SUPERCONDUCTING RF SYSTEMS AND CRYOGENICS
Subgroup Summary Report

C.Benvenuti (CERN), Ph.Bernard (CERN), J.Bisognano (CEBAF), R.Boni (LNF), I.E.Campisi (CEBAF, Chairman), E.Chiaveri (CERN), U.Gambardella (LNF), E.Haebel (CERN), Ch.Leeman (CEBAF), H.Lengeler (CERN), M.Minestrini (CERN), G.Modestino (LNF), H.Piel (Wuppertal), D.Proch (DESY), B.Spataro (LNF), F.Tazzioli (LNF)

1. - GOALS

The subgroup on Superconducting RF Systems and Cryogenics was assigned the following tasks:

i) provide acceptable design recommendations for the accelerating structures and related RF and Cryogenics systems based on the parameters established by High Energy and Nuclear Physics needs (namely a final energy of 2.5 and 8 GeV at the end of the first and second stage, respectively, and the ability of accelerating simultaneously the 200uA Nuclear.Physics beam and the three bunches for High Energy Physics).

ii) estimate the cost of such systems based on realistic, present day technology, with some assessment of future costs as technology and cavity manufacturing processes will improve.

These tasks were carried out for the case of the original design which includes two racetracks of similar structure and with different energies, as well as for the more recent design of Amaldi and Coignet which is capable of reaching a center of mass energy of 15 GeV (alternate design). Design and cost estimates were done for a few cases of possible achievable gradients.

2. - GENERAL DESIGN CONSIDERATIONS AND CRITERIA

Table I describes the main parameters established by the the general machine plan and around which our group has worked the design of the RF and Cryogenics systems.

TABLE I

	INJECTOR	1st STAGE	2nd STAGE
APPROX. ENERGY GAIN/PASS [MeV]	100	350	950
MAXIMUM BEAM CURRENT [mA]	~1	3.7	2.8

The beam current in the 1st stage has been calculated for the injector-side linac which, due to the recirculation scheme, accelerates the beam four times, whereas the opposite linac and the linacs in the second stage see the beam only three times. For symmetry both linacs of the first stage have been designed for the same beam loading.

The energy gain per linac and the linac lengths have been slightly changed with respect to the original design for the main reason that in the process of determining the cost of the RF systems it appeared immediately clear that not all the cavities could be powered by single RF sources, as for instance in the case of CEBAF. The price estimate of the sources alone was well over 100 GLit (1GLit=1Billion Italian Lire), which would constitute an unacceptable burden on the budget. The alternative solution of using one high power RF source to power many (in our case 16) cavities necessarily quantizes the linac length and energy gain per linac on a coarser scale.

3. - SUPERCONDUCTING CAVITY PARAMETERS

For a conservative approach to the cost estimate we have adopted presently available cavity parameters and operating conditions: these are summarized in Table II and are essentially the design and operating parameters of the DESY cavities (Fig.1).

TABLE II

CAVITY PARAMETERS	
Material:	Niobium (RRR=300)
Frequency:.	500 MHz
Unloaded Quality Factor:	2×10^9
Average Accelerating Gradient (MV/m):	5
Operating Temperature (°K):	4.3
r / Q (Ω/cavity)	460
Number of Cells per Cavity:	4
Number of Higher-Order Mode Couplers:	2 per cavity; Tuned filter type.
External Quality Factor for all relevant HOMs:	< 15,000
Active length per cavity (m) :	1.2
RF Power Dissipation per cavity @ 5 MV/m (W):	40

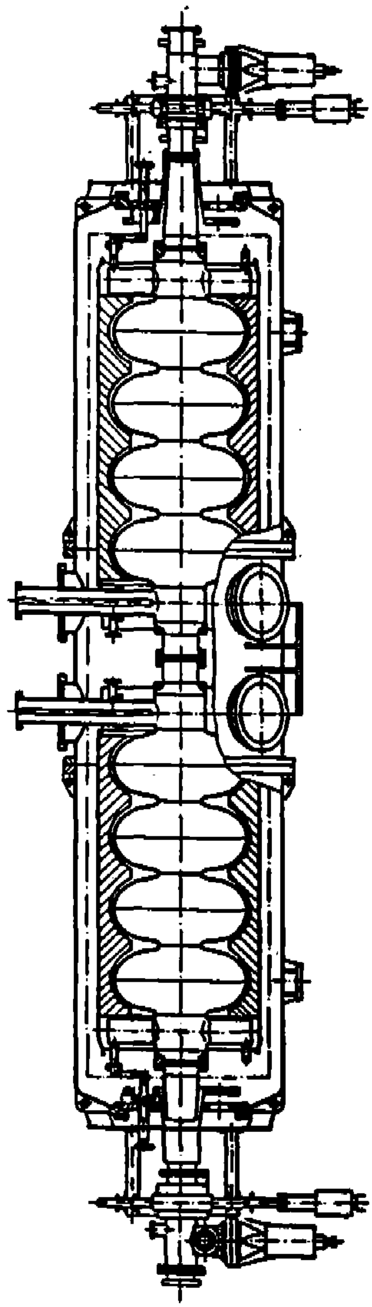

Figure 1. Cross section of the 500 MHz, 4-cell DESY cavity.

The choice of frequency is dictated by beam quality and machine physics considerations and the solutions of 500MHz provides immediate design and operating experience of other laboratories, notably CERN and DESY.

Operation at a field gradient of 5 MV/m is considered a safe design assumption, although indications exist that in a not too distant future, possibly before the machine undergoes the final design, gradients of around 7 MV/m could be reached. At the design gradient, typical unloaded Q values of 2 10^9 are routinely achieved.

An operating temperature of 4.3 °K as been adopted, based on DESY's operation, although a possible optimization to minimize cryogenic investment and operating costs might lead to a slightly different value, between 4.2 and 4.5 °K.

A final answer on how many cells per cavity are optimal or acceptable will be left as a preconstruction Research and Development issue: the four cell approach is considered a safe one from the point of view of coupling of the Higher Order Modes, although measurements exist on the CEBAF/Cornell 5 cell structures which indicate that no deleterious effect on the beam should be expected with the 5-cell geometry. A final choice might depend on CEBAF's operating experience. The partial benefits of a larger number of cells per cavity, mainly a slightly lower construction cost, must be weigthed against the risk of beam instabilities and, possibly even more immediately, against the needs of the beam transport optics elements, which may not allow a longer distance between warm sections of the machine. With the present DESY HOM tuned filter design, external Q's in the range 500-5000 have been obtained.

The cryostat design has also been taken from DESY's experience (Table III): it has a length of about 4.3m and a liquid Helium capacity of slightly under 200 liters. It has valves and pumps on either end of the beam pipe, with a total length of 5.26m: this length could probably be decreased by eliminating at least one pump per cryostat, thus allowing more flexibility in locating the beam optics elements. Under the present design the cryogenic filling factor is approximately .45; by allowing for an additional 90 cm (3 $\lambda/2$) in between modules for the optics elements, the filling factor drops to an approximate value of .40. This value has been used in determining the physical length of the linacs.

TABLE III

CRYOSTAT PARAMETERS	
Cryomodule length (m):	4.3
Liquid Helium Storage Capacity (l):	200
Cryomodule + Valves + Pumps (m):	5.26
Cryogenic Filling Factor :	.45
Total Filling Factor(includes Optics):	.40
Static Heat Losses per Module (W):	10
Total Heat Losses per Module (RF + Static) (W):	100

The DESY cryostat is expected to have static heat losses of about 10W. Some improvement could be achieved in this value, although the overall heat losses could not be improved by more than a few percent, since the static losses account for only 10% of the overall heat load, which is dominated by the RF losses.

4. - BEAM LOADING AND RF POWER REQUIREMENTS

We have assumed that in STAGE 1 and STAGE 2 of the machine a full beam is circulating with the following components:

1) A CW beam for Nuclear Physics with an average current of 200uA.
2) Two pulsed (12 kHz repetition frequency) electron bunches of 8 and 25 $\times 10^{10}$ electrons/bunch, the second being used for positron production.
3) One positron bunch (12 kHz) of 5×10^{10} particles/bunch.

The average current seen by the cavities is (for beam loading purposes)

$$I=\{[(|Q1|+|Q2|+|Q3|)\cdot f_r] + I_{np}\} \times N_r$$

where Q_i are the electric charges associated with the HEP bunches, f_r is the repetition frequency (12 kHz), I_{np} is the nuclear Physics current and N_r is the number of recirculations in that stage.

For the second section of the injector (the first section does not accelerate positrons) the average current is

$$I_{inj} = [(5+8+25)\cdot 10^{10} \cdot (1.6\times10^{-19})(1.2\times10^{4})] + 200\ \mu A = .92\ mA$$

In the first linac of the first stage the beam is being recirculated four times with an average current of: $I_1 = I_{inj} \times 4 = 3.7$ mA.

In the second linac of the first stage and in both linacs of the second stage the beam recirculates three times, with an average current of : $I_2 = I_{inj} \times 3 = 2.8$ mA.

The RF power necessary to give the beam current I_1 an energy gain of 6 MeV (the energy gain of the 4-cell cavity operated at 5 MV/m x 1.2 m) is given by : PB = $I_1 \times E$ = 3.7 mA x 6 MV= 22.3 kW.

Under matched conditions for this beam power, the cavity external Q should be

$$Q_{ext} = Q_o\ (P_d / PL) = 2 \times 10^9\ (40\ W / 22.3\ kW) = 3.6 \times 10^6$$

which corresponds to a coupling coefficient of : $\beta = Q_o/Q_{ext} = 555$.

For actual operation, a $Q_{ext} = 2x10^6$ has been chosen for the first stage, whereas the second stage, having a lower beam loading, can be designed with a $Q_{ext} = 4 \times 10^6$, thus reducing RF power reflection and improving the efficiency.

5. - PRE-CONSTRUCTION R&D

Possible pre-construction R&D issues which have been identified and recommended and which might have a beneficial impact on the performance and costs of the machine are:
- studies on improving cavity design and material technology;
- simplification of cavity tuning mechanism;
- choice of 4 or 5 cell cavities.

Other suggested studies, such as the impact of placing more than two cavities per cryostat to decrease costs, will have to be evaluated against other machine requirements.

6. - CAVITY COST ESTIMATE

The cost estimate arrived at includes the following components (Fig.1): two cavities, tuners, cryostat, vacuum system, beam pipe.

The estimates were based on the CERN, DESY and CEBAF experience and on the estimate provided by F. Tazzioli. Although the costs were based on diverse parameters, different frequencies, various vendors etc., all estimates were within approximately 10% of each other, at the level of .8 GLit per module (the sum of the components mentioned above).

TABLE IV

BREAKDOWN OF CAVITY COSTS (kSF)			
		4-CELL 350 MHz, l=1.7m	5-CELL 500 MHz,l =1.5m
Niobium (577 SF/kg, RRR>100)+ (250 SF/kg, RRR=40)	(kSF/m)	63	30
Manufacturing		61	69
Surface treatments		3	2.5
Cryostat (CERN design)		88	92
Fundamental mode couplers		7	8.3
HOM couplers		10	11
Tuners		9	9
Vacuum system		26	29
Total per unit		451	377
Total per meter		265	251

Table IV has been provided by H. Lengeler (CERN) and shows the cost breakdown of similar systems in Swiss Francs (1.1 SF = 1 kLit).

An additional cost, estimated by Lengeler to be as high as 30% of the costs shown here, might have to be added for cavity testing at low temperature.

The costs apply to single units or to small productions (less than 10): considerably lower unit costs can be expected for a larger number of units.

7. - PRELIMINARY CONSIDERATIONS FOR RF SYSTEM DESIGN

The goal in designing the RF generation and distribution system was to reach the pre-assigned energy gain per linac while minimizing the cost of the sources. An estimate done by Lengeler on the cost of CW RF sources indicated that, for low and medium power sources (less than 50 kW) the cost per RF Watt is approximately 6 SF, whereas the unit cost for high power sources (hundreds of kilowatts) is approximately 2 SF/W. Based on this consideration, the individual power sources for each cavity throughout the machine were ruled out, as they would add an extra cost of well over 80 GLit to the total.

Fig. 2 and 3 show the RF system layout based on the use of high power sources for as many cavities as possible to reach the design energy gain, while still allowing for some individually controlled cavities for phase and amplitude compensation. A more detailed analysis of the implications of this choice on the beam properties will have to be carried out together with the accelerator physicists.

A possible pulse operation of the second stage was considered in order to decrease the operating costs of the machine whenever the CW Nuclear Physics beam was not being used. This option is not feasible, since a truly pulsed operation at 12 kHz requires both a variable coupling system to the cavities (the filling time of the cavities is of the order of 1 msec, while the interbunch period is 83usec) and a parallel set of pulsed power RF sources, which provide enough energy over a pulse length much shorter than the 83 usec. The cost of the additional systems would add a prohibitive amount to the RF costs. On the other hand, a low duty cycle operation is possible, but it would detract from the attractive features of the accelerator, notably the luminosity.

8. - RF SYSTEM

Table V shows the main parameters of the accelerators, including the number and power output of the RF sources.

The power requirements have been determined from the beam power figures, by adding a 10% margin for reflections due to mismatch and 20% for waveguide losses. For the individual power sources for single cavities (either tetrodes or low power klystrons) an additional 30%

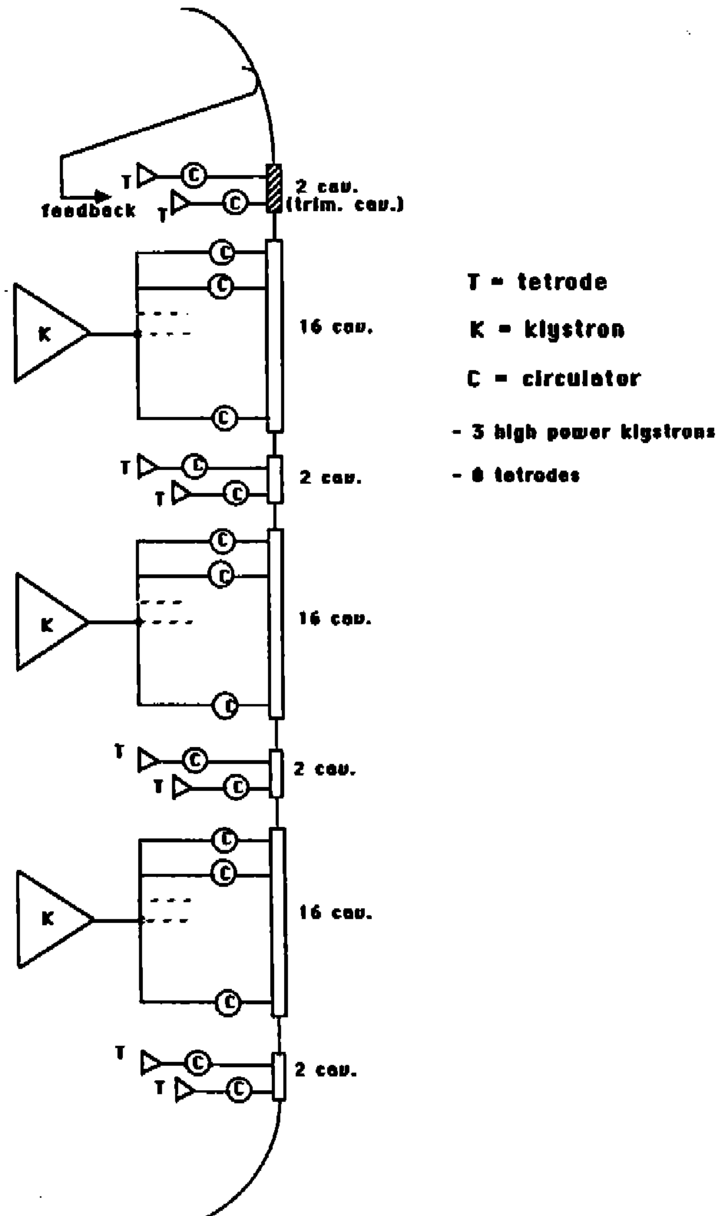

Figure 2. Layout of the RF system for one racetrack of the first stage.

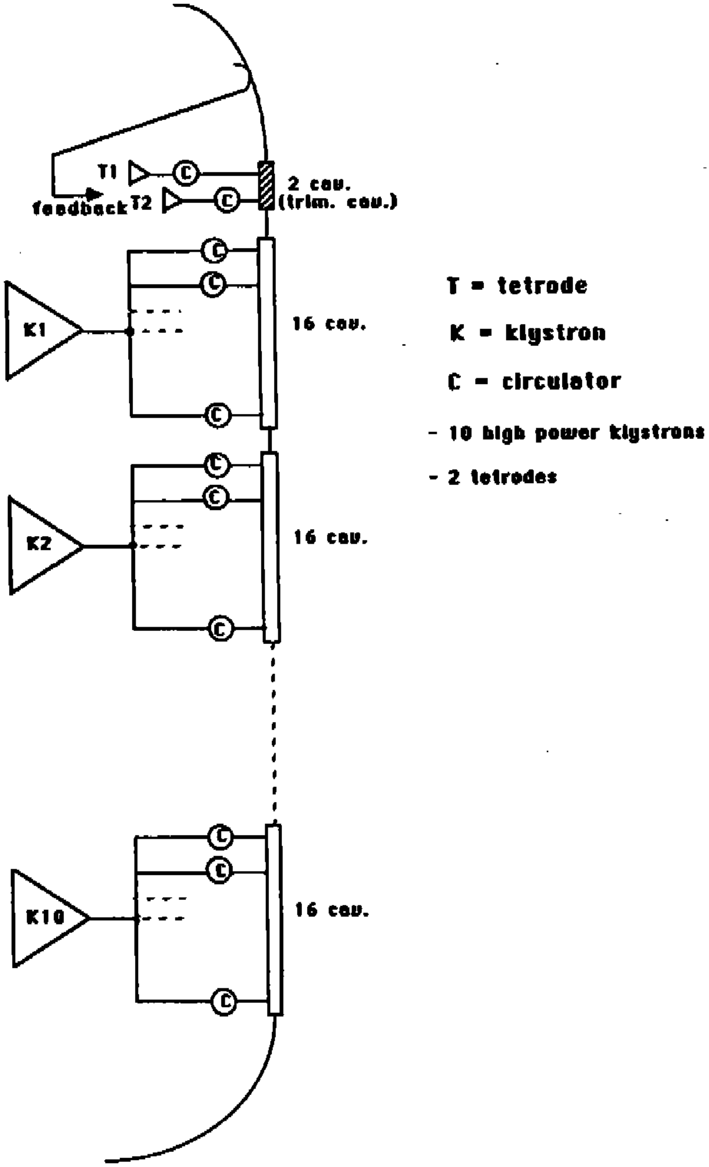

Figure 3. Layout of the RF system for one racetrack of the second stage.

margin has been considered for phase and amplitude control. This brings the power rating of the individual power sources to about 40 KW.

The sources powering multiple cavities (16 cavities/source) have been chosen to have an RF power output of 500 kW for the first stage and 400 kW for the second stage, due to the different beam loading requirements. Possibly only the higher power sources could be purchased without a significant increase in costs for the second stage, also allowing for later operation at higher gradients. For the first stage three high power klystrons per linac have been chosen, which lead to an energy gain of 336 MeV, slightly lower than the design value of 350 MeV. In the second stage the energy gain is 972 MeV with ten klystrons per linac. Sixteen cavities would have individual RF sources in the first stage, and four in the second stage. The injector RF need could be accommodated for by a single high power klystron which would provide close to 100 MeV of energy gain. Based on beam stability considerations, the use of circulators will have to be evaluated.

TABLE V

SYSTEM PARAMETERS				
		Injector	1st Stage	2nd Stage
Average current	[mA]	.92	3.7	2.8
Number of recirculations	1	4 (3)	3	
Beam power per cavity	[kW]	5.5	22.3	16.3
Number of modules		8	56	162
Total active length	[m]	19.2	134.4	388.8
Length of each linac	[m]	48	168	486
Energy gain per linac	[MeV]	96	336	972
Total energy gain	[MeV]	96	2350	5832
Input energy	[MeV]	0	96	2446
Output energy	[MeV]	96	2446	8278
Number of klystrons+tetrodes		1+0	6+16	20+4
Total beam power	[MW]	.09	2.35	5.44
Maximum power of RF sources	[kW]	200+0	500+40	400+40
Maximum RF power available	[MW]	.2	3.6	8.2
Wall plug power (50% efficiency)	[MW]	.4	7.2	16.4
Heat load @4.3 °K	[kW]	.8	5.6	16.2
Refrigerator power (50 % margin)	[MW]	.4	2.8	8.1
Total installed power required	[MW]	.8	10.0	24.4
Total installed site power required for RF and Cryogenics	[MW]		35.2	

The total RF power requirements for the site add up to about 12 MW which could be presumably lowered slightly by a more careful detailed design. We assume a conversion efficiency of 50% from the wall plug to the RF source output, thus requiring 24MW of DC power for the RF system alone.

9.- COST OF THE RF SYSTEM

The driving factor in the choice of the RF system has been the need to limit the use of single low power sources: this solution would have costed almost four times as much as the proposed one, both according to estimates of Lengeler and Boni. According to Lengeler, the cost of the sources scales as $P^{-1/3}$, thus making the higher power sources much more economical.

This statement has been recently verified by H. Piel, who placed an order for a 40 kW klystron at a cost of 6.3 SF/W. A larger number of smaller sources also add to the cost by multiplying and complicating the RF control systems.

A substantial fraction of the cost of the RF system is made up by the circulators. A total of 452 of them are required throughout the machine, adding more than 13 GLit to the cost. Unless CEBAF's operating experience would prove the opposite, though, they might be a necessary item to guarantee proper operation and a stable beam.

10. - CRYOGENIC SYSTEM

The heat load to the refrigeration system has been calculated based on the load due to the RF modules alone: transfer lines and other components which add to the load have not been analyzed in detail, but a generous safety margin of 50% has been added to the refrigerator capacity in order to cover these and other unknown sources of heat losses. Also, the refrigeration needs of the injector have been added to the first stage refrigerator, without having to provide the more costly solution of an independent unit for the injector.

The total heat load due to the modules is approximately 22.6 kW at 4.3 °K. We assume a cryogenic efficiency of 1/330, which might be marginal. With the 50 % safety margin, this figure translates into a room temperature power requirement of about 11.3 MW.

The cost estimate of the refrigerator plant is based on the empirical formula

$$\text{Cost [GLit]} = 2.5\ \{P[\text{kW @ } 4.3°\text{K}]^{.6}\},$$

well verified for other systems.

The total cost of refrigeration for two stages amounts to 25.9 GLit.

11. - LIQUID HELIUM DISTRIBUTION SYSTEM

Transfer lines and valve boxes have been included as an additional item in the cost of the refrigeration system, partly because their cost can be independently controlled by a careful choice of how many modules can be tied together to form a single cryogenic unit. We have adopted an initial solution of placing one valve box for each four modules, similar to CEBAF's solution of connecting four cryounit into one cryomodule. In this way four modules at a time would have to be cooled down and warmed up together, which seems an acceptable practice in the operation of the accelerator. Then the total number of valve boxes would be approximately 60, for a total cost of about 7.2 GLit. The estimate of .12 GLit per box is based on DESY's costs. The length of the transfer lines for the site has been estimated at about 1700 m, at a total cost of 4.2 GLit (2.5 MLit/m).

12. - TOTAL COST AND CONCLUSIONS

Table VI gives an overall view of the costs related to cavity, cryostat, refrigeration and RF systems.

TABLE VI

OVERALL COSTS [GLit]								
		INJECTOR		STAGE 1		STAGE 2		TOTAL
ITEM	UNIT COST	# OF UNITS	TOTAL COST	# OF UNITS	TOTAL COST	# OF UNITS	TOTAL COST	
MODULES	.8	8	6.4	56	44.8	162	129.6	180.8
KLYSTRONS	2 kLit/W	1	.4	6	6.0	20	16.0	22.4
TETRODES	.25	0	0	16	4.0	4	1.0	5.0
CIRCULATORS	.03	16	.5	112	3.4	324	9.7	13.6
REFRIGERATOR	2.5 $P^{.6}$	0	0	1	8.9	1	17.0	25.9
LHe DISTRIBUTION								
- LINES	2.5 MLit/m	50m	.1	440m	1.1	1200m	3.0	4.2
- VALVE BOXES	.12	2	.36	15	1.68	40	5.0	6.8
TOTAL			7.66		69.9		181.2	259

Although the total cost of these systems is close to 260 GLit, several factors in the cost have been probably overestimated. First, since the cost of the modules contribute close to 70% of the total, it is clear that this is the item that demands closest attention to reduce the overall costs. Two concurrent ways of reducing these costs consist first in decreasing the unit cost of the modules by simplifying construction and assembly (this should be possible on a large production scale, which might decrease the costs by as much as 20%), and second in investing in R&D activities which would allow operation at a higher gradient. This second option would considerably decrease the number of necessary modules, without degrading the energy of the machine.

The possibility has been investigated of designing the second stage of the machine to operate at 7 MV/m: this seems a plausible assumption if the machine will be built in a modular way: by the time the first stage will be in a final design stage, improvement in the properties of production cavities should have pushed the reliably attainable gradient up from the presently available 5MV/m. In the following Tables we give the parameters and costs for a machine with the second ring designed for operation at 7 MV/m.

13. - ALTERNATE DESIGN

Based on the recent design of Amaldi and Coignet (these Proceedings) we calculated parameters and cost estimates for a single racetrack accelerator.

TABLE VII

SYSTEM PARAMETERS FOR 7 MV/m IN THE SECOND STAGE				
		Injector	Stage 1	Stage 2
Average current	[mA]	.92	3.7	2.8
Number of recirculations		1	4 (3)	3
Beam power per cavity	[kW]	5.5	22.3	23.5
Number of modules		8	56	114
Total active length	[m]	19.2	134.4	273.6
Length of each linac	[m]	48	168	336
Energy gain per linac	[MeV]	96	336	958
Total energy gain	[MeV]	96	2350	5746
Input energy	[MeV]	0	96	2446
Output energy	[MeV]	96	2446	8192
Number of klystrons+tetrodes		1+0	6+16	14+4
Total beam power	[MW]	.09	2.35	5.4
Maximum power of RF sources	[kW]	200+0	500+40	500+40
Maximum RF power available	[MW]	.2	3.6	7.2
plug power (50% efficiency)	[MW]	.4	7.2	14.3
Heat load @ 4.3 °K	[kW]	.8	5.6	20.4
Refrigerator power (50 % margin)	[MW]	.4	2.8	10.1
Total installed power required	[MW]	.8	10.0	25.4
Total installed site power required for RF and Cryogenics : 36.2 MW				

The constraints imposed on the design are the following:

ENERGY GAIN PER LINAC	1.05 GeV
AVERAGE CURRENT	1.2-1.7 mA

This current includes a 200 uA (2.5 x 10**6 e-/ bunch)nuclear physics beam with a duty cyle of 80% and the bunches for High Energy Physics with charges of 8x10**8(e-); (2.5-5)x10**11 (e- for e+ production) and (2.5-5)x10**10 (e+).

TABLE VIII

OVERALL COSTS (2ND STAGE @ 7 MV/m) [GLit]								
		INJECTOR		STAGE 1		STAGE 2		TOTAL
ITEM	UNIT COST	# OF UNITS	TOTAL COST	# OF UNITS	TOTAL COST	# OF UNITS	TOTAL COST	
MODULES	.8	8	6.4	56	44.8	114	91.2	142.4
KLYSTRONS	2 kLit/W	1	.4	6	6.0	14	14.0	20.4
TETRODES	.25	0	0	16	4.0	4	1.0	5.0
CIRCULATORS	.03	16	.5	112	3.4	228	6.8	10.7
REFRIGERATOR	$2.5xP^{.6}$	0	0	1	8.9	1	19.6	28.5
LHe DISTRIBUTION								
- LINES	2.5 MLit/m	50m	.12	.44Km	1.1	1 Km	2.5	3.7
- VALVE BOXES	.12	2	.36	15	1.68	30	3.6	5.7
TOTAL			7.66		69.9		138.7	216

TABLE IX

SYSTEM PARAMETERS FOR A SINGLE RACETRACK ACCELERATOR				
		5 MV/m (4.97)	6 MV/m (5.76)	7 MV/m (6.84)
Average current	[mA]	1.2-1.7	1.2-1.7	1.2-1.7
Number of recirculations		3.5	3.5	
Beam power per cavity	[kW]	10.3	12.3	14.4
Number of modules		178	146	130
Total active length	[m]	410	350	300
Length of each linac	[m]	530	440	380
Energy gain per linac	[MeV]	1050	1050	1050
Total energy gain	[MeV]	7350	7350	7350
Input energy	[MeV]	96	96	96
Output energy	[MeV]	7450	7450	7450
Number of klystrons+tetrodes		22+2	18+2	16+2
Total beam power	[MW]	3.7	3.6	3.7
Max. power of RF sources	[kW]	250+40	300+45	350+50
Max. RF power available	[MW]	5.6	5.5	5.7
Wall plug power (@50% efficiency)	[MW]	11.2	11.0	11.4
Heat load @4.3 °K	[kW]	17.8	18.3	22.1
Refrigerator power (with 50 % margin)	[MW]	8.8	9.1	11.0
Total installed power required	[MW]	19.0	20.1	22.4

The injector power of about .8 MW must be added to these figures.

Table IX summarizes the accelerator RF and Cryogenics parameters.

TABLE X

OVERALL COSTS OF RF AND CRYOGENICS FOR THE SINGLE RACETRACK ACCELERATOR [GLit]

ITEM	UNIT COST	5 MeV/m # OF UNITS	5 MeV/m TOTAL COST	6 MeV/m # OF UNITS	6 MeV/m TOTAL COST	7 MeV/m # OF UNITS	7 MeV/m TOTAL COST
MODULES	.8	178	142.4	146	116.8	13	104.0
KLYSTRONS	2 kLit/W	22x250	11.0	18x300	10.8	16x350	11.2
TETRODES	.25	2x40	.5	2x4	.5	2x50	.6
CIRCULATORS	.03	356	11.0	292	8.7	260	7.8
REFRIGERATOR	$2.5 \cdot P^{.6}$	14.1		14.3		16.0	
LHe DISTRIBUTION							
- LINES	2.5 MLit/m		3.5		3.1		2.9
- VALVE BOXES	.12	45	5.4	37	4.4	33	4.0
TOTAL			188		157		146

To these figures the cost of the injector (7.7 GLit) must be added.

The overall cost of RF and Cryogenics for the whole machine operated at 7 MV/m is of about 154 GLit.