REVIEW OF PROGRESS IN THE FIELD OF SUPERCONDUCTING CAVITIES

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Abstract: Superconducting cavities are now becoming standard tools for particle accelerators. Research and development are going on at more than 25 laboratories and universities. There are 5 operating and 6 constructing (heavy) ion accelerators in the world. For electron acceleration, 3 systems are being operated and 5 are under construction. Continued R&D towards higher accelerating gradient have already made it feasible and attractive to apply superconducting cavities to high energy proton LINACs. Further improvement in accelerating gradients will make superconducting cavities competitive candidates for accelerating structures of the TeV Energy Linear Collider.

I. Introduction

The only one but very conspicuous merit in the application of superconducting RF cavities is their negligibly small wall loss. The wall loss P_0 in the RF cavity is given by the following surface integral of the magnetic field H.

$$P_0 = \frac{R_s}{2} \int |H|^2 dS \quad (1)$$

Here R_s is a RF surface resistance of a wall material and is given by the inverse product of the electric conductivity σ and the skin depth δ in the normal conducting case.

$$R_s = \frac{1}{\sigma\delta} \quad (2)$$

For the room temperature Cu, R_s is 8.3 mΩ at 1 GHz.

On the other hand, R_s for the ideal superconductor is given by the following BCS surface resistance R_{BCS}.

$$R_{BCS} = A \frac{f^\alpha}{T} \exp\left(-\frac{\Delta}{kT}\right)$$

$$: T \leq \frac{T_c}{2} \quad \text{and} \quad hf << \Delta \quad , \quad (3)$$

where A : material constant, 2Δ : Energy gap,
Tc : critical temperature, k : Boltzman constant
and h : Planck constant .

The exponential part of Eq. (3) expresses the density of unpaired normal electrons.

Table I shows some material parameters of well investigated superconductors, where the maximum accelerating gradient Eacc,max is calculated by using the maximum RF magnetic field H_{sh} (T = 0°K) and the typical ratio of the peak surface magnetic field and the accelerating gradient, 45 Oe/MV/m, in the accelerating mode of ß = 1 structures.

Table I Parameters of RF superconductors

Material	Tc (°K)	Δ/kTc	A (f=1GHz)	α	H_{sh} (Oe) (T=0°K)	$E_{acc,max}$ (MV/m)
Pb	7.2	2.0	9.5×10^{-5}	1.75	1050	23
Nb	9.2	1.9	9.0×10^{-5}	1.9	2400	53
Nb_3Sn	18.2	2.2	9.4×10^{-5}	2	4000	90

In Fig. 1, R_{BCS} for these materials together with that for Cu and the best values for $YBa_2Cu_3O_{7-x}$ single crystal platelets are shown as a function of RF frequency.

In practice, however, R_s of the real superconducting cavity does not become zero but approaches asymptotically to some finite value

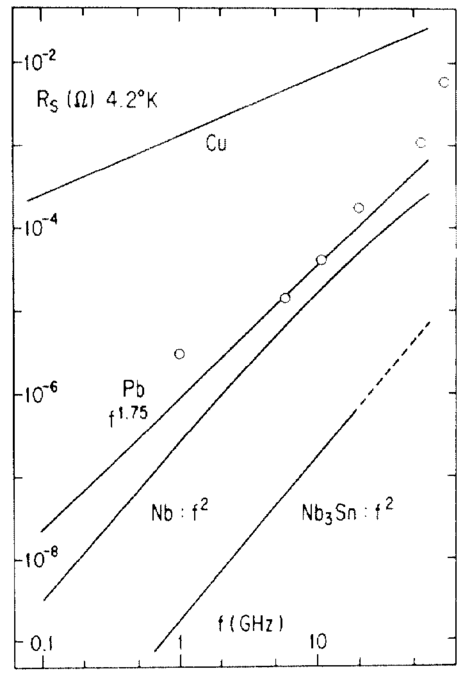

Fig. 1 R_{BCS} of well investigated superconductors, o: the best values of $YBa_2Cu_3O_{7-x}$.

R_{res} when the temperature is lowered. R_{res} is called the residual surface resistance and is considered to come from contaminations like chemical residues, dusts, impurities in the material, adsorbed gases and probably from grain boundary losses. Present-day typical ratio, R_{res}/R_{BCS}, is about 0.2 for Pb, 0.1 for Nb at most but for Nb_3Sn it sometimes exceeds 10.

Research for the application of superconducting cavities to accelerator started at Stanford university in the early 1960's. In 1965, they accelerated the first electron beam of about 1 μA by a 3-cell Pb plated disk loaded structure of 2.8 GHz.[1] The accelerating gradient was 5.5 MV/m with a Q_0 value of 1.5×10^7 at 2°K. After that, they got very excellent results with a 8.6 GHz cavity made from bulk Nb in 1970. Those were peak surface electric, magnetic field of 70 MV/m, 1080 Oe and Q_0 of 3×10^{10} at 1.2°K.[2]

The advantages of superconducting accelerating cavities, which come from small R_s, over normal conducting ones are

1. Only the beam RF power is needed, so the power efficiency is very high even if the cryogenic efficiency of 0.1 ~ 0.2 % is taken into consideration.
2. Higher order mode impedances or wakefields can be minimized by making cavity irises larger and smooth.

The first advantage is very attractive for low current accelerators, because neither high power RF sources nor high power couplers are necessary. Therefore, the application to these accelerators has been done very early stage. Stanford (HEPL) electron recyclotron[3] has started operation in 1974 and Argonne heavy-ion booster linac[4] in 1978. This field is still growing up and will be.

The second advantage is beneficial for the application to $e^\pm$ storage rings. In 1975, the first beam test of a 11-cell S-band Muffin Tin structure was successfully performed in the Cornell Electron Synchrotron.[5] From 1982, many groups performed beam tests of prototype cavities in the existing $e^\pm$ storage rings, where higher order mode damping, high RF power capability, dynamic frequency tuning system, controllability and reliability were studied. In 1988, TRISTAN prototype 5-cell cavities stored a single bunch beam of 69 mA and accelerated 25 mA with a field gradient of 5.7 MV/m.

In the meantime, the continued efforts have pushed up the cavity performance. As mentioned many times, the following improvements should be emphasized.

1) Elimination of electron multipacting by appropriate choice of cavity geometry.
2) Improvement of thermal stabilization by increasing the thermal conductivity of the cavity walls.
3) Reduction of electron field emission by advanced surface treatments and handling techniques.

In the following, the present status of the accelerator application,the fundamental researches and perspectives on the future are reviewed.

II. Recent progress

II.1 Low-velocity accelerating structures

These structures are mostly used in booster linacs for electrostatic accelerators. In early 1989, however, the tandem injector was replaced by a superconducting injector linac at Argonne. There are many advantages in these applications, even though the obtainable accelerating gradient is lower than that in structures for electrons because of complex geometry and higher surface peak electric field. Table II summarizes the structures under operation.

The other accelerators nearly complete or under construction are those of Kansas State University (10 Nb Split Ring), Daresbury (10 Pb-Cu Split Ring), JAERI (40 Nb Quarter Wave), Australian National University (40 Nb-Cu Quarter Wave), Legnaro (93 Pb-Cu Quarter Wave) and Munich (TRITRON).

Among them, TRITRON is not a linac but a separated orbit cyclotron, where both magnets and cavities are superconducting. The first PbSn plated cavity reached to 6.1 MV/m in an accelerating gradient with a Q value of 1.5×10^8.

The development of higher ß (0.1 ~ 0.5) structures for high current proton and deuteron acceleration is in progress and also the first test of an RFQ structure have been successfully performed at Argonne.[6]

II.2 Accelerating structures for electrons

Table III summarizes the operating and the major systems under construction. In addition, there are three systems under construction. At Frascati, a four 4-cell 500 MHz Nb cavity system (LISA) is nearly complete and will be used as an FEL driver. JAERI has started the construction of an FEL driver using two 5-cell KEK type cavities. Saclay is constructing a five 5-cell 1.5 GHz cavity system for the R&D on the next large nuclear physics accelerator.

These structures are classified into two categories, those used in linacs or recyclotrons for nuclear physics or FEL and those used in storage rings. In the former application, the typical average beam current is ~ 100 µA at present and higher RF frequencies are used. In the latter, however, beam currents of more than 10 mA require the developments of high RF input and heavy HOM damping couplers.

CEBAF, the largest superconducting RF accelerator, will give us many know-hows to construct a large system reliably, efficiently and economically.

II.3 Operating experiences at TRISTAN[7,8]

Construction of the superconducting RF system started in the spring of 1987. The first 16 cavities have been operated more than 6000 hours from Nov. of 1988 and the latter 16 cavities have been installed in the summer of 1989. Two cavities among the latter 16 cavities are not powered at present, because of low maximum accelerating gradient for one cavity from the beginning and too many fault rates for the other.

The system consists of 32 cavities in 16 cryostats, 8 – 1 MW klystrons with 32 circulators, a 6.5 kW helium refrigerator system and an RF control system. The RF control system is almost the same as used for the normal conducting system, however the following 3 modifications are needed and very helpful.

1) Fast quench detection system.
2) Tuning offset pattern generation for static Robinson instability.
3) RF recovering procedure under beam circulation.

Table II Low velocity structures for heavy ion accelerators

Laboratory	Material	Structure Type	Number	Velocity (ß)	Frequency	Operating Gradient	Commissioning
Argonne ATLAS	Nb	Split Ring	11	0.06	97 (MHz)	2 ~ 3 (MV/m)	1978
			22	0.10	97		
			9	0.16	145		
	Nb	4-Gap Interdigital	4	0.008~0.06	48~73	3.0~4.4	1989
Stony Brook SUNYLAC	Pb-Cu	Split Ring	16	0.055	150	2.0	1983
			24	0.10	150	2.5	
	Pb-Cu	Quarter Wave	16	0.055	150		1990
Saclay	Nb	λ/2 Helix	16	0.085	81	2.2	1987
		λ Helix	34	0.085	135	2.2	
University of Washington	Pb-Cu	Quarter Wave	24	0.10	150	2.5	1987
			12	0.21	150		
Florida State University	Nb	Split Ring	1	0.06	97	2.0	1987
			13	0.11	97		

Table III Superconducting cavities for electron accelerators * Design value, † Recirculation test is in progress

Laboratory	KEK	CERN	DESY	HEPL	DARMSTADT	CEBAF
Accelerator	TRISTAN	LEP	HERA	Recyclotron	Recyclotron	Recyclotron
Energy	32 GeV	64 GeV	33.5 GeV	130 MeV	130 MeV	4 GeV
Purpose	$e^{\pm}$ Collider	$e^{\pm}$ Collider	e^-p Collider	FEL Nucl. Phys.	FEL Nucl. Phys.	Nucl. Phys.
Accelerating Structure						
Material	Nb	Nb – Nb/Cu	Nb	Nb	Nb	Nb
Frequency	508 MHz	350 MHz	500 MHz	1.3 GHz	3 GHz	1.5 GHz
Operating Temperature	4.2°K	4.2°K	4.2°K	1.9°K	2°K	2°K
Number of Cells	5	4	4	1 – 3 – 6 m	5 – 20	5
Number of Structures	32	24 Nb – 8 Nb/Cu	16	1 – 1 – 5	1 – 10	360
Maximum Gradient (Fully Equipped)	9.4 MV/m	10 MV/m	8.5 MV/m	—	5.5 – 6.6 MV/m	15.3 MV/m
Operating Gradient	3 ~ 6 MV/m	4.4 MV/m	5*MV/m	2 ~ 3 MV/m	2 ~ 6.6 MV/m	5*MV/m
Commissioning	16 - Nov.,1988 16 - Oct.,1989	4 Nb - Mar.,1990 28 - End of 1991	End of 1990	1974	1989†	1994
Upgrade	—	+ 160, (1994)	+ 16	—	—	—

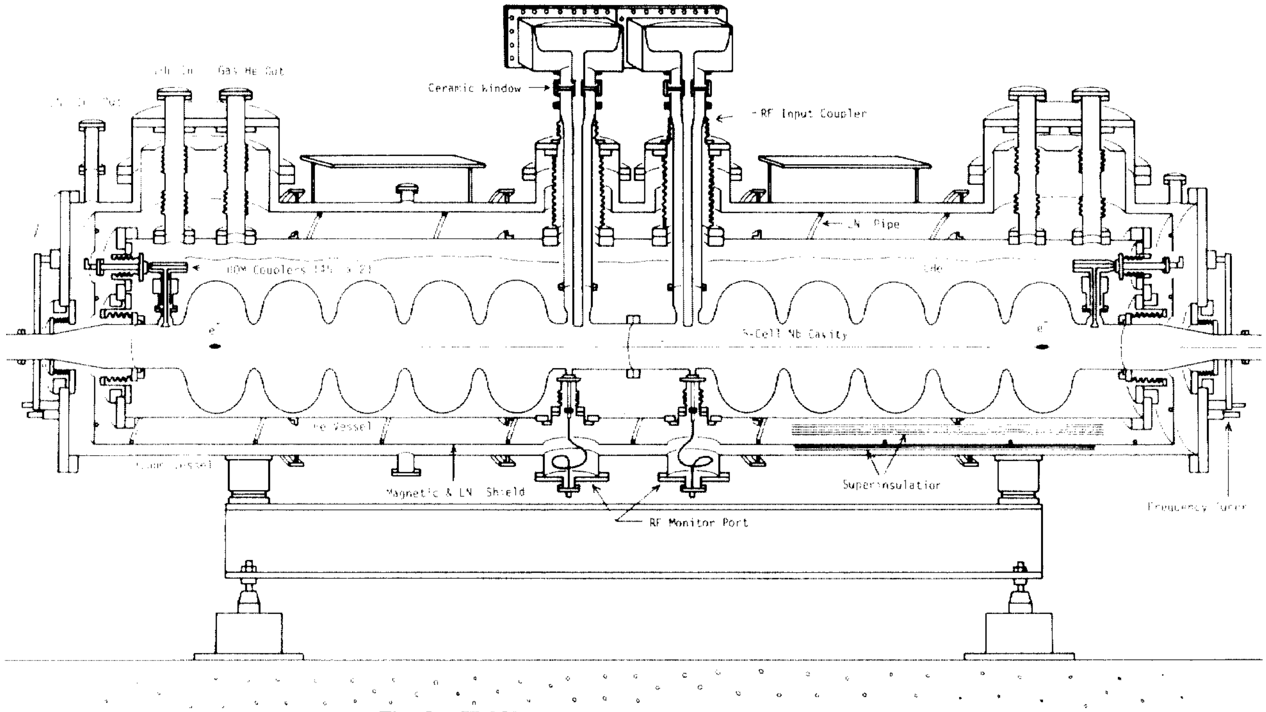

Fig. 2 TRISTAN superconducting cavities in a cryostat.

2) and 3) are necessary because the beam induced voltage is comparable to the generator voltage. Fig. 2 shows the TRISTAN superconducting cavities in a cryostat.

In the present physics run, which has begun at the midle of Feb., the beam energy has been lowered to 29 GeV from 32 GeV but the average beam current at the beginning of the experiment has been increased to 12.5 mA from 11 mA. Because of this current increase and the long accumulated beam time, the vacuum base pressure is getting worse, it becomes 2 ~ 5 x 10^{-9} Torr. Accordingly the fault rate looks to be increasing, which is about 2 times/physics run (120 min.) and about 60 % is concentrated on few cavities. Masks for synchrotron radiation are set on warm beam pipes of every bending magnet side of the cavities. However, the radiation from the final bending magnet can see directly three upstream beam pipes between cavities, where the radiation level is 1 ~ 10 kR/mA·h.

The performance of the cavities is measured routinely whenever it is possible. Fig. 3 shows the change of the average maximum gradient of cavities driven by one klystron. Except the following three cases, there are not definite degradation.

1) Two cavities in the same cryostat of group 10 B have degraded just after the beginning of operation and not recovered. These cavities show heavy field emissions and low Q values at relatively low field.
2) One of N_2 leaked cavities of 10 B to replace the melted N type ceramic connector for HOM extraction degraded, but after operation of about 100 days it recovered.
3) Recently two cavities of 10 D, both of which trip very frequently during acceleration, have degraded very much.

At present 30 superconducting cavities provide 160 MV and the maximum average operating gradient ever achieved is 4.7 MV/m.

Hardware failures experienced in the tunnel are followings.

1) 4 N type ceramic connectors were melted or burnt because of loose pin contacts. Two of them were due to excessive fundamental power by HOM coupler quench. These are the reason limiting the current below 13 mA. The replacement of connectors to new ones is scheduled in this autumn.
2) 3 ceramic windows of the input couplers leaked. One was cracked during cavity aging and contaminated two cavities in the same cryostat, which had to be replaced. The other two had no visible cracks.
3) 2 piezoelectric transducers were short-circuited probably because of radiation.
4) 1 liquid helium vessel leaked. So the vacuum vessel is continually evacuated.

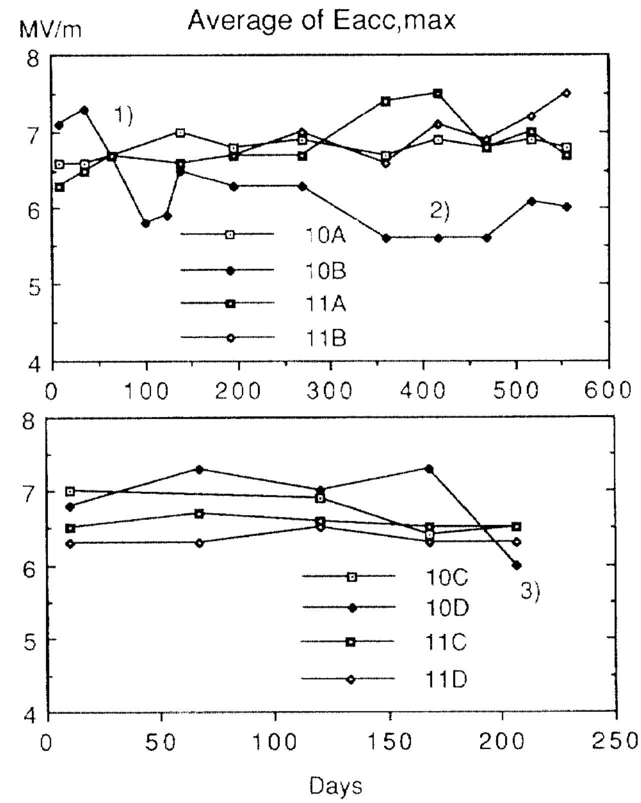

Fig. 3 Change of the maximum accelerating gradient in the ring.

The most distressed phenomenon is the fast quench of some cavities. The characteristics of this phenomenon are

1) It concentrates on some special cavities installed at the bending magnet side of the RF section in the last summer.
2) It occurs only when the beam is on, and looks to move one to another cavity in some cases when the operating condition like COD of the beam is changed.

3) In some cases, it is confirmed to be caused by the beam coming from the bending magnet side.
4) Cavity voltage becomes almost zero very rapidly within 10 µsec. In the usual thermal quench observed in the no-beam test, voltage does not become zero and the time constant is about 50 msec.
5) It is accompanied, more or less, with a gas burst.

It seems clear that this is a sparking triggered by something from the beam.

This phenomenon amounts to more than 70 % of the faults, and really one cavity where it occurs more than 5 times in one cycle is being unpowered, and other two cavities are caused during almost every acceleration periods.

II.4 Status of basic researches

Basic researches are being continued in two directions. One direction towards higher gradient is vigorously investigated at Cornell, Wuppertal and recently at Saclay, using L and S band cavities.

At present, the maximum field gradient is limited by thermal quench due to field emitted electrons. So in addition to further improvement in thermal conductivity,the nature of electron emitters should be investigated.

Cornell group has performed extensive study using a high speed temperature mapping system, under various surface treatment conditions. The results show that the emitter size is $10^{-7} \sim 10^{-11}$ cm^2 and the density of emitters is about $0.1/cm^2$ with their standard treatment. Vacuum heat treatment at 1350°C for more than 4 hours reduces the density by one order and also shifts the distribution of ß (field enhancement factor) to lower side by about factor 2. This shows that soft emitters which seem to be evaporated are chemical residues, which are not removed by successive rinsing after chemical polishing. Clean water (resistivity 18 MΩ·cm, filtered by 0.2 µm filters) and clean semiconductor grade methanol are proved not to bring emitters in cavities.

Recently they have gotten the peak surface electric field, Esp, of 60 MV/m and the peak magnetic surface field, Hsp, of 1500 Oe, which is the highest magnetic field ever achieved, with a single cell 1.5 GHz Nb cavity.[9] The distribution of the maximum accelerating gradient is shown in Fig. 4. They have also achieved Esp of 145 MV/m and Hsp of 1300 Oe with a "mushroom" shaped cavity at 5.8 GHz.

The effect of heat treatment has been confiremed also at Wuppertal. They have achieved Esp of 70 MV/m and Hsp of 1130 Oe without any detectable field emission with a single cell 3 GHz cavity. These efforts will be continued with a Nb of higher thermal conductivity and increased heat treatment temperature and will give better results.

The other way towards higher gradient might be a high power pulsed RF processing, which is in progress at Cornell (3 GHz) and Saclay (1.5 GHz).

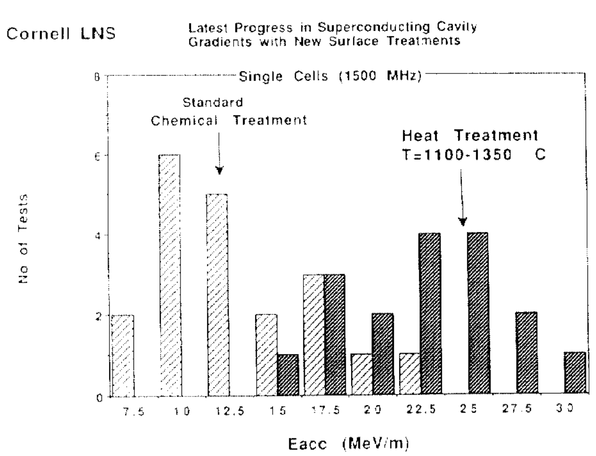

Fig. 4 Distribution of the maximum accelerating gradient.

The second direction is an application of higher Tc materials. Nb_3Sn has been extensively studied at Wuppertal over wide frequency range. In spite of the potential advantages, many difficulties in the forming process limit the achievable performance. The maximum accelerating gradient is typically 5 MV/m,with 10 MV/m as the best value at 3 GHz.

Development of NbN and NbTiN coatings is being pursued at CERN, Saclay and Frascati.

Ceramic superconductors are also investigated at many laboratories with verious forming techniques over wide frequency range[10]. However it is far from the application stage in accelerators, at the present state of preparation techniques and materials.

III. Future application of superconducting cavities

Recent improvements of the superconducting RF cavities and the successful application of them to TRISTAN, make it feasible to apply them to other kind of accelerators.

At Cornell, the development of the single cell cavity for the B-factory ring is in progress, where the main items are high power couplers (> 400 kW) and strong damping of higher order modes rather than the cavity itself. Design work on a crab cavity has also started.

At Los Alamos, the application to compact FELs and high current CW proton linacs has been proposed and the basic study is in progress. They have achieved 8 MV/m in the first test of a 3 GHz Nb cavity.

Nb sputtering technique on to Cu cavities has been established at CERN and two 4-cell LEP type cavities are being operated in SPS with an accelerating gradient of 5 MV/m.[11] This technique is promissing for the applications where medium accelerating gradients ($\lesssim$ 10 MV/m) are sufficient, and might be for higher gradients.

The biggest interest of our society is now moving on to the application in the future TeV $e^{\pm}$ linear collider. An international working group on a TeV Energy Superconducting Linear Accelerator (TESLA) has been organized and the first workshop will be held in July at Cornell.

In this application also, good power efficiency permits to operate superconducting cavities in the standing wave and rather long pulsed mode with RF power sources which are already available. There is no reason to use high frequency structures. Therefore, it is possible to accelerate many particles in one bunch and many bunches in an RF pulse with sufficiently long separation. Damping structures are not necessary, requirements to make a beam size small and the tolerance of the alignment are much relaxed.

Based on these considerations, the application of the superconducting cavities to a TeV linear collider was proposed already 14 years ago by Amaldi[12] and Lengeler[13]. At present, we have three design parameter sets including cost estimation.

Amalidi et al.[14] proposed a 2 x 1 TeV collider with a luminosity, L, of 1 x 10^{34}. The characteristics of this design are small beam size, $\sigma_{x,y}$ = 13 nm (R = 1), small number of particles per bunch, N = 6.5 x 10^8, high duty factor, D = 15 %, and large number of bunches, N_b x f_{rep} = 9.6 x 10^4. They also proposed an energy recovery scheme with different parameters.

On the other hand, Sundelin's parameters[15] for a 2 x 1 TeV collider with an L of 1 x 10^{33} are not far from the existing SLC parameters. These are $\sigma_{x,y}$ = 0.4 µm (R = 1), N = 5.5 x 10^{10}, D = 1 % and N_b x f_{rep} = 2070.

Cornell group examined the SLAC TLC parameters in an S band superconducting linac.[16] According to the computer simulation where the cavity HOM parameters are scaled from or measured values in the Cornell-CEBAF 5 cell 1.5 GHz cavities, more than 100 bunches with 3 x 10^{11} particles spaced 1 µsec apart can be accelerated with small emittance growth ($\lesssim$ 10 %) and energy spread ($\lesssim$ 10^{-5}). So there is enough room to increase the number of particles in a superconducting linac.

Table IV shows some examples of TESLA parameters together with those of JLC[17] and CLIC[18] for the comparison. As is seen in the Table, increased numbers of particles can increase beam sizes. Damping rings become large (L $\simeq$ 3 km) but requirements on the damping time and the ring emittance are relaxed. Repetition frequency should be low to keep the total AC power within an acceptable amount. If the number of damping rings is doubled, f_{rep} can be reduced to a half, which saves the total AC power by 25 %.

Table IV Examples of TESLA parameters * Drive SC LINAC

		TESLA 10	TESLA 20	TESLA 30	JLC	CLIC
Beam Energy	E (TeV)	2 x 0.5	2 x 0.5	2 x 0.5	2 x 0.5	2 x 1.0
R.M.S. Beam Height at IP	σ_y (nm)	10	20	30	1.4	12
Normalized Emittance	ε_y (x 10^{-7} rad·m)	2.0	4.3	5.7	0.3	10
Beta Function at IP	β_y (mm)	0.4	0.8	1.3	0.05	0.3
Aspect Ratio	R	150	85	60	167	5
R.M.S. Bunch Length	σ_z (μm)	350	600	800	76	200
Number of Particles per Bunch	N (x 10^{10})	10	13	15	1.0	0.5
Disruption Parameter	Dy	13.4	13.1	12.6	13.3	3.3
Beamstrahlung Parameter	$\bar{Y}$	0.17	0.11	0.09	0.49	0.71
Energy Loss by Beamstrahlung	δ	0.13	0.12	0.12	0.14	0.27
Repetition Frequency	f_{rep} (Hz)	8	9	8	200	1690
Number of Bunches per Pulse	N_b	100	100	120	10	1
Beam Power	P_b (MW)	12.8	18.7	24.0	3.2	2.7
Luminosity Enhancement	H_D	1.5	1.7	1.9	1.3	2.37
Luminosity	L (x 10^{33}/cm^2·sec)	6.4	6.1	6.1	6.2	1.1
Accelerating Frequency	f_{RF} (GHz)	1.3	1.3	1.3	11.4	29
Geometrical Factor	R/Q (Ω/m)	900	900	900	1.4 x 10^4	2.8 x 10^4
Accelerating Gradient	E_{acc} (MV/m)	30	30	30	100	80
Bunch Spacing	T_b (μsec)	3	4	5	1.4 x 10^{-3}	0.59
Peak RF Power	P_{RF} (MW/m)	0.160	0.156	0.144	120/0.7 m	38/0.25 m
RF Pulse Width	T_{RF} (msec)	1.36	1.49	1.80	1 x 10^{-4}	1.1 x 10^{-5}
Duty Factor	D (%)	1.09	1.34	1.42	2 x 10^{-3}	CW*
Number of Klystrons	N_{kly}	1000	1000	1000	3600	300*
Peak Power of Klystrons	P_{kly} (MW)	6	6	5.5	150	1*
Total AC Power for Klystrons	$P_{AC,kly}$ (MW)	116	140	139	120	140*
Q_0 of Accelerating Cavity	Q_0 (x 10^9)	8	8	8	—	10*
Cryogenic AC power for Cavity Loss	P_{cavity} (MW)	24.2	31.4	36.6	—	67*
Dumped Stored Energy Loss	P_d (MW)	25.5	29.4	28.3	—	0*
Cryogenic AC Power for Static Loss	P_{static} (MW)	35	35	35	—	3*
Total AC Power for Refrigerators	$P_{AC,Ref.}$ (MW)	84.7	95.8	99.9	—	70*

The overall AC power efficiency is assumed to be 50 % for RF and 0.1 % for cryogenic power. A choice of RF frequency is rather arbitrary, however, L band frequency is preferable because of lower impedances and probably from the view of construction cost.

So the many difficulties in the normal conducting case are reduced to one, that is, how to achieve higher gradient reliably and economically. As mentioned already, there are no fundamental limits for the surface peak electric field up to 140 MV/m and for that of magnetic field up to 1500 Oe under CW operation. With a present design of TESLA structures, these values correspond to accelerating gradients of 70 MV/m and 33 MV/m. Although these are demonstrated only in single cell cavities, continued efforts will push up the limit even in multi cell structures. Reliability and cost will be much improved by making a thoroughly controlled production line from material to the final assembly with an investment of several % of the total construction budget.

Acknowledgements

The author would like to thank his colleagues from many laboratories and universities for kindly supplying informations including unpublished recent results. He also would like to thank Professor Y. Kimura for introducing him to this work.

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