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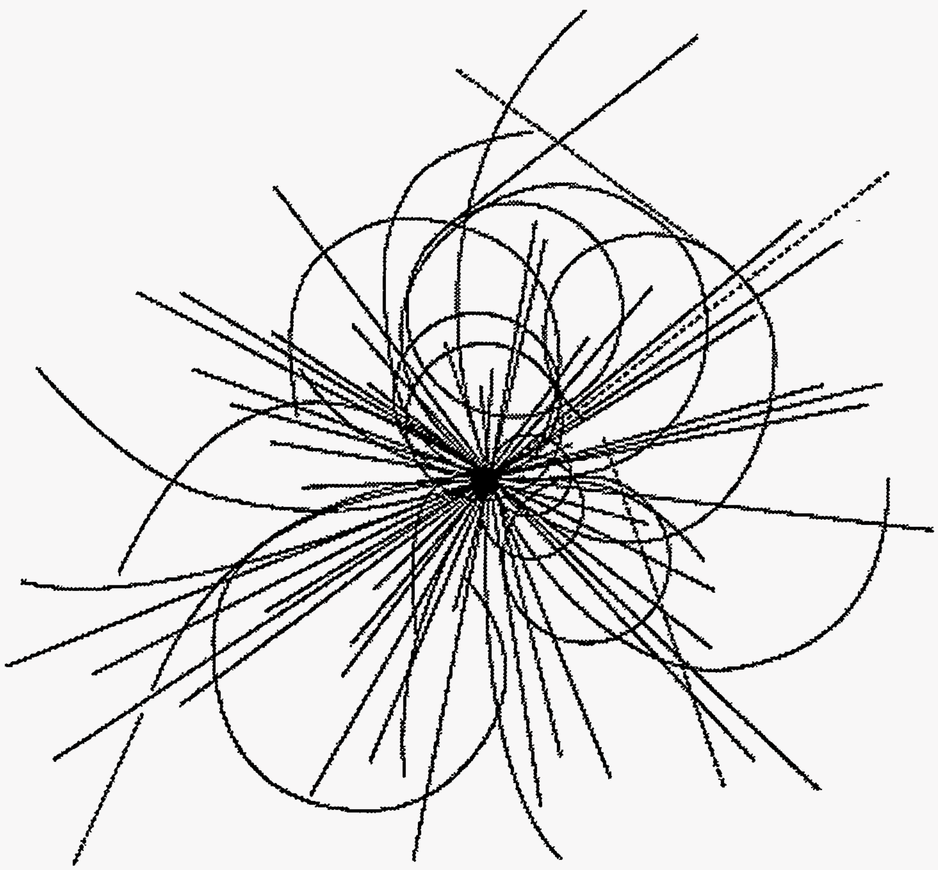

Superconducting Super Collider Laboratory

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Evolution of the RF Systems Layout for the SSC Collider Rings *

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October 1993

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Evolution of the RF Systems Layout for the SSC Collider Rings*

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Abstract/Summary

This note contains information on the results of ongoing reviews concerning the basic design of the 360-MHz rf systems for the 2 × 20 TeV Superconducting Super Collider (SSC).

For generation of 20-MV peak voltage per ring, with proton beams of 2 × 70 mA, several versions have been investigated:

Version A (baseline design and modified baseline): 2 × 8 five-cell normalconducting cavities;
Version B: 2 × 24 single-cell normalconducting cavities; and
Version C: 2 × 8 or 2 × 10 single-cell superconducting cavities.

For reasons of easier High Order Mode (HOM) damping, multicell cavities have been found inferior in performance when compared to single cells.

Superconducting cavities have been found superior in handling transient beam loading when compared to normalconducting cavities. A threefold higher voltage, and a reduced R/Q value of superconducting cells (about 40 Ω vs. 120 Ω per cell) lead to a ninefold increase in stored electromagnetic energy which, by the same factor, reduces the speed of phase changes originating from notches in the circulating beams.

The theoretical possibility to operate superconducting cavities half-detuned in order to supply reactive power to the beam (which otherwise the rf generator has to provide) may also lead to considerable savings in overall power consumption.

On the other hand, many challenges are involved with the use of superconducting cavities, such as the delicacy of the superconductive state, the complexity of cryostat design and operation, tuning requirements, sensitivity to vibration, and other issues.

As to the rf power system, klystron amplifiers in the range between 200 and 500 kW maximum output power are foreseen. The number of modules per ring will be greater than or equal to four. The klystrons would be located in a surface building.

Finally, the overall system cost (capital investment and operation) is of interest. Our analysis indicates a 50% higher capital investment for a normalconducting vs. a superconducting single-cell cavity system.

I. BASIC REQUIREMENTS OF THE COLLIDER RF

RF frequency	360 MHz
Peak rf voltage	20 MV
Accelerating voltage per turn	3.6 MV
Voltage per turn at storage	0.12 MV

The Collider operating cycle is shown in Figure 1.

II. THE STUDY TEAM

Table 1 lists persons belonging to various SSCL Divisions, Committee members, and consultants who studied the rf issues of the SSC Collider Rings and made major contributions to the systems design during 1992/93.

III. THE BASIC EVOLUTION

The evolution of the Collider rf system design toward superconducting cavities is schematically shown in Figure 2.

The initial conceptual design (baseline, version A) contained 8 five-cell copper cavities per ring, similar but not identical to the cavities used for PEP [1]. PEP cavities were fabricated in aluminum, and for a frequency of 352 MHz.

Approximately 1 MW of rf power fed to the cavities provides the necessary peak rf voltage of 20 MV. During acceleration, an additional 400 kW is needed for increasing the energy of the injected beam from 2 TeV to 20 TeV. Some power is required for waveguide losses, and reflections from the cavity, which will be over-coupled, leading to the specification of 2 MW per ring [1].

In version B, single-cell copper resonators are used for more efficient damping of higher order modes [2,3], and the total number of cells per ring is reduced from 40 to 24. This leads to higher copper losses, and the rf power required is nearly 3 MW, generated by six 500-kW klystrons [4] per ring.

Finally, in the superconducting version C, the 24 single-cell copper cavities are replaced by 8 or 10 superconducting single cells per ring, operating at a temperature of 4.5 K. The maximum available rf power per ring may now be cut from 3 MW to 1 MW, and the main power consumption (including the cryoplant) would also be drastically reduced. [5-18].

IV. PHASE MODULATION DUE TO BEAM GAPS

One of the most detrimental mechanisms for reaching and maintaining the specified collider luminosity is excessive phase modulation of the rf voltage by (transient) beam loading. Longitudinal shifts of bunch positions would result, and consequently, the beam collision areas would be lengthened and displaced.

Transient beam loading occurs during the injection of particle batches from the 2-TeV High Energy Booster (HEB), and in the acceleration and storage modes due to beam gaps necessary for the kicker filling time of the beam dumps.

If we consider the storage mode and neglect the small energy losses by synchrotron radiation (order of 100 keV per turn at 20 TeV), rf acceleration voltage V and beam current Ib are to be kept 90° out of phase, as illustrated by Figure 3.

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Beam-induced signals in the accelerating structure tend to shift the phase of the accelerating voltage with a certain speed that is proportional to the ratio (R/Q)/V, i.e., inversely proportional to the "tank current" of an accelerating cavity.

Possible methods to increase the tank current are to increase the voltage per cavity and/or reduce the R/Q value. This leads to rapidly increasing copper losses in normalconducting cavities, while it is relatively easy in superconducting cavities.

Feedforward and feedback corrections become significantly easier and less critical if the speed of beam induced phase changes can be slowed down. Actually, with the use of superconducting cavities, an order of magnitude can be achieved with today's operational fields of 5 to 6.5 MV/m in such cavities. Also, the voltage needed for bunch-to-bunch corrections (by broadband active HOM damping systems) is going down, by an order of magnitude, to technically feasible values.

V. TRADE STUDY

The compliance of the baseline and of alternative designs with the rf requirements was assessed by the ASD/RF Engineering Department and the PMO/Collider Group. A trade study (performance and costs) has been completed, with the following conclusions:

- "A superconducting (SC) system has superior beam loading and Coupled Bunch Instability (CBI) performance.
- Normalconducting (NC) and SC systems are judged to be equally reliable.
- SC system costs are lower or comparable to NC options.
- The SC system is the optimal choice."

It has also been stated that future luminosity upgrades would probably require a superconducting rf system.

VI. CONSIDERATIONS BY THE RF SUBCOMMITTEE

Before this trade study was completed, the chairman of a newly created RF subcommittee (see Table 1) invited a number of rf experts from various accelerator laboratories in order to discuss the options in detail.

The key factors considered by the subcommittee were the following:

BEAM LOADING

COLLECTIVE BEAM INSTABILITY

- growth time large compared to synchrotron period (0.25 s)

RELIABILITY/AVAILABILITY

- accelerating gradients NC below 2MV/m (cooling) SC below 5 MV/m (field emission)
- window power below 200 kW
- single klystron failure should not interrupt operation (still at least 15 MV achievable)
- trip rates and susceptibility to contamination
- degree system is amenable to analysis (technical risk).

VII. CONCLUSIONS BY THE RF SUBCOMMITTEE

Issues considered and results of the discussions by the subcommittee are summarized in Table 2.

In the assessment of the merits of the various options, the (modified) baseline option obtained 10% of the votes, the NC single-cell and SC single-cell options 30% and 60%, respectively.

VIII. COST STUDY RESULTS

Since the beginning of 1992, several attempts were made to determine costs for the various options [19]. One of the more recent results is shown in Figure 4.

The cost estimates could be based, in most cases, on real expenditures in other laboratories for projects like CERN-LEP, DESY-HERA, KEK, ANL-APS, and others.

Not surprisingly, the NC single-cell solution turned out to be the most expensive one, due to the great number of units and the enormous amount of rf power necessary to cover the copper losses in the cavities. Compared to the SC solution, the projected increase in capital investment for installed rf equipment and for the total cost including buildings and utilities was found to be about 50%.

The absolute figures are subject to continuous revision, but it is unlikely that the cost ratios will basically change.

IX. CAVITY TYPES

Cavity types considered for the different options are illustrated by Figure 5 (PEP 5-cell cavity), Figures 6 and 7 (ANL-APS single cell), Figure 8 (single cell with modified cooling method, similar to a PEP II single cell cavity), and Figure 9 (CERN-single-cell SC cavity for the Large Hadron Collider, LHC).

While in NC cavities the efficiency and simplicity of the water cooling technique is a crucial point, the challenge to SC cavities is mainly how to design the cryostat and the tuning devices for operation at a temperature of 4.5 K.

Typical solutions are shown in Figures 10 and 11 for the LEP-II 4-cell cavity operating at a frequency of 352 MHz [10,11]. The technical specifications for the manufacturing of these cavities have undergone only minor changes since the procurement of 20 units in 1989. The cryostat operates without a heat shield and uses liquid and gaseous helium only. The standby losses are specified not to exceed 10 W/m; actual losses are 8 W/m using 80 layers of superinsulation [20,21]. The CERN cryostat design is considered to be a real step forward [22].

The specified and achieved Qo is 3×10^9 at a field strength of 5 MV/m.

For the LEP energy upgrade, 192 SC cavities (of 4 cells each) are required and under construction. In comparison with the projected SSC Collider rf system, the size of the LEP rf upgrade program is an order of magnitude larger.

For the SC single-cell cavity design of the SSC project, the current CERN-LHC cavity development results will be of greatest interest.

In order to facilitate the frequency tuning of single-cell SC cavities, the length of the tuning devices as shown in Fig. 11 (magnetostrictive Ni tubes) should not be reduced too much [23]. Since a cavity assembly, including input coupler and two HOM couplers, is approximately 1.5 wavelengths long, the overall length of one cryostat may be chosen to be 125 cm. Pairs of cryostats can be mounted together to form one cryomodule. This would mean 4 or 5 modules per ring, each being fed by a single klystron via a 3-db hybrid.

X. CRYOGENICS

The refrigeration load estimates for a system consisting of 10 single cells per ring are approximately 700 W at 4.5 K, for the cavities with their cryostats only. The estimate of heat loads related to the distribution system are about 300 W, resulting in a total refrigeration load of about 1000 W.

Estimated liquefaction loads (i.e., He gas returned at temperatures between 4.5 and 300 K) are 0.65 g/s per module or 6.5 g/s for 10 modules.

The following cryosystem options have been considered:

(a) a stand alone system, offering full independence from the operation of the cryoplants used for the collider magnets,
(b) a series connection to the collider cryosystem, and
(c) a hybrid system with independent local refrigerator.

Solution (a) is solely recommended by some experts, on the grounds of the relatively small size of the collider rf system and in view of the necessary decoupling of rf test, commissioning, and operation from magnet tests and operations, as well as from commissioning and test of their own cryoplants [20].

XI. INSTALLATION STUDIES

Figure 12 shows a complete rf system as it could be built and installed in the Collider West Utility Area. This example is based on 10 SC single-cell cavities per ring and a total of ten 200-kW klystron amplifiers plus one standby unit. The standby klystron may replace any other operational one in case of trouble, via a waveguide switching loop, or it may be used for test purposes during regular operation.

Figure 13 shows the rf tunnel cross section. The oval shape is about twice as large as the magnet ring tunnel. A shielding wall provides extra space for equipment, which must be located close to the beams or cavities, like the active longitudinal damper systems, cold boxes of the cryosystem, etc.

Figures 14 and 15 are plan and elevation views showing the installed cryomodules, rf power splitters, waveguides, and shafts for waveguide connections to the rf surface building.

Also shown is the tunnel of the 2-TeV injector synchrotron (HEB) in the immediate vicinity of the collider rf area.

XII. STATUS OF WORK AND OUTLOOK

In the course of the last and present year, various detailed studies have been made on the selection and possible location of cavities and power sources for the collider rf system, on longitudinal beam dynamics issues, and on fast beam control systems.

Proposals and recommendations have been made, but no formal decision by the project management has been taken.

Visits of experts and trips to their laboratories have been of very great help.

Cost limitation and reduction efforts dominate the present phase of funding difficulty.

Issues and plans for future work are: (a) to widen the present technical know-how in close collaboration with other research centers, (b) to undertake a detailed cavity design, (c) to issue preliminary cavity and cryostat specifications, (d) to clarify questions concerning the cryoplant layout, and (e) to intensify collaboration with industrial manufacturers.

ACKNOWLEDGMENTS

Besides the persons listed in Table 1, many more colleagues and assistant staff of the SSC Laboratory and from other Laboratories (especially CERN, DESY, KEK, ANL, CEBAF, Cornell and SLAC) have been involved in the rf studies for the Collider rings. Diana Watson's skilled assistance was indispensable. The author also wishes to thank representatives from industry for their interest and for valuable information.

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[22] R. Burns, private communication, this workshop.
[23] E. Haebel, private communication.

Table 1. Contributors to the Study.

ASD - RF Engineering Department	RF Subcommittee
Rogers, Jimmy (Head)	Watson, Jerry (Chairman)
Coleman, Dale	Boussard, Daniel (CERN)
Cornelius, Wayne	Coleman, Dale
Mustaine, Bob	Griffin, Jim (FNALret.)
Schaffer, Georg	Morton, Phil (SLAC)
Wallace, Jerry	Padamsee, Hasan (Cornell)
Zhao, Yongxiang	Rogers, Jimmy
	Saito, Kenji (KEK)
PMO - Collider Group	Sundelin, Ron (CEBAF)
Meinke, Rainer (Head)	Wilson, Perry (SLAC)
Parker, Brett	
Wang, Xiao-qing	**ASD - Cryogenics Department**
	Ballam, John
PMO - Accelerator Physics Group	
Chou, Weiren	**Conventional Construction Division**
	Molenar, Richard
Consultants	
Morton, Phil (SLAC)	**Magnet Systems Division**
Wang, Tai-Sen (LANL)	Shu, Quan-Sheng

Table 2. Collider RF System Comparisons.
(by RF Subcommittee)

	Baseline	Modified Baseline	NC Single-Cell	SC Single-Cell	
Number of cavitites per ring	8 (× 5)	8 (× 5)	24	10	
Number of Klystrons per ring	**2**	4	6	5	At least 4 in desirable
Klystron Power (kW)	1000	500	500	*100*	
Location of Klystrons	**Collider**	Surface	Surface	Surface	
Window power (kW)	**220**	**220**	110	*43*	Less than 200 is desirable
Beam loading at injection (degrees)	**17–64**	**17–64**	6–34	*1–6*	Worst with 7 batches
V(gen)/V(beam) with feedback	8	**5**	8	*55*	At least 5 is desirable
CBI (HOM) growth (sec)	**1.7**	7	*19*	*34*	Greater than 0.25 is desirable
HOM active damper voltage (kV)	**16**	**8**	3	1	Less than 10 is desirable
Reliability / Availability (1-5)	2	3	4	*4*	High power vs. contamination
Annual Operating cost impact (M$)	0	0	1	*-2*	
Stretched schedule Impact	0	0	0	0	3-yr extension
Subcommittee Vote	0	1	3	6	
	MARGINAL		*SUPERIOR*		

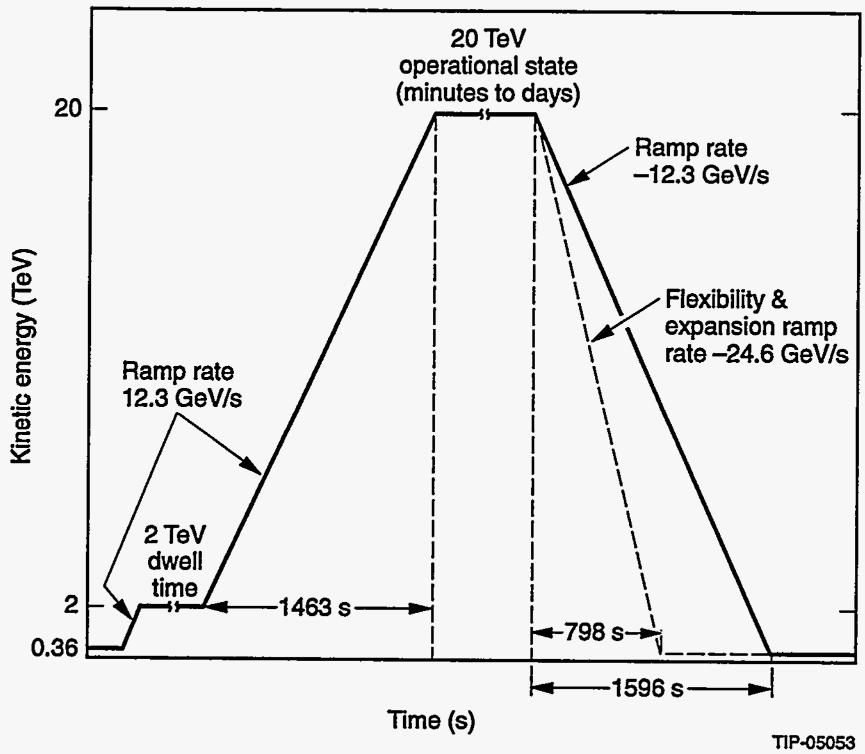


Figure 1. Collider operating cycle.

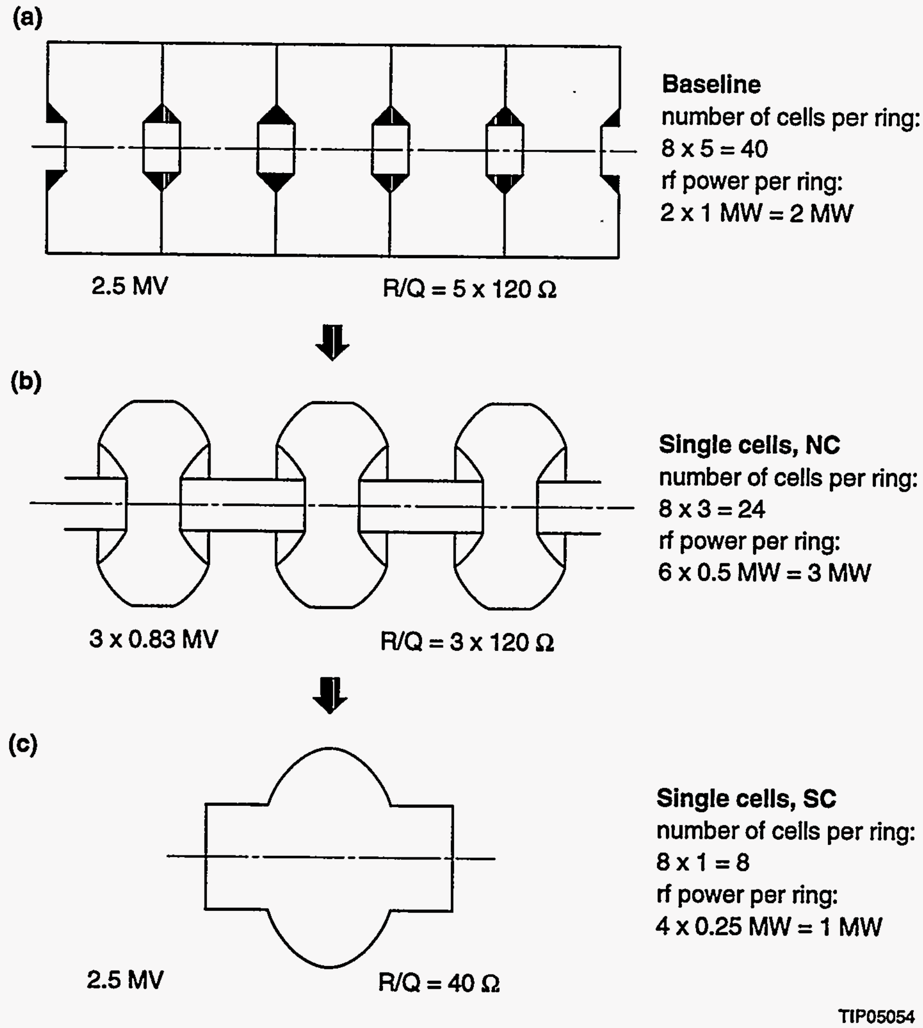


Figure 2. Evolution schematic of rf systems layout.

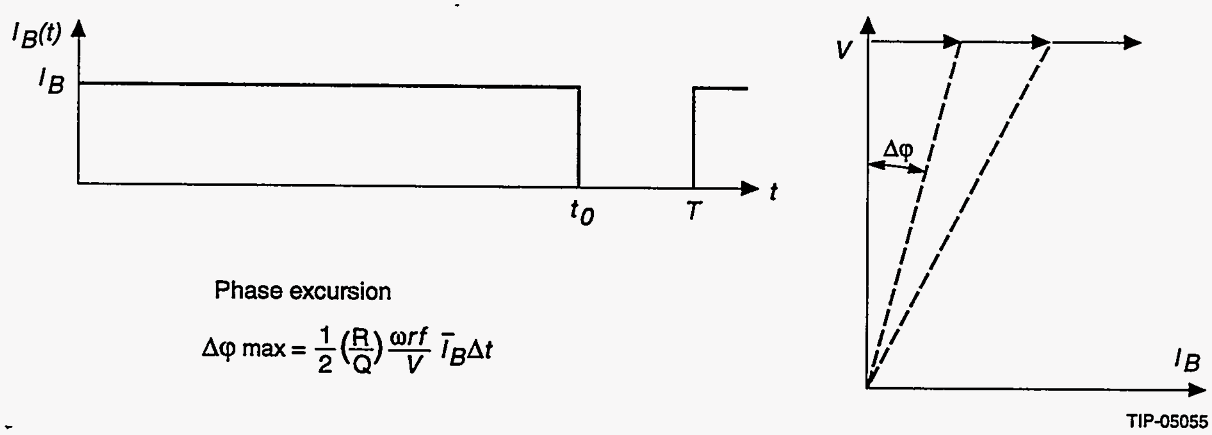


Figure 3. Phase modulation due to transient beam loading. For small phase change, make (R/Q) small and V large.

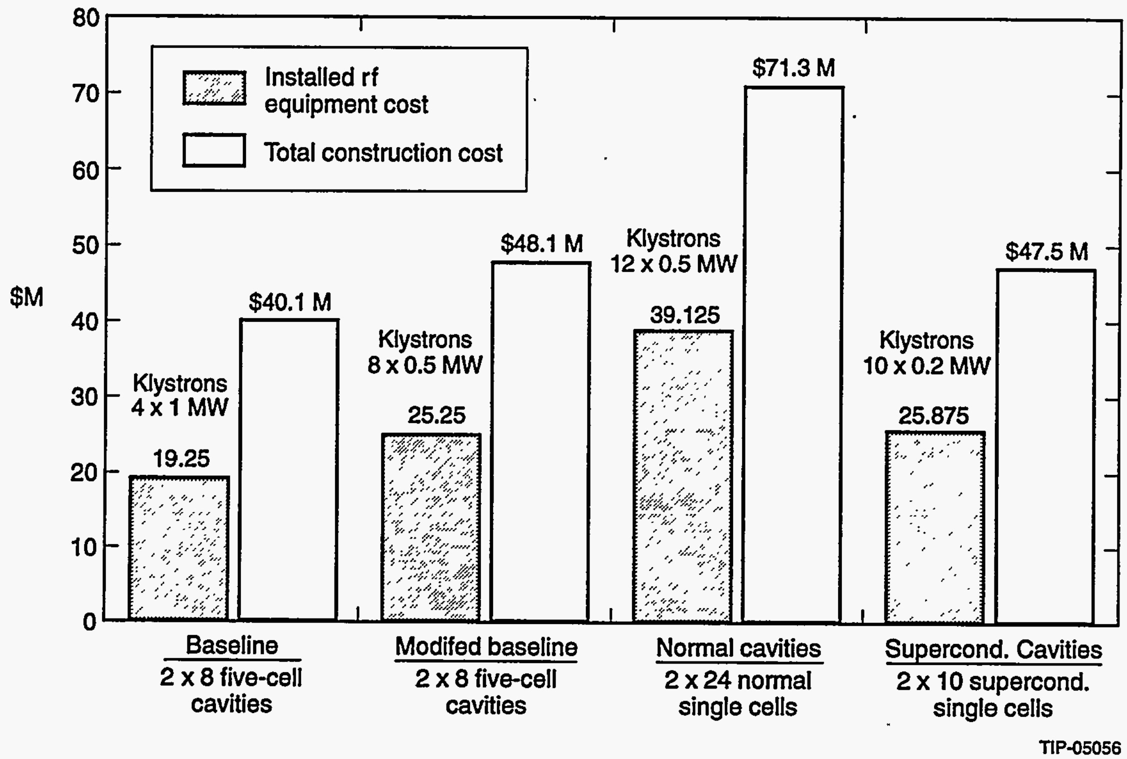
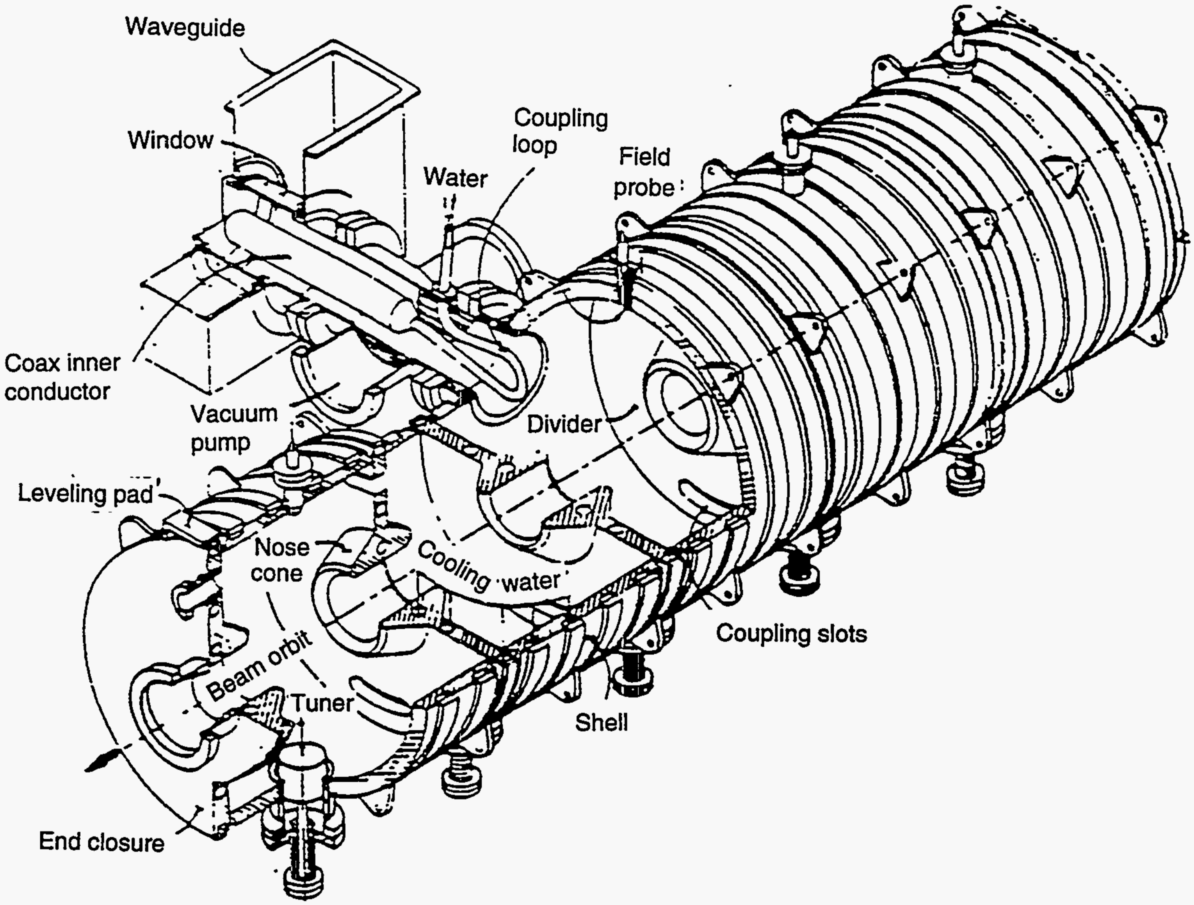


Figure 4. Collider rf system and total construction cost (without active damper systems).



Cavity to be kept in resonance, required generator power given by:

$$P_g = \frac{1}{4\beta}\left[(1+\beta)^2\frac{V^2}{2R_s} + (1+\beta)I_B V \sin\,\phi_B + \frac{1}{2}I_B^2 R_s\right]$$

Optimum coupling and generator power for five-cell cavities:

	β	P_g (MW)
Acceleration	1.92	1.65
Storage	1.73	1.37

Figure 5. A five-cell structure (PEP) for the collider.

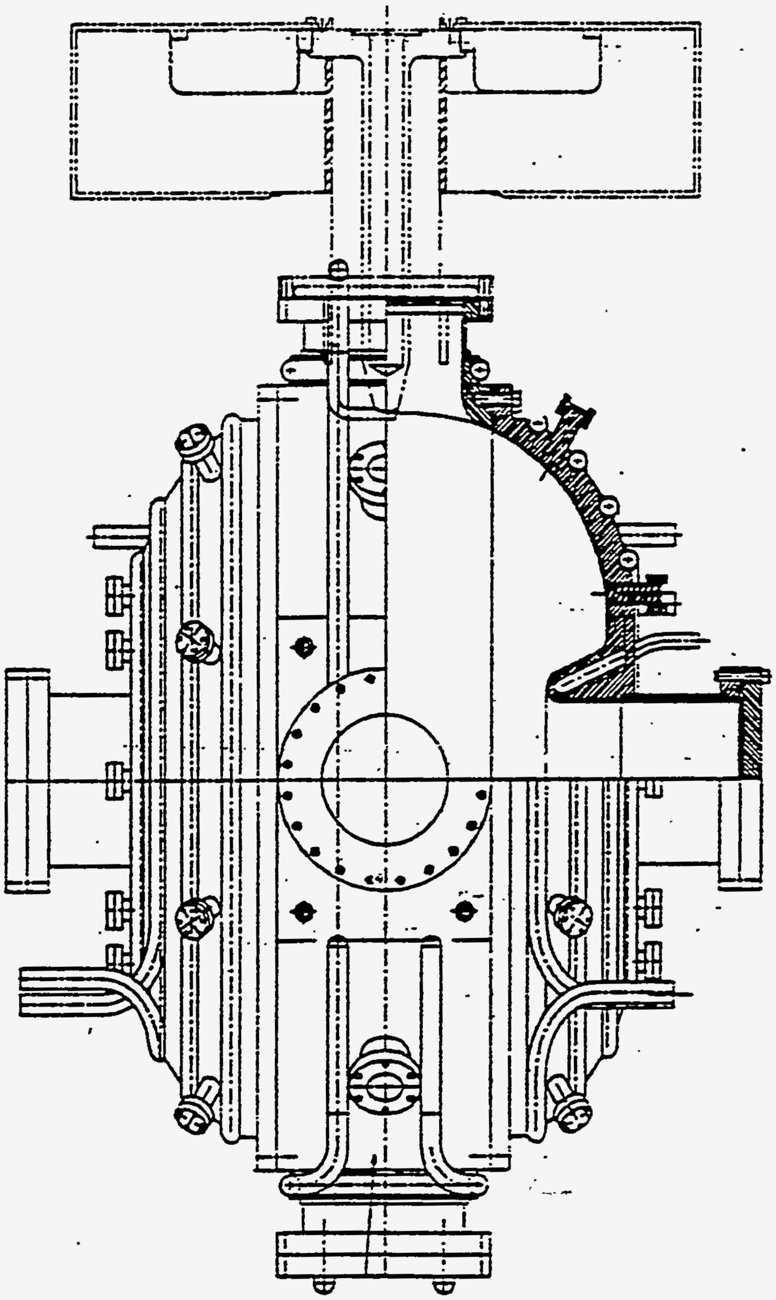


Figure 6. Schematic of the ANL-APS cavity.

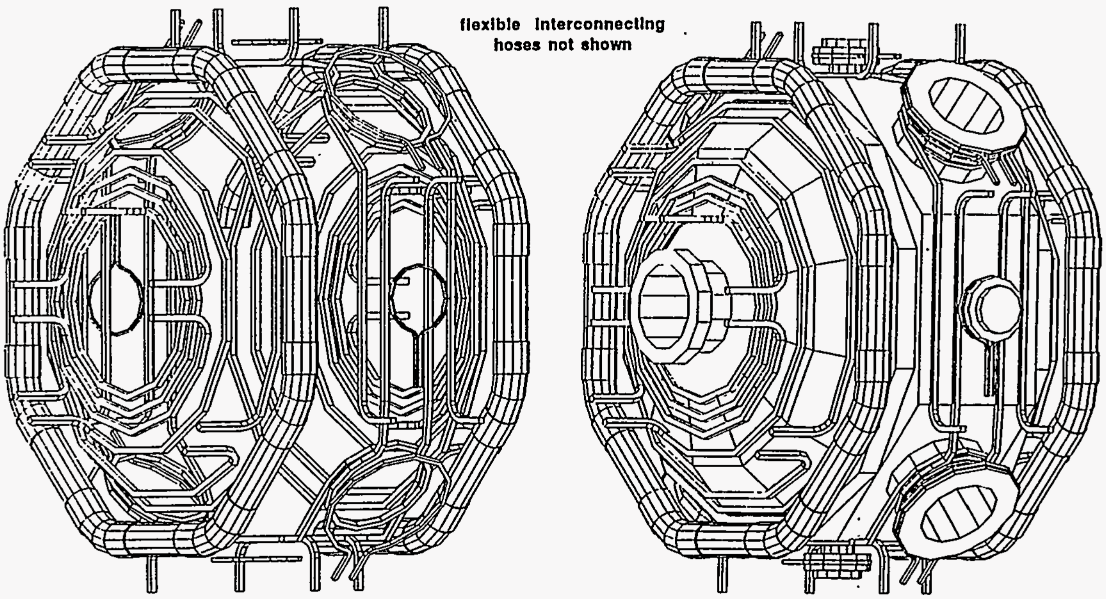


Figure 7. Struggling with copper losses: water pipes and manifold without and with cavity (ANL).

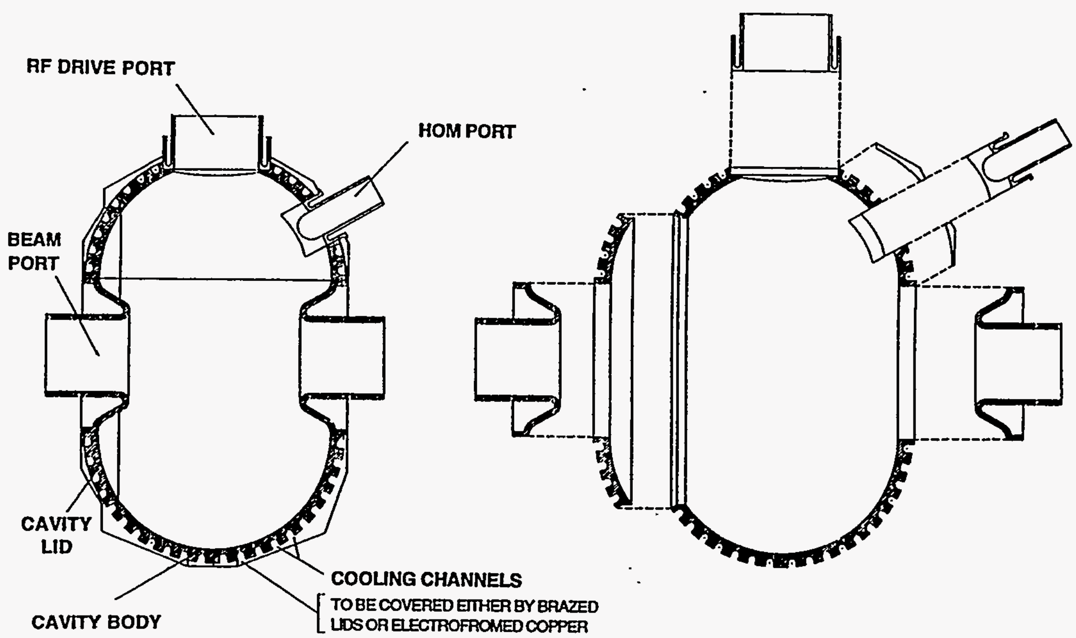
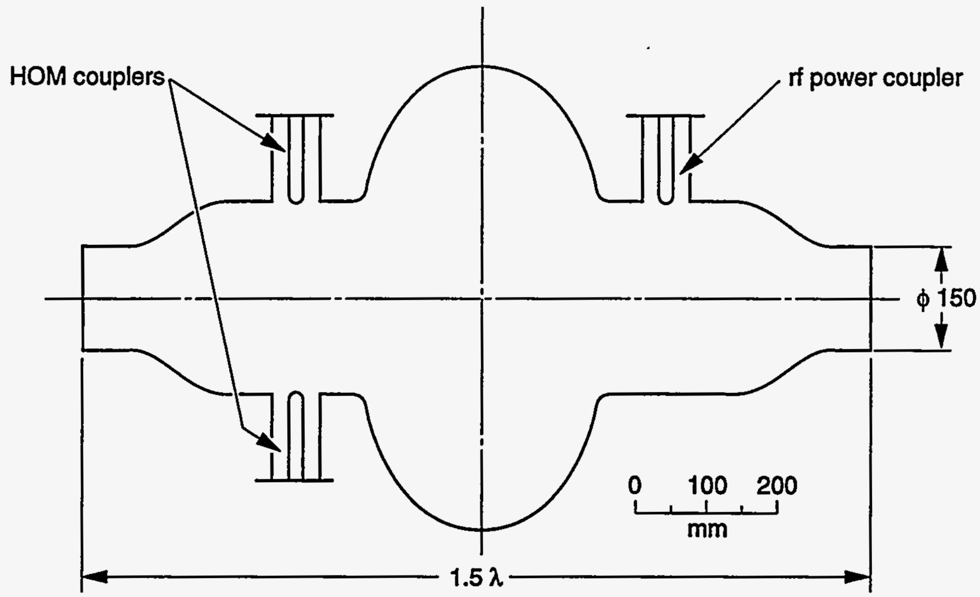


Figure 8. PEP-II high-power test cavity design.



R/Q (depending on exact shape) between 35 and 43 Ω.

Estimated HOM data for collider single-cells

Mode	Frequency (MHz)	R/Q (Ω)	Q_L
TM_{011}	639	55	500
TM_{012}	1006	22	1250

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Figure 9. Schematic shape of a CERN-LHC superconducting cavity.

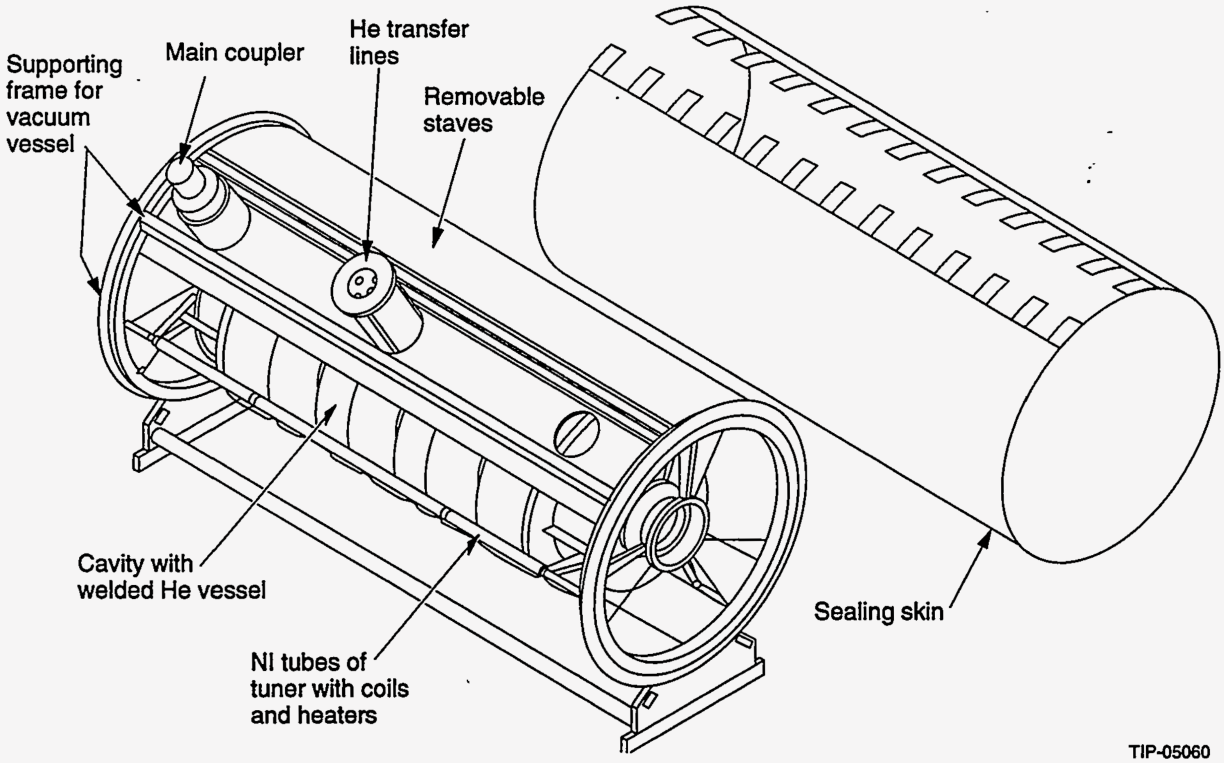

Figure 10. Cavity and cryostat design example from CERN-LEP/LHC.

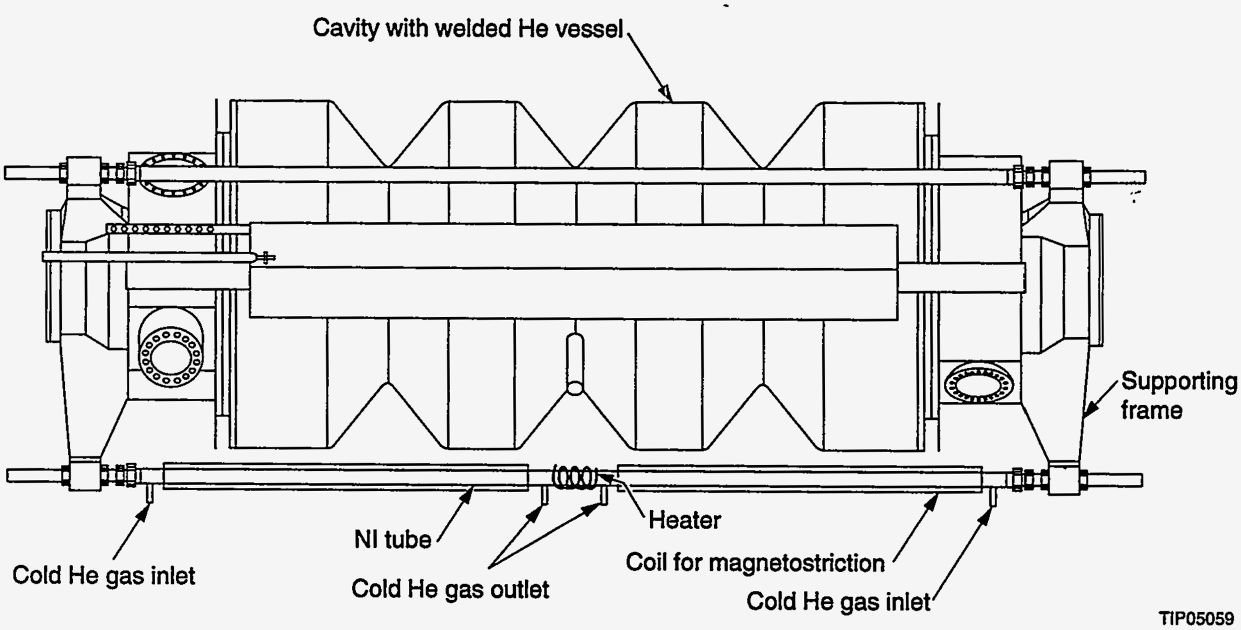

Figure 11. Tuning system design example from CERN-LEP.

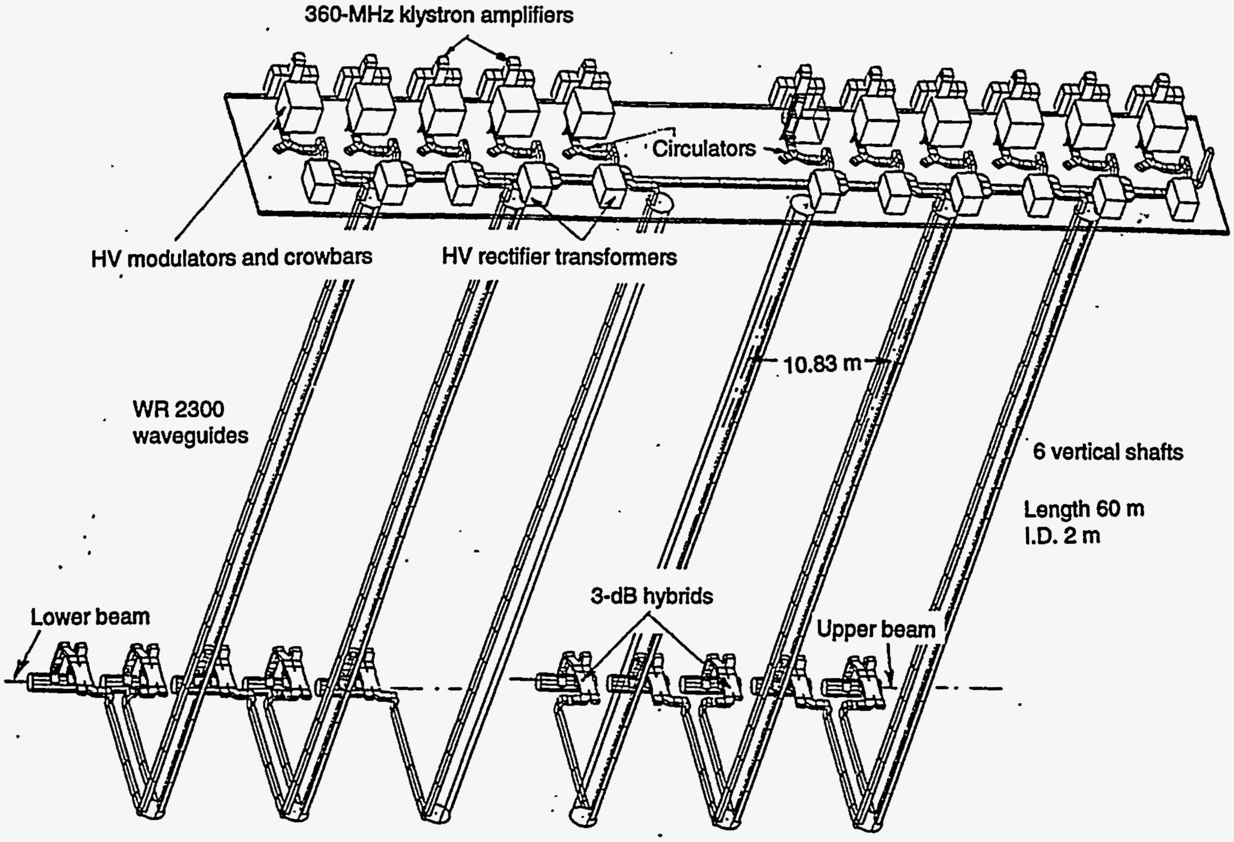

Figure 12. Superconducting rf system with 2 × 10 single cells, fed by 2 × 5 klystrons (+1 standby).

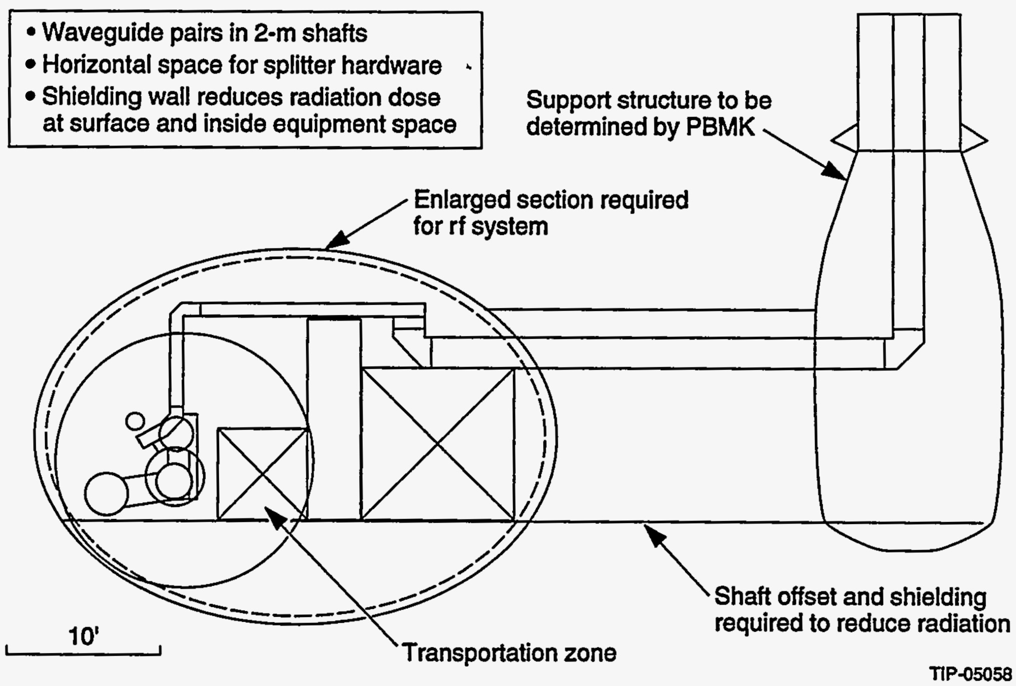

Figure 13. Rf tunnel cross section schematic.

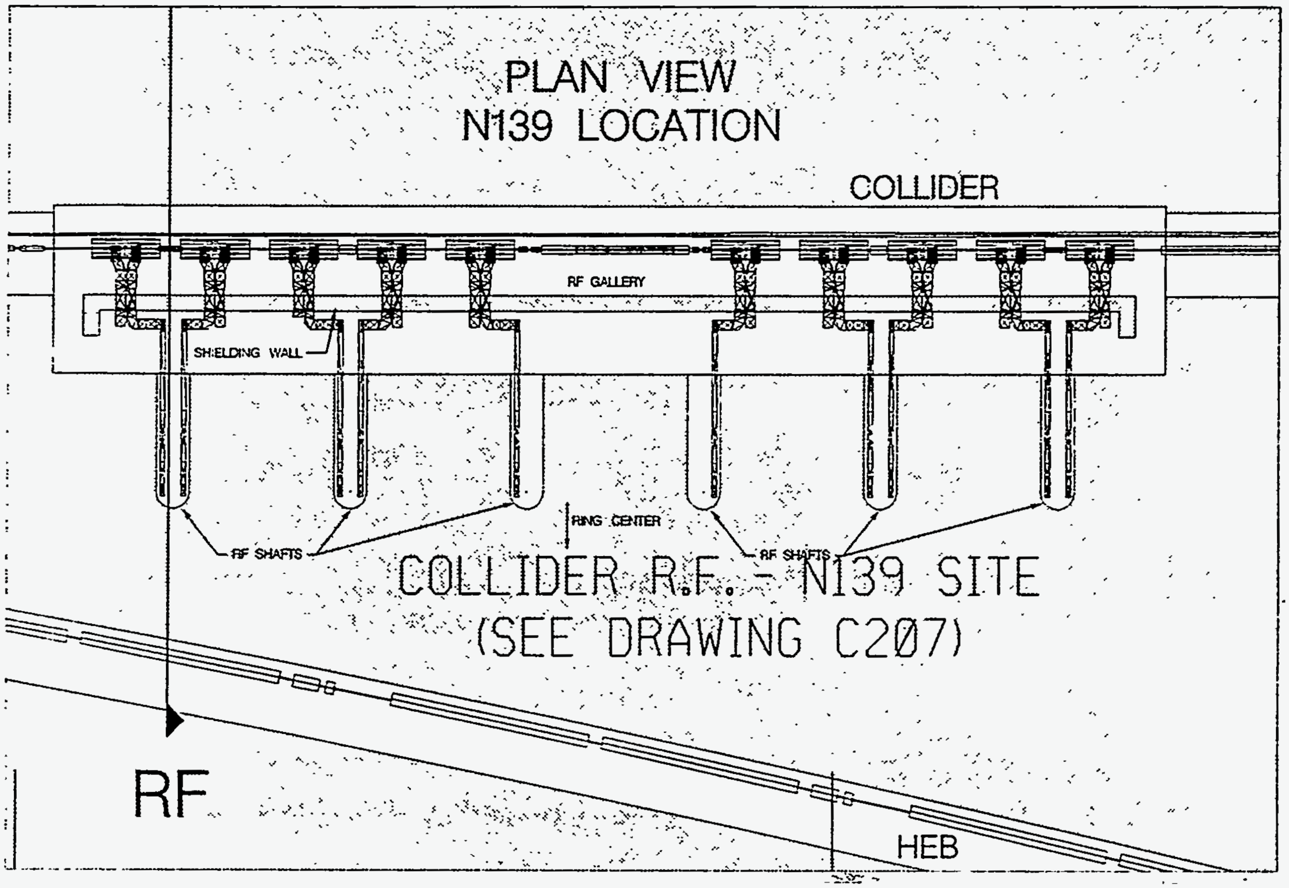

Figure 14. Plan view, N139 location.

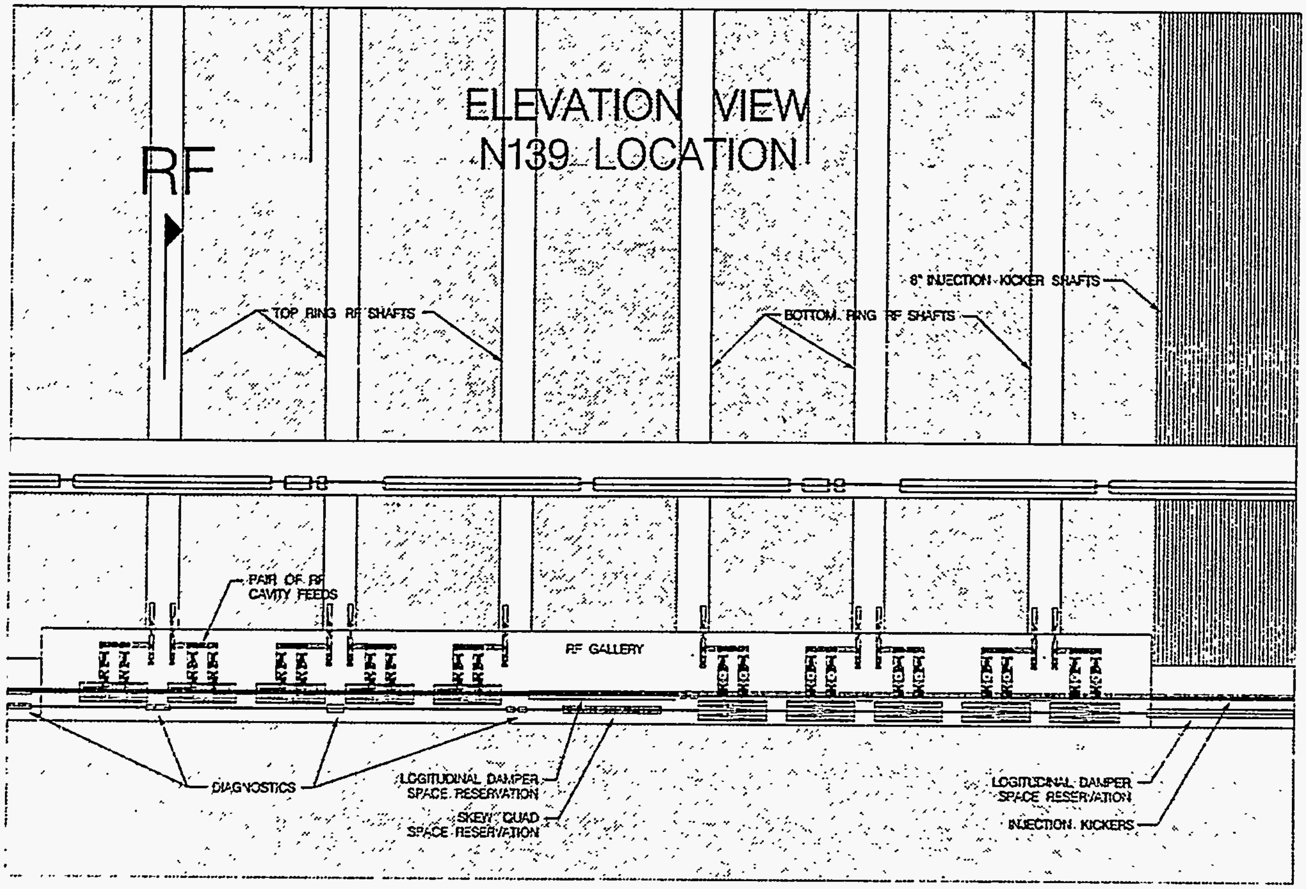

Figure 15. Elevation view, N139 location.