

TECHNICAL CHALLENGES OF SUPERCONDUCTIVITY AND CRYOGENICS IN PURSUING TESLA-TTF*

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Abstract

TESLA (TeV Energy Superconducting Linear Accelerator) Collaboration is an international R & D effort towards the development of an e^+e^- linear collider with 500 GeV center of mass by means of 20 km active superconducting accelerating structures at a frequency of 13 GHz. The ultimate challenges faced by the TESLA project are (1) to raise operational accelerating gradients to 25 MV/m from current world level of 5-10 MV/m, and (2) to reduce construction costs (cryomodules, klystrons, etc.) down to \$2,000/MV from now about \$40,000/MV.

The TESLA Collaboration is building a prototype TESLA test facility (TTF) of a 500 MeV superconducting linear accelerator to establish the technical basis. TTF is presently under construction and will be commissioned at DESY in 1997, through the joint efforts of 24 laboratories from 8 countries. Significant progress has been made in reaching the high accelerating gradient of 25 MV/m in superconducting cavities, developing cryomodules and constructing TTF infrastructure, etc. This paper will briefly discuss the challenges being faced and review the progress achieved in the technical area of superconductivity and cryogenics by the TESLA Collaboration.

INTRODUCTION

There is a widespread consensus within the high energy physics community that the next electron positron collider would be built with a center of mass energy of 500 GeV and luminosity of a few times $10^{33} \text{ cm}^{-2}\text{s}^{-1}$. Such a collider would provide for top analyses and discovery reach up to a Higgs mass of $\approx 350 \text{ GeV}$. Worldwide, there are a number of groups pursuing different linear collider designs. The TESLA collaboration is an international R & D effort to develop a linear collider using superconducting accelerating structures (25 MV/m, $Q_0=5 \times 10^9$) at low frequency (1.3 GHz)^{1,2,3}. The TESLA collaboration consists of 24 institutes from 8 countries.

Advantages of TESLA

The technical advantages of superconducting RF cavities is their high Q value and low RF wall losses (less than Cu cavities by a factor of 10^5). It allows us to use large aperture structures operating at low frequency (1.3 GHz, L-band) with long macro pulse length and low peak power requirements. The large aperture has a beneficial consequence of substantially reducing transverse and longitudinal wake field effects, leading to relaxed Linac alignment and tolerances.

Challenges of tesla

Despite the attractive feature of the TESLA design, a major effort is needed to demonstrate that a linear collider can be built at a cost competitive with its normal conducting counterparts. The two technical challenges being faced and the key approaches to reach the ultimate goals can be summarised as follows^{4,5}:

(1) Increase operational accelerating gradients of SRF cavities to 25 MV/m from current levels of 5-10 MV/m by eliminating field emission and thermal breakdown.

(2) Decrease structure cost by utilising multicell structure, long cryostat, high efficiency klystron and cost effective fabrication techniques.

We believe that the construction cost can be reduce to \$2,000/MV compared to the current \$40,000/MV. The TESLA Collaboration is building a test facility (TTF) of a 500 MeV superconducting linear accelerator to establish the technical base.

BASIC INFORMATION ABOUT TESLA AND TTF

* Advances in Cryogenic Engineering, Vol, 41 Edited by P. Kittel. Plenum Press, New, York, 1996

TESLA Layout

The overall layout of the TESLA 500 is illustrated in Figure. 1^{1,6}. The electron beams (e^+ & e^-) are accelerated to 250 GeV by RF fields in each main linac. Each linac has an active accelerating length of 10,000m consisting of about 10,000 superconducting RF cavities. Total length of TESLA-500 is about 32 km. A discussion of the layout is introduced in the reference ⁶. An overview of the main parameters of TESLA-500 is given in table 1.

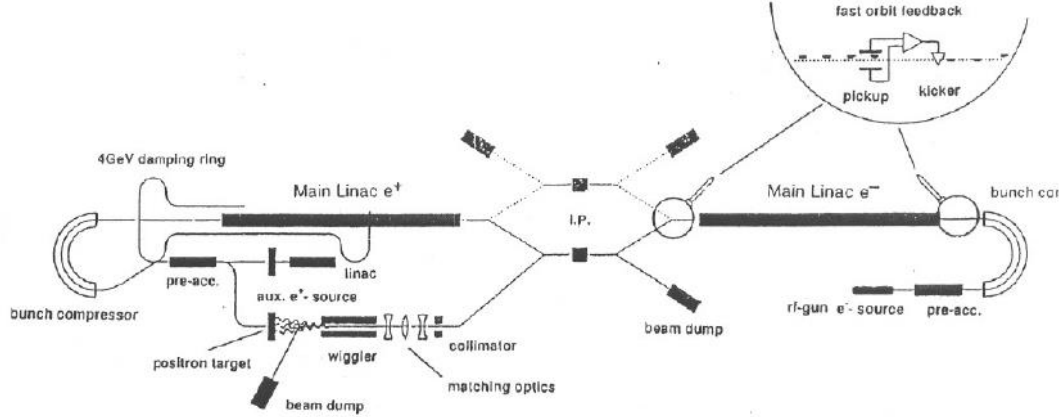


Figure 1. An overall layout for TESLA-500.

Table 1. Parameters of TESLA-500

linac energy	$2 \times 250 \text{ GeV}$	Luminosity
	$6 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$	
Beam pulse current	8 mA	Bunch separation
0.7 μs		
Number e/bunch	3.63×10^{10}	Bunch length
0.7 mm		
Nu. of bunches/pulse	1130	Rep rate
5 Hz		
RF pulse length	1.3 ms	Total Length (incl. inter, reg.)
32 km		
Beam pulse length	0.8 ms	RF Freq.
		1.3 GHz

As shown in Figure 1. TESLA is composed of many components. However, here we only introduce the technical issues relevant to cryogenic engineering. For convenience of discussion, we consider the TESLA-500 as a superconducting and cryogenic structure which is energized through thousands of high power RF couplers and cooled by a huge superfluid-He refrigeration system. The structure of the 20-kilometer active accelerating machines is summarised in Table 2 with a SRF cavity ($E_{\text{acc}} = 25 \text{ MV/m}$, $Q_0 = 5 \times 10^9$) as the smallest unit. The basic cryogenic structure unit is a cryomodule consisting mainly of 8 cavities. 4 cryomodules share a klystron of 10 MW peak power. The heat load to 2K from a cryomodule is 21.4 W including dynamic (RF) and static losses ⁷. To keep the TESLA machine in superconducting state, the total estimated cooling Power is: 51 kW at 2 K, 37 kW at 4.5 K and 314 kW at 40-80 K ⁸. Sixteen 2 K-refrigerators are needed to provide the cooling power distributed over the machine. The total liquid He inventory estimated in the TESLA machine is about 87,200 - 102,800 kg (depending on the version of cooling loops to be selected).

Table 2. TESLA-500 as a superconducting and cryogenic machine
(consider SRF cavity as basic unit)

Unit	Group
9 SRF cavity cells	A cavity (including LHe vessel. RF couplers)
8 cavities (incl. quadr. packages)	A cryomodule of 12.2 m. and (4 cryomodule share one 10 MW klystron)
12 cryomodules	A string of 148 m, has an individual cryo-loop
12 strings	A TESLA subunit of 1830m (one subunit has a 3.2 KW/2K cryo-plant)

TTF Layout

Figure 2 is a schematic layout of the TTF consisting of an injector with a capture cavity, 15 MeV beam analysis area, TTF Linac with four cryomodules (the design requirement of the TTF cavities is $E_{acc} = 15 \text{ MV/m}$ and $Q = 3 \times 10^9$) and a high energy experimental area. The TTF is refrigerated by a He II refrigerator: 100 W at 1.8 K, 400 W at 4.5 K and 2000 W at 70 K (the refrigeration power will be expanded to 200 W at 1.8 K).

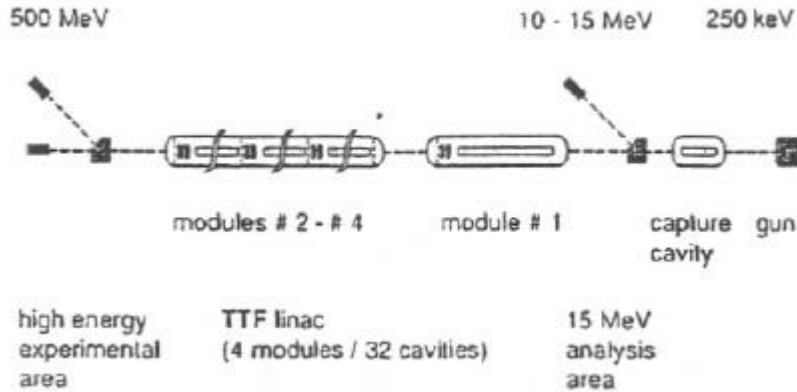


Figure 2. Schematic layout of the TESLA Test Facility (TTF).

With the TTF, we will demonstrate and verify many technical issues, such as, cavity processing technologies, cavities performance, design and performance of couplers and cryostat, cryogenic operation, energy and position feedback, alignment, etc.

The TTF is also being considered for use as a Free Electron Laser Facility.

TESLA SRF CAVITIES

The TESLA SRF cavity is shown in Figure 3 and an overview of the main parameters is given in table 3. The TESLA cavities are made of high purity Nb sheets (2.8 mm thick) with a RRR of about 300. The cavity shape combining an elliptical iris and a spherical equator results in more satisfactory electromagnetic parameters than other combinations. Another consideration to TESLA cavity design is to minimize the ratio both of E_{peak}/E_{acc} (2.1) and H_{peak}/E_{acc} (4.2 mT/MV/m) in order to reach the highest gradients^{3,7}.

The maximum cell number of 9 is determined by effective HOM damping requirement. There is one input power coupler and two HOM couplers for a cavity. Each cavity has a liquid He vessel with small LHe inventory which reduces the coldmass and allows a fast cooldown and warmup of the cavity.

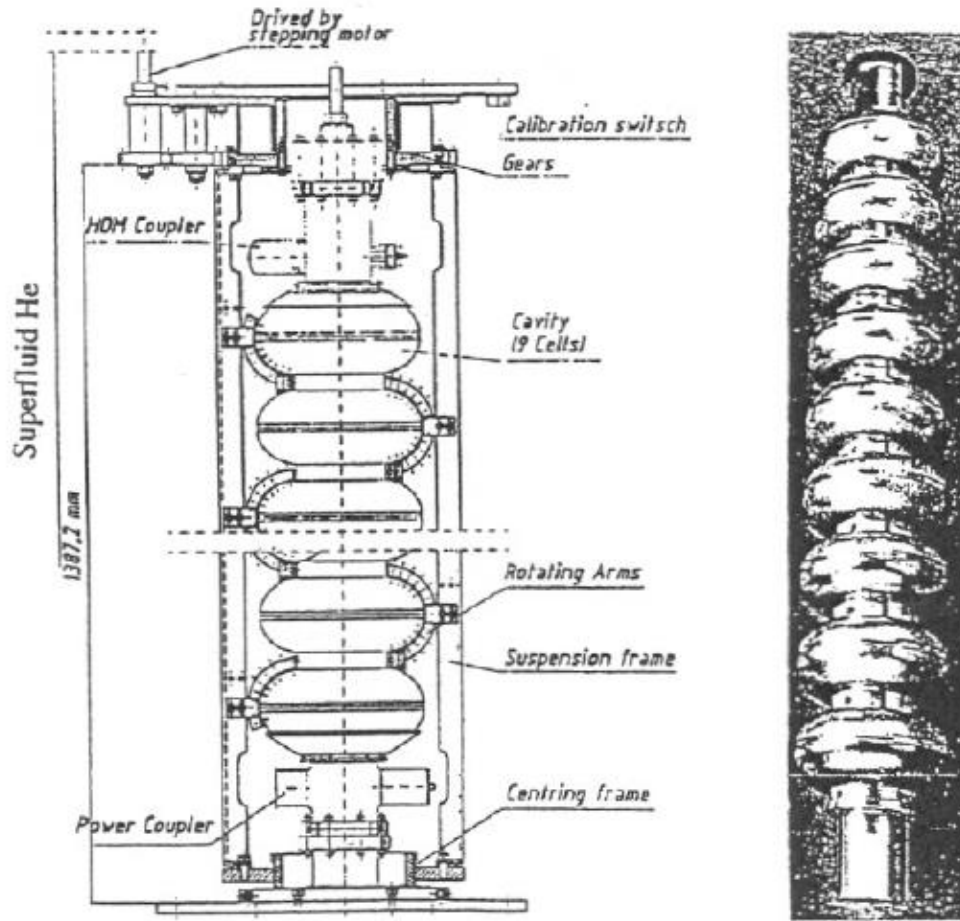


Figure 3. TESLA cavity with LHe vessel & 2K forward line, and a picture of the prototype cavity

Table 3. Parameters of the TESLA cavity

RF Freq.	1.3 GHz	Gradient	25 MV/m
Cavity cell	9	Cavity aperture	35 mm-radius
Effective length	1.035 m	E_{peak}/E_{acc}	2
B_{peak}/E_{acc}	4.2 mT/MV/m	R/Q	1011 Ω /cavity
Peak RF power	206 kW/m	Stored energy	0.127J/(MV/m) ²
Cryo load/module	21.4W	$G(R_s=G/Q_0)$	271
Coupling cell-cell	1.87%	HOM K(11)	9.24V/pC

QUEST FOR HIGHEST ACCELERATING GRADIENT - AN ULTIMATE TASK

The TESLA collaboration aims for the highest operating gradients E_{acc} in SRF cavities using economically affordable approaches.

Theoretical Limit of E_{acc}

The limit magnetic field in RF is larger than B_c (type I superconductors) and B_{c1} (type II) respectively, and is called superheating critical field B_{sh} . Table 4 gives the B_{sh} values of typical materials studied in SRF technology compared with the maximum surface field B_{exp} experimentally obtained so far⁹. Using a rule of thumb that 40 Gauss (4mT) is equivalent to 1 MV/m accelerating gradient in cavities with the TESLA shape, the theoretical limit for Nb by B_{sh} is then about 60 MV/m, and for Nb₃Sn, 100 MV/m⁹.

Table 4. Critical field in DC and RF superconductivity

Materials	Tc[K]	B _{eth} [mT]	B _{c1} [mT]	B _{c2} [mT]	B _{sh} [mT]	B _{exp} [mT]
Su	3.7	30.9	-	-	68	30.6

In	3.4	29.3	-	-	104	28.4
Pb	7.2	80.4	-	-	105	112
Nb	9.2	200	185	420	240	160
Nb ₃ Sn	18.2	53.5	20	2400	400	106

Bth - thermodynamic critical field
Bsh - superheating critical field

Bexp - experimentally obtained maximum field
All data refer to values at T = 0 K

Achievements And Limit In Operating Accelerators

Since the early 1970s, significant progress in the state of the art SRF accelerating cavities have been achieved. The operating accelerating gradients in more than 10 laboratories (such as Argonne¹⁰, CEBAF¹¹, CERN¹², Cornell¹³, Darmstadt¹⁴, DESY¹⁵, KEK¹⁶, Saclay¹⁷, etc.) and 400 structures reached 5-10 MV/m, compared to design goal of 5 MV/m. These achievements are attributed to anti-multipactor, round cell shape, high thermal conductivity Nb to avoid thermal breakdown (TB) and clean surface preparation to avoid field emission (FE). However, the excellent performance of the operating cavities is not adequate for the proposed TESLA machine. Tremendous efforts are still needed to comfortably reach the TESLA goals of $E_{acc} \geq 25$ MV/m and $Q \geq 5 \times 10^9$. The main obstacles still to overcome are FE and TB. Investigation and elimination of FE and TB have become one of the highest priorities in TESLA and TTF projects.

Understanding FE And TB

Significant efforts have contributed to understanding and defeating FE and TB by the TESLA Collaboration. Electrons on the cavity surface can be pulled out and accelerated in the cavity vacuum by RF electrical fields. These field emitted electrons absorb energy from RF fields and deposit the energy in their landing area on the cavity, resulting in degradation of Q value and limiting the E_{acc} . Studies with DC FE scanning microscope and in SRF cavities^{18, 19, 20, 21} indicate that most FE electrons come from submicro-size foreign particles of a metallic nature with irregular shapes. Some studies also found that the condensed gases and heat treatment at 200-600°C will activate FE^{21, 22}. Thermal breakdown is due to imperfections of the RF surface. For a given imperfection, the thermal breakdown field scales roughly as the (thermal conductivity)^{1/2}. The residual resistance ratio (RRR) is used to characterise the thermal conductivity in a convenient way.

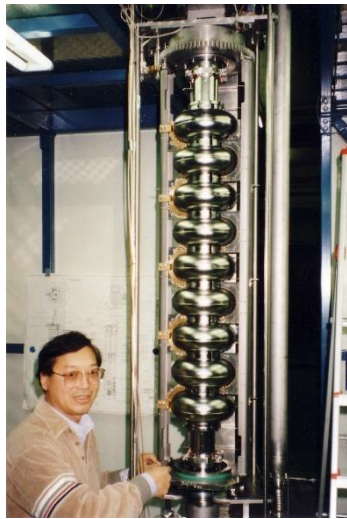


Figure 4. Rotating T-R mapping system for diagnostics of TESLA 9-cell cavities.

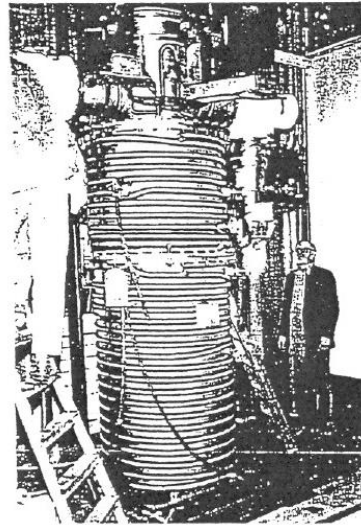


Figure 5. The ultrahigh vacuum oven for Ti-gettering purification of cavities.

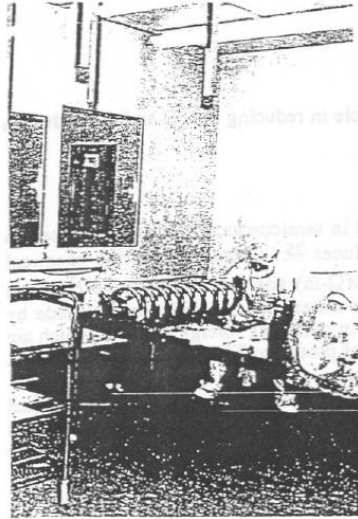


Figure 6. The clean room for cavity processing And assembling.

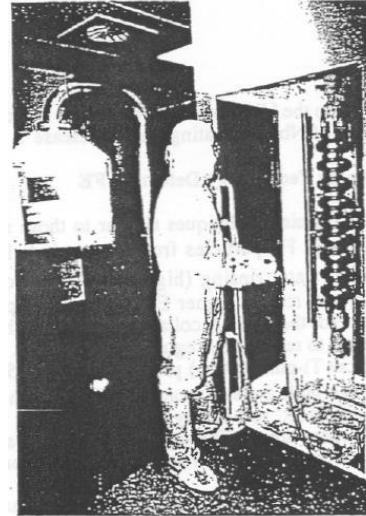


Figure 7. Chemistry and rinsing of cavity in the clean room.

It is impossible to directly observe the FE and TB on the inner surface of cavities during RF operation. Therefore, the main approach to understanding the FE and TB of cavities is to study the hot spots and X-rays (induced by impacting FE electrons) generated on the cavity surfaces during RF operation. At DESY a rotating T-R mapping system for TESLA 9-cell cavities has been developed and more than 10,000 spots on the cavity can be investigated in one turn with 10° stepping. We have used it to successfully identify the TB location, trace the dynamic progress of cavity quench, locate the heating areas by FE electrons and simulate the emitter locations²³.

Reducing FE and TB

For years in many laboratories around the world, there have emerged many comprehensive approaches for cavities processing in order to reach the highest possible gradient. Many of these approaches have been adopted, further developed and used by TESLA collaboration at DESY.

Reducing TB with UHV Oven

Over the last 10 years the RRR of sheet Nb delivered by industry for cavities has been improved to 300 from 30 by better melting practices removing most of the dissolved impurities of O, N, H, C, etc. Cavities using these sheets produce a range of TB at 13 – 19 MV/m. Higher RRR of > 500 is desired for reaching a $E_{acc} > 25$ MV/m. Currently the way to increase RRR is to employ solid state gettering^{19,24}. In this technique, both the inside and outside surface of a prepared cavity are exposed to Ti vapors at 1400°C for 24 hrs. The oxygen which diffuses to the cavity surface is gettered by the evaporated layer. After improvement of RRR, both surfaces are etched to remove the foreign metal layer. Figure 5 is the UHV oven used at DESY (1400°C at 10^{-7} mbar). The control samples Nb indicate that RRR of 250-300 is raised to > 500 after the Ti-purification treatment. Several TESLA 9-cell cavities show E_{acc} increase to 20 - 26 MV/m.

Also the UHV oven has played an important role in reducing the FE and the hydrogen content of Nb, eliminating the "H-disease."

Cleaning Technology Defeating FE

Cleaning techniques similar to those utilized in semiconductor industry are used to remove all FE particles from the cavity's RF surfaces²⁵. Cleanliness during chemical etching, water rinsing (high purity water of $15\text{ M}\Omega\cdot\text{m}$) and assembling have played a important role in higher E_{acc} . The high pressure water rinsing (HPR) device made by CERN for the TESLA collaboration is very helpful in removing foreign particles which are difficult to remove by regular water rinsing. Several prototype TESLA cavities after HPR (without Ti-purification) produced $E_{acc} > 15$ MV/m.

We built a clean room of 300 m^2 with class 10 and 100 areas in 1993 for chemical etching, HPR, and cavity assembling (also we can load cavities into the UHV oven in a clean room area). The capability of HPR is as high as 200 bar. Figure 6 is a part of the clean room and Figure 7 shows the clean chemical etching of a TESLA cavity.

High Peak Power RF Processing - Last Chance to Reduce FE

Despite how good a job performed to eliminate FE, there is always a possibility that particles escape removal and stay on cavities surfaces. Therefore a technique that can eliminate the emitters in situ is highly desirable. The technique, called HPP - high power processing developed at Cornell University, is to apply a high power RF pulse to the cavity in situ and eliminate the FE through an explosive process²⁶. The idea is to raise the electric field at an emitter as high as possible in a short time (μs - ms) which generates a very high FE current. The transient high current melts, evaporates and activates a RF spark to destroy the FE emitters. The high RF pulse power processing of cavities provides a final, effective way to destroy the remaining FE emitters²². At DESY a HPP facility has been used successfully in raising Eacc. The peak klystron power is 4.5 MW with pulse length of 2 ms.

The key technologies we have used to reduce FE and TB can be summarized in Table 5.

Table 5. Key technologies of cavities processing for highest Eacc

Techniques	Short Description	Impact on FE	Impact on TB	Results
Clean cavity Handling	Class 10-100 clean room for chemistry,rinsing & assembling	Eliminating foreign particle contamination	Deep chemistry may remove some impurities	Good for Q and Eacc
Heat treatment+ Ti-purification in UHV oven	Heat cavity at 1400°C for 1-4 hrs,Ti vapor coated in vacuum	Greatly reduce emitters existing on cavities	Improve RRR by a factor of 2,(improve K)	Substantially increase Q and Eacc
High pressure water rinse ²⁴	Rinse cavity by high purity water(15M Ωm)at 200 bar	Reduce emitters density		Increase Q and Eacc
High RF power processing	Apply high RF power pulse(1-2MW, μs -ms)to cavity surface	Eliminat emitters in situ		Substantially increase Q and Eacc

Encouraging Achievements with TTF Project

With the above techniques, we significantly increase thermal conductivity and educe FE Two 9-cell TTF prototype cavities reached respectively Eacc= 16 MV/m and 21 MV/m both with $Q > 6 \times 10^9$ in CW mode. The first series TTF 9-cell cavity (RRR=350) reached Eacc=26 MV/m in 1 ms RF power length (TESLA operational condition) and 22 MV/m in CW²⁷. Also, a TTF injector cavity provided by Saclay reached 21MV/m, $Q > 4 \times 10^9$. Compared to the TTF goal of Eacc=15 MV/m and $Q=3 \times 10^9$, these initial result is very encouraging. Continuing progress is expected with improvements in processing technologies and diagnostic testing. Some representative results are plotted in figure 8.

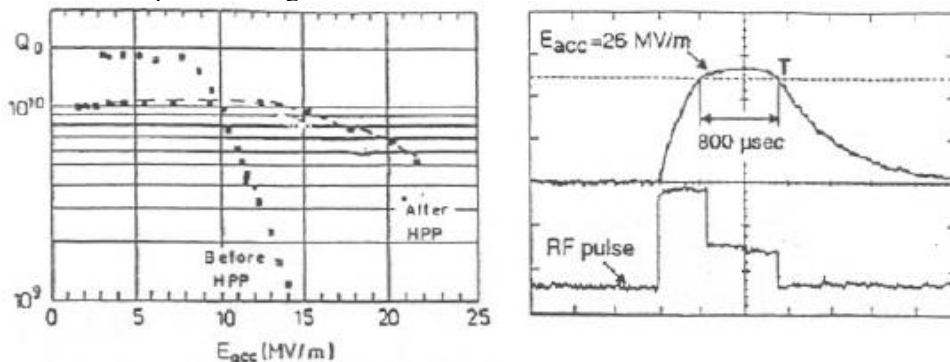


Figure 8. (A) Q vs. Eacc plots of TTF 9-cell cavity -1. (B) The performance of cavity D2 in pulse RF condition similar to TTF operation. 26 MV/m of Eacc is reached.

TESLA PROTOTYPE CRYOMODULE

The cryomodule is 12 m long and consists of 8 SRF cavities with LHe vessels, one quadrupole magnet package, associate fixtures (RF couplers, tuner, alignments, etc.) and a cryostat in which all the above components are housed. The TTF cryomodule also has some special requirements due to SRF cavity technologies. For instance:

(1) To eliminate FE, the eight cavities and quadrupole package must be assembled together in a clean room and be inserted in the cryostat as a single UHV tight unit.

(2) To improve cavity Q, magnetic shields are needed to reduce residual earth magnetic fields to less than 20

mGauss.

(3) Due to beam dynamic consideration, the axes of the cavities to the ideal beam axis need to be within $\leq \pm 0.5\text{mm}$.

Based upon cost effective design philosophy, most of the needs for keeping such special technical features must be addressed in the cryostat design. Figure 9 is a cross section of TTF cryomodule³.

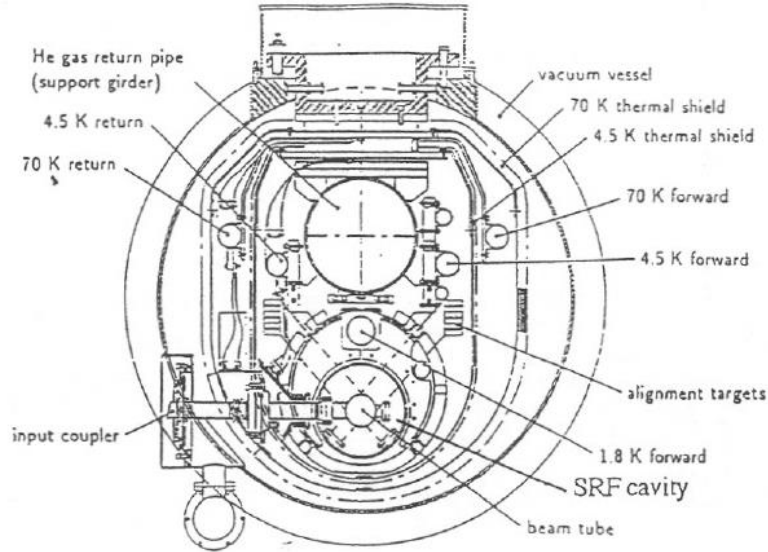


Figure 9. A cross section of TTF cryomodule.

TTF Cryostat

The technical features and design details of the cryostat are discussed in the references^{28,29}. The total heat load to 2K from a cryomodule is estimated to be 21.4 W. The anticipated static heat load budget for one cryomodule is 4W at 2K, 14W at 4.5K and 120 W at 70K^{28,29,30}. Since dominate heat load in cryomodule is RF dynamic heating, not the static heat leak, the primary interest of measuring the heat load is to verify the RF dynamic load. With the heat attributed to the RF loss, we can calculate the Q of each individual cavity or cavities. A comprehensive verification plan have been developed³ (with about 135 thermometers, 2 accelerometers, etc.) that will allow us to study the heat leak through the power and HOM coupler and the thermal performance of the cryostat as well.

Special Magnetic Shield

The trapped magnetic flux from ambient fields (even less than 3 gauss) during cool down will seriously impact the cavity performance. The trapped flux will raise the RF power dissipation and gives an equivalent local residual resistance about $R_s = R_n(H/H_c2)\sin\alpha$. For a TESLA cavity ($RRR=300$, $f=13\text{ GHz}$), a conversion factor of $0.35\text{ n}\Omega/\text{mGauss}$ closely matched experimental data. In order to get $Q=5\times 10^9$ as specified for TESLA, surface resistance can not be larger than $25\text{ n}\Omega$, equivalent to 70 mGauss. Considering other contributions to the residual resistance and possibly increasing the Q, the remaining field around the TESLA-TTF cavities should be $\leq 20\text{ mGauss}$. There are two shielding approaches in use: passive shields made of Cryoperm and active cancellation coil, both of which have been designed and examined³¹.

Quadrupole Package

There is a quadrupole package³² as shown in Figure 10, located at the end of each cryomodule, which includes: (1) a superferic quadrupole doublet (maximum gradient of 20 T/m and integrated gradient of 3T at 55.7 A) enclosed in a 4K LHe vessel, (2) two pairs of single layer dipole steering windings inside the quadrupole yoke bore, (3) a section of beam tube equipped with a beam position monitor (BPM) and HOM absorber (20 W), and (4) the He gas cooled power leads (0.1 g/s) for energising the magnets. At the end plate, there are two arms each holding reference targets for alignment.

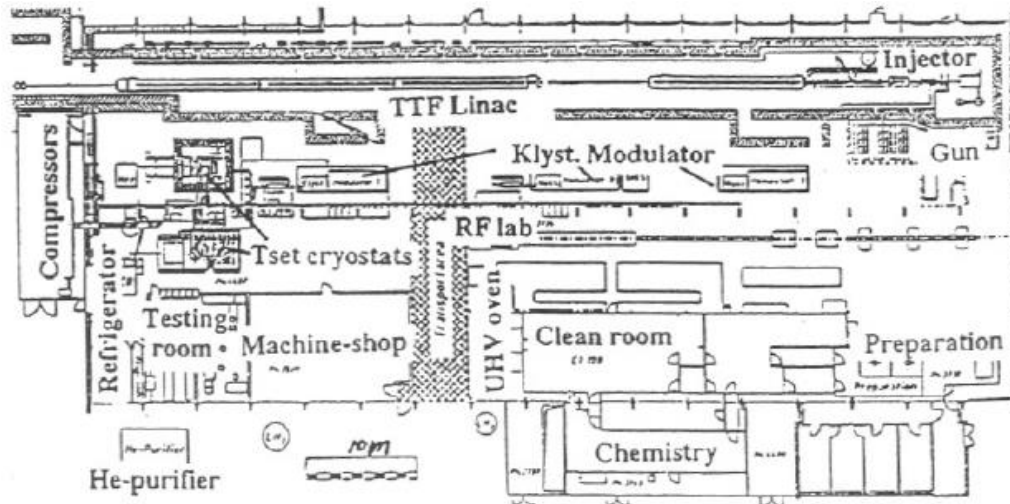


Figure 10. A quadrupole package.

Power and HOM Couplers

The TESLA input couplers^{33, 34, 35} are articulated with bellows to allow for the cavity moving during cooldown. The couplers also have an adjustable external Q of over a factor 10 range. The allowed RF heat load and heat leak are very low. All the above features make the coupler mechanically complicated. The input coupler is directly connected to the cavity cut off tube. It does not penetrate the LHe vessel, but is thermally anchored to the radiation shields with radiation cones. The thermal budget is 6W at 70 K, 0.5 W at 4.5 K and 0.06 W at 2 K. For TTF, two 5 MW peak Power klystrons TH 2104 C from Thomson will power the four cryomodules and an extra 300 kW pulse klystron is needed for the injector.

To restrict the multi-bunch phenomena due to wakefields, the higher order modes (HOM) of the TESLA cavities must be damped (with $Q_{ext} = 10^4$ - 10^5) by two coaxial HOM couplers for each cavity³⁵. The accelerating mode is not affected by the HOM couplers.

Capture Cavity

Besides the standard cryomodule there is an important cryo-component, called the capture cavity³⁶ in TTF. The capture cavity terminates the bunching upstream and provides the necessary energy for injection into the first cryomodule. The capture cavity is a standard TESLA 9-cell cavity and is installed in a separate cryostat at the end of the injector. It shares a common cryogenic feed box with the other four cryomodules. The capture cryostat only has an 80K insulation shield with 40 MLI layers. Epoxy-fiberglass rods are used instead of posts. The focusing superconducting solenoid magnet is conduction cooled from the 4K loop.

TTF STATUS

A 3000 m² of building, Hall III, has been assigned to host the TTF Linac and TTF infrastructure^{5, 25}. We plan to deliver a beam through injector and first cryomodule with energy of about 140 MV/m by the end of 1995 (or early 1996). The complete 500 MeV TTF Linac will be commissioned in 1997. Figure 11 is an overview of the TESLA Test Facility.

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