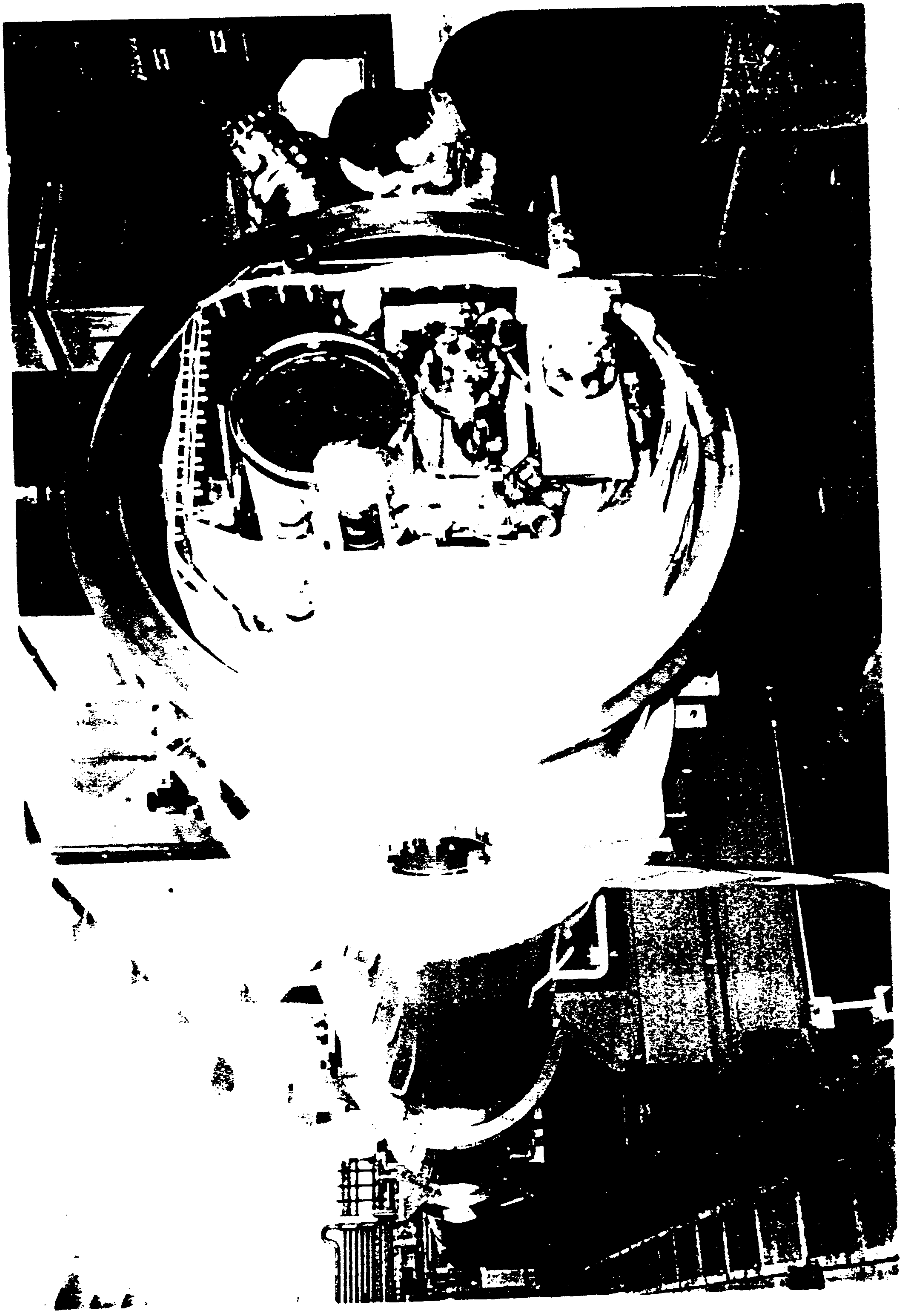


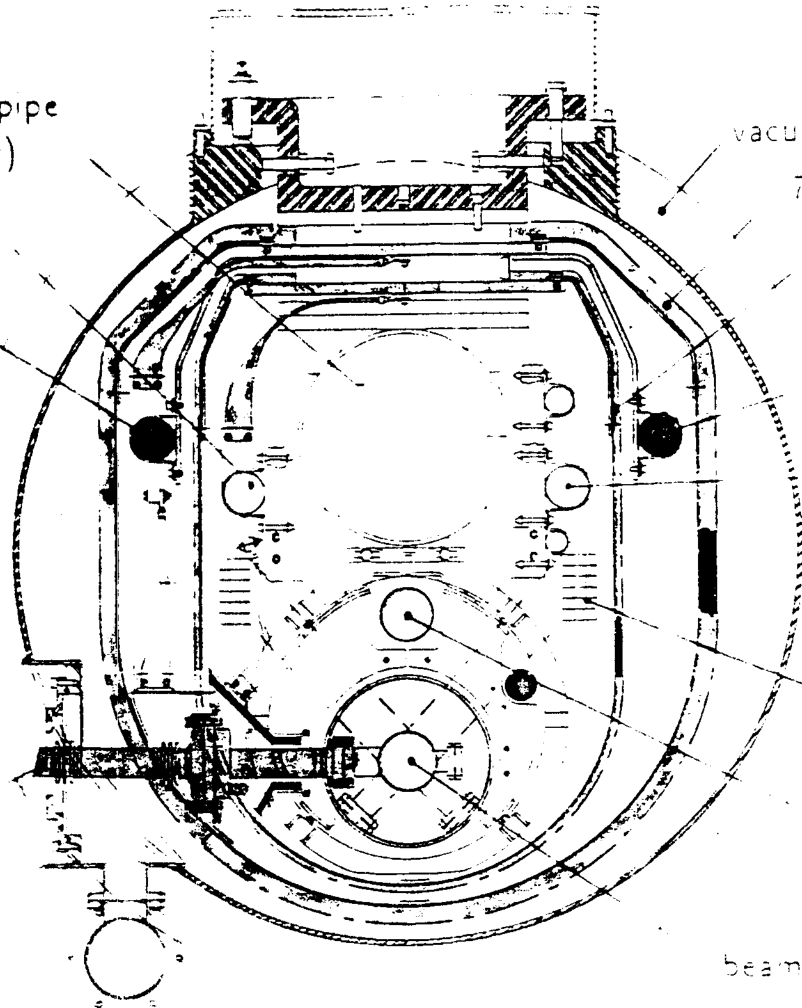
$/peak RF Watt for klystrons is determined from the following graph derived from klystron catalog information:



$$LCrf := 0.708 \cdot \log\left[\frac{trf}{10^{-6}}\right] - 3.335$$ Log of cost

$$Crf := 10^{LCrf}$$ Cost of Peak power ($/watt)





- He gas return pipe (HeGRP) is supported from above by three support posts (fiberglas pipe); it acts as a girder and is used for alignment
- the 8 cavities, the quadrupole package and aux equipment are attached to the HeGRP by means of stainless steel collars
- two aluminium radiation shields are at intermediate nominal temperatures of 4.5 K and 70 K; they are cooled by means of flexible copper braids connected to the centerline of the shield upper section
- the input coupler penetrate both shields and have special radiation shield cones
- approx. 128 temperature sensors and 2 accelerometers are foreseen on the prototype cryomodule
- the anticipated static heat load budget for one cryomodule is

$$\leq 4\ W \ @\ 1.8\ K$$
$$\approx 14\ W \ @\ 4.5\ K$$
$$\approx 120\ W \ @\ 70\ K$$

Reasons for Gradient Advances

High purity niobium

- higher thermal conductivity
- higher stability against quenches

prescreening of niobium to eliminate defects

dust free surface preparation and assembly

- avoids field emission

Industrial cost study carried out for TESLA with help of industry!

$$C_N = C_1\ 0.8^{\log N}$$

$$C_{10,000} = C_1\ 0.8^4 = C_1\ 0.41$$

C_1 = 200 TDM = 133 K$

$$C_{10,000} = \$\ 54,000$$

Includes:

niobium, cavity fabrication, couplers, tuners, LHE tank, magnetic shielding, inner cabling

HEMC (5 TeV) TESLA (0.25 TeV)

AC POWER

HEMC		TESLA
210 MW	Klystrons ($\eta = 0.65$)	40 MW
11.4 MW	AC Power FRIG.	30 MW
222 MW	TOTAL AC POWER	70 MW
53%	EFFICIENCY = $\frac{\text{Ave Beam Power}}{\text{AC Power}}$	23%

CHALLENGES!

① Beam Induced HOM Power

HOM Loss factor $K = 6.6 \times 10^{12} \frac{V}{C}$

$$P_{HOM} = K L (Ne)^2 f N_r$$

$f = \text{rep} \times 2$ ($\mu^+ \mu^-$)

$$= 14.8 \text{ MW} = 7 \text{ KW/m}$$

Compare to Average Beam Power = 117 MW

ALL MUST BE REMOVED!

② MUON DECAY POWER ≈ 0.7 MW

ALL MUST BE INTERCEPTED!

(3) $\frac{\text{Energy extracted by bunch}}{\text{Stored energy}} = 17\%$

Fill time = 180 μsec

Bunches come in 50 μsec

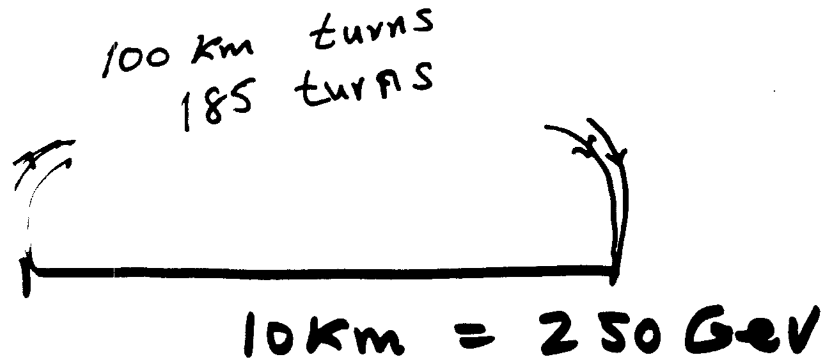
Possible Solution

Overcouple × 3 ⇒ More RF Power

CAP Cost ↑ 515 M$

Δ = 75 M$

HEMC 50 TeV



N = 0.8×10^{12} Better !

Rep = 8 Hz

Beam Duty Factor = 49%

Peak Beam Power = 193 MW

Q_L (matched) = 3×10^{7}

Cavities must be Stiff – microphonics

P_{HOM} = 3 MW

Input Coupler = 20 kW/m

Easy!

Q_0 = 2×10^{10}

Refrigerator = 160 kW !

CAPITAL COST = **1.36 B$** **(= SNS)**

AC POWER = 413 MW → **332 MW**

Efficiency = 23% → **33% for**
$Q_0 = 10^{11}$

CONCLUSIONS

- 10 TeV Main Acceleration cost modest compared to 0.5 TeV TESLA
- Challenges for 10 TeV and 100 TeV are different

SIGNIFICANT GAPS NEEDING R+D

- Low frequency RF for front end
- **HIGHER Q_0**
- Higher gradients help, but not crucial
- Super efficient HOM extraction

HEMC 10

- Higher Input power couplers

HEMC 50

- Structures resistant to microphonics

RF Frequency (MHz)	100	200
Cell voltage (MV)	15	11.3
Ncells	13	36
Total Lactive (m)	20	27
Fill time (ms)	6	6
QL	2×10^6	4×10^6
Duty Factor (%)	10	10
Coupler Power (MW)	1.1	0.32
Peak RF Power (MW)	15	11
Q0	10^{10}	6×10^9
Pdiss/cell (watts)	23	21

Total RF length 47 m
Real estate length 54 m

Total RF Peak Power 26 MW
(nc version would need 1000 MW)

Total 4.2 K heat load = 2 kW

Refrigerator size 3 KW (smaller than CEBAF)
< 10 M$

SC RF for the Front End

In the first linac after cooling
0.2 -> 1 GeV

Why SC?

- Lower peak RF power demand
- An early demonstration of SRF with muons will be helpful for 100 GeV Higgs or 3 TeV Stage

Strategy

From B-factory experience and pulsed operation chose E_{acc} = 15 MV/m

Use NRF in first stage 50 MHz
200 -> 400 MeV

Use 100 MHz SRF, from 400 - 600 MeV
and 200 MHz SRF, from 600 - 1000 MeV

Single cell active length
100 MHz 1.5 m
200 MHz 0.75 m

Start with 200 MHz
credible extrapolation from LEP 350 MHz

2.1 Fabrication of Cavities

The cavities are made of 2.5 mm thick niobium with RRR being ~200. Cavity cells were spun from sheet material and electron beam welded. The procedure of surface treatment was as follows: 1) electropolishing 80 μm, 2) degassing at 700°C for 1.5 hours and 3) electropolishing 15 μm and rinsing with 3-4 ppm ozonized water.

2.2 Assembly with Cryostat, etc.

After cavity-alone tests in a vertical cryostat, cavities were chipped-off at flange valves and transported to a class 100 clean room, vented with filtered nitrogen gas and assembled with extension pipes made of stainless steel at both ends. Then, they were assembled with cryostats, and finally end cones that had been pre-assembled with dampers and gate valves were mounted at both ends.

3 PERFORMANCE OF THE CAVITIES

Figure 3 shows unloaded quality factor, Q_0, of the four cavities as a function of accelerating field. In the figures, open circles are the results of cavity themselves measured in a vertical cryostat. Open squares are the results of bench tests after fully equipped with horizontal cryostat and other parts before installation in the tunnel. Solid triangles and solid circles are the results measured in the tunnel on Nov. 27, 1998, before first operation and on Jan. 13, 1999, before second operation.

Although the designed voltage for operation is 1.5 MV or 6 MV/m per cavity, we set our target at 10 MV/m and $Q_0 \geq 1\times10^9$ to have enough margin for stable operation and in case of the operation with fewer modules. Cavity RA could not reach this target due to a defect on the equator. After the defect was ground off, the cavity showed nearly 10 MV/m. Cavity RB surpassed our record on vertical tests (15 MV/m) [5], reaching 19 MV/m. Using the numbers given in Table 1, one can obtain surface peak field of 35 MV/m and magnetic field of 750 Gauss. To our knowledge, this is the highest value ever reached with 500 MHz range cavities at 4.2 K. Cavity RC degraded during first vertical test due possibly to some damage created by discharge.

As to the results after full assembly and installation, the remarkable point is that very little degradation from cavity-alone tests occurred compared to the results of TRISTAN cavities [6]. Note that the highest fields are not marked in Fig. 3 since it is difficult to measure Q_0. Cavity RA got even better in Q_0 for some reason. As for cavity RB, we did not try to go much higher because the field is more than enough for operation and due to available power.

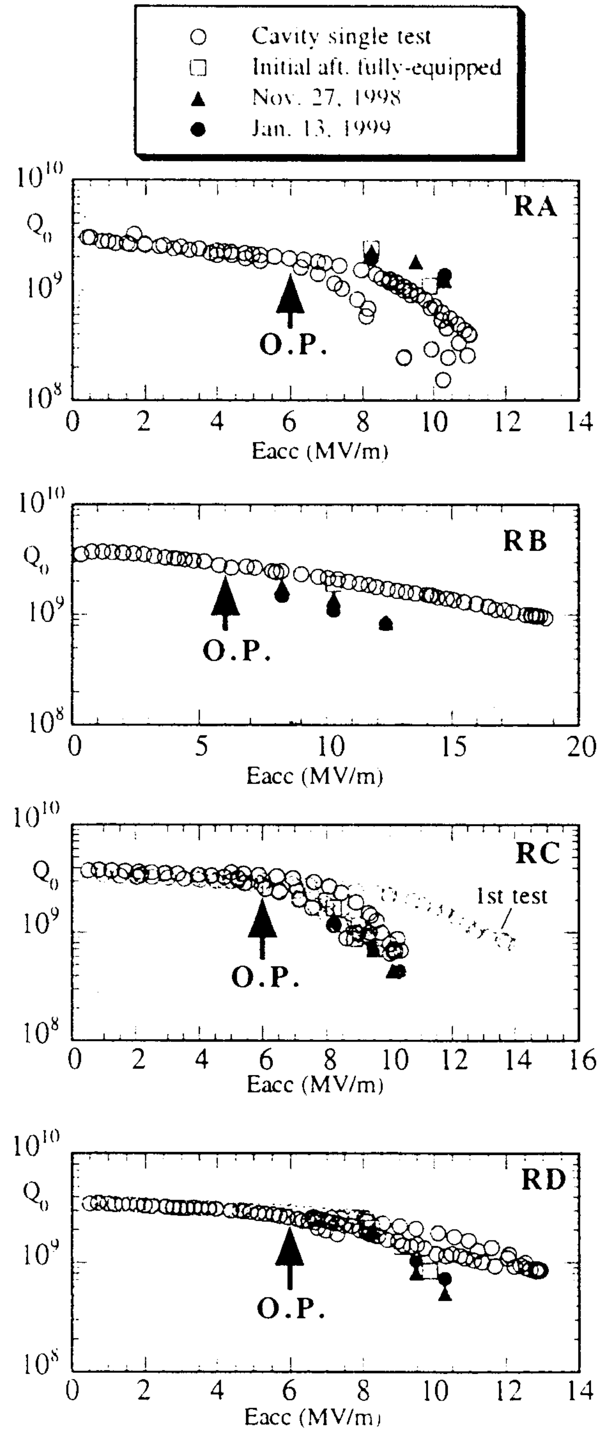


Figure 3: Unloaded Q vs. accelerating field of all the cavities. O.P. stands for operation point.

4 BEAM OPERATION

4.1 Conditioning

Before cooling down the cavities, we condition the input coupler up to 300 kW with perfect reflection condition, and up to 200 kW with dc bias voltages applied on the

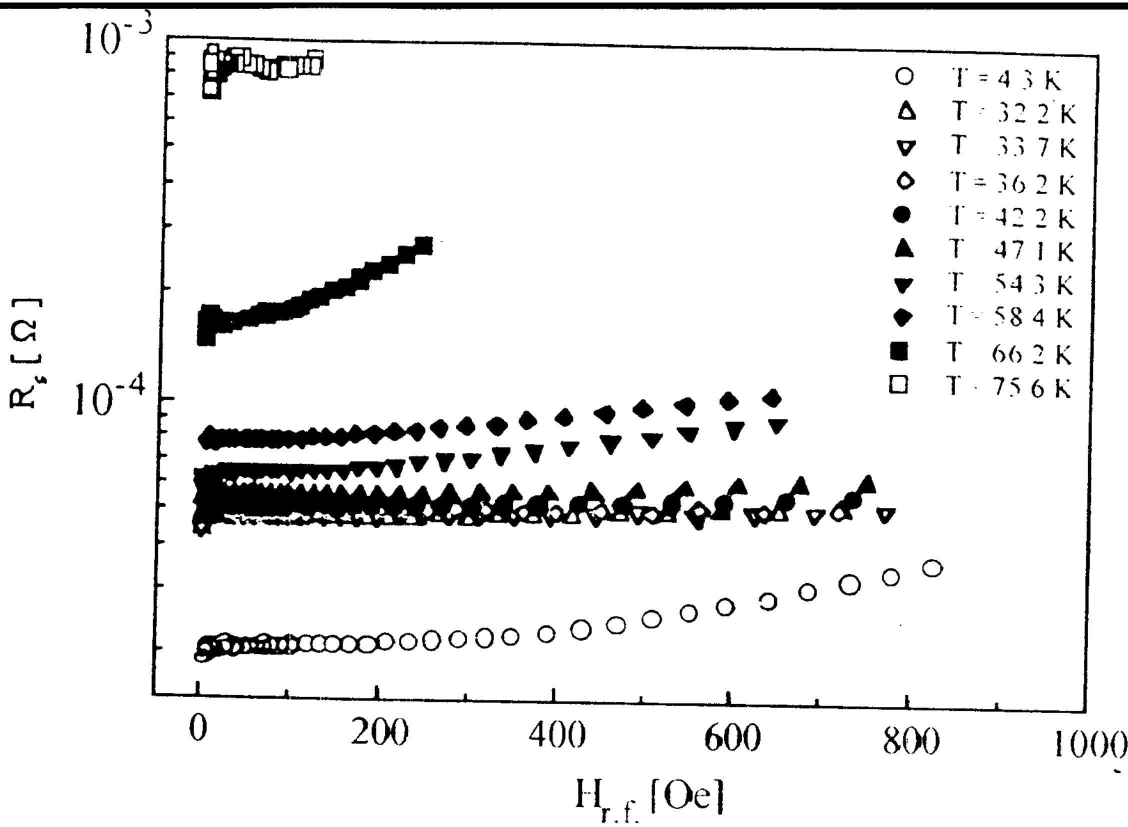


Fig.6: R_S vs $H_{r.f.}$ at different temperatures in the first resonant mode (f_1 = 2.2 GHz) for a YE film grown by a high oxygen d.c. sputtering technique.