Application of Superconducting RF to Linear Colliders*

H. Padamsee

Laboratory of Nuclear Studies, Cornell University.

ABSTRACT

With successful operation of SRF systems in TRISTAN, LEP and DESY, the importance of SRF to high energy electron accelerators is growing rapidly. If gradients continue to improve and costs drop, there will be many compelling attractions to a fully superconducting TeV linear collider. These include a drastically low RF peak power and a low RF frequency that curtails wakefields and relaxes tolerances on alignment and jitter. The RF pulse length can be many thousand times longer than for copper cavities, allowing acceleration of several hundreds of bunches. Resulting conversion efficiencies as high as 20% from ac power to beam power are possible, in contrast to room temperature linac efficiencies of 1%. By making the most of this high efficiency, the final focus spot size can be relieved to 100 nm from the miniscule 3 nm for TLC. Both the energy spread and the beamstrahlung parameter can be substantially reduced, improving physics potential. With the long RF pulses, the bunches can be spaced very far apart so multibunch instabilities are avoidable even if Q's of higher modes are as high as 10^6. A Workshop on a TeV Energy Superconducting Linear Accelerator (TESLA) was held at Cornell last July. Parameter sets for 5 machines were generated, from 0.1 TeV to 1.5 TeV CM, including Z^0 and Top factories. Linear colliders have the advantage that the length can be extended periodically while using progressively higher gradients from 15 MeV/m to 40 MeV/m. The major challenges are to increase the gradients from 5 - 10 MeV/m possible today and to lower the costs. Recently, at 1.5 and 3 GHz, several labs have provided existence proofs for Eacc > 15 MeV/m in multi-cell structures. With specially developed heat treatment techniques to reduce field emission, 1-cell Nb cavities regularly reach fields corresponding to Eacc = 25 MeV/m. Many ideas were advanced at the workshop for lowering structure costs. These and other results of the TESLA workshop are presented.

INTRODUCTION

For the next linear collider of 500 GeV CM energy, the beam energy needs to be increased by a factor of 5 over the SLC, but the luminosity needs to be increased by 5 orders of magnitude ! A technological approach, like superconducting RF (SRF), which relieves many of the difficult challenges of high luminosity must then be taken very seriously, even though the potential gradients are not as high as normal conducting (NC) RF. By virtue of the high efficiency of conversion of wall plug power to beam power in an SRF linac, a tractable approach to high luminosity is offered through use of high beam power rather than through a miniscule spot size at the collision point. Ensuing benefits discussed below can be considerable. It is true that an SRF linac could be 4 times longer than a NC machine, but the cost impact of this deficiency may be more than compensated by the 3 orders of magnitude decrease in the peak RF power demand of the high Q SRF linac. At the same time there is an outstanding issue of whether a NC linac can be operated at high gradients (100 MV/m) in the presence of the enormous field emission (dark) currents.

PAST PARAMETER PHILOSOPHIES FOR SRF LINEAR COLLIDERS

In the past, several different approaches have been used. For the 1987 PAC, Sundelin [1] adopted round beams with SLC-like parameters for the source and final focus, with the rationale that as these parameters were already demonstrated, no protracted developmental efforts on these fronts would be necessary. With a beam power of 36 MWatts, and a final focus spot size 400 nm, the design luminosity was 10^{33} in cgs units at 2 TeV CM.

At about the same time, Amaldi et al [2] parametrized a 2 TeV machine with higher luminosity (10^{34}) and lower beam power (20 MWatts) by supposing that the round beams have an order of magnitude smaller emittance than the SLC, and that β^*y is reduced 10 fold over the SLC. The resulting final focus spot size was 12 nm.

At the 1989 PAC, Rubin et al [3] adopted all the advances in source and final focus that a normal conducting TLC [4] would count on, such as flat beams with aspect ratio 100, final vertical spot size 2.2 nm, source emittance 0.05 µm, β^*y 0.1 mm and a very short bunch length 70 µm. With a beam power of 8 MWatts, a 1 TeV CM machine with $L=8\times10^{33}$ was parametrized by substituting a low frequency (3 GHz) SRF linac for the high frequency, high gradient normal conducting linac.

In all these superconducting approaches, it was recognized that even for Q values of 10^{10}, the RF must necessarily be pulsed to keep the refrigerator associated capital cost and operating cost of such machines affordable. Although pulsed, a high duty factor (few %) retains many of the inherent advantages of the superconducting approach as discussed below.

TESLA WORKSHOP

In July 1990, a 4-day workshop on a TeV Energy Superconducting Linear Accelerator (TESLA) was held at

*Suported by the National Science Foundation with supplementary support for the US-Japan Collaboration

Cornell [5]. The purpose of the meeting was to work on an improved parameter list and accelerator physics issues, explore ideas on improving gradients and on developing structures/cryostats suitable for TESLA, review costs, advance ideas for cost reduction and arrange collaborations for work on TESLA issues. About 70 scientists participated from the laboratories of Argonne, BNL, CEBAF, CERN, Cornell, Darmstadt, DESY, Fermilab, IHEP Protvino, INFN Frascatti, Genova, Milano, KEK, Lawrence Livermore, Los Alamos, Saclay, SLAC, Stony-Brook and Wuppertal.

A staged approach for TESLA, suggested by U. Amaldi [6] was adopted (Table 1). Linear colliders have the advantage that, if a suitable site is selected, the length and gradients can be extended periodically. For superconducting machines, there is no need to change RF frequency as the energy is increased. However the starting energy is a function of physics interest and of progress in developing higher gradients in SRF cavities. The lowest energy considered was for a Z^0 factory with luminosity 10x peak LEP, to be followed by a Top factory. Resolution of the mass difference of the excited states of the toponium system, requires that the energy spread from beamstrahlung be less than 1 GeV. For such an application, use of SRF is imperative since a comparable machine built with NC RF would use prohibitively higher AC power. Important physics issues can be addressed along the way to TeV energies. A W factory (200 GeV CM) could also be included as part of the staging.

Table 1: Possible TESLA machines depending on High Energy Physics Interest.

CM Energy	Lum	Length	Gradient	Beamstrahlung
GeV	10^{33} c.g.s	km	(MeV/m)	δ
100	2.6	6.6	15	.006
300	1.8	15	20	.003
500	2	20	25	.006
1000	5.1	33.4	30	.09
1500	10	37.6	40	.62

In addition to the machines parametrized in Table 1, two novel concepts for application of SRF linacs were presented. In one, an alternate Top factory design was suggested using recirculating arcs to effectively double the gradient of SRF cavities. In this case presently achievable gradients of 10 MeV/m are already useful, if costs can be reduced. This idea is presented fully in another paper at this conference [7]. The second idea was for a 300 GeV superconducting electron linac to collide with 1 TeV HERA protons. Given the limits on achievable stored proton beam density, the needed luminosity for e-p physics can only be met with the high beam power allowed by an SRF linac. This concept is also presented in another paper at this conference[8].

For the e^+e^- linear colliders, the parameter philosophy followed was to attempt the desired lumnosities by taking advantage of the high beam power offered by an SRF linac by virtue of its higher efficiency. Focussing beams to very small sizes becomes unnecessary. Thus it was possible to relieve the final focus spot size from < 5 nm typical for NC designs to 100 nm, using a vertical emittances of 10^{-6} m instead of 10^{-8} m and final focus β^*_y of 5 mm instead of 0.1 mm. The benefits resulting from this approach are detailed in the next section along with the many attractive features of the superconducting linear collider.

ATTRACTIVE FEATURES OF TESLA

Table 2 reveals the promise of the superconducting approach by comparing some of the parameters for a superconducting and normal conducting machine[9], each with 0.5 TeV CM energy and L = 2×10^{33} in cgs units.

Table 2: Comparison between Normal and Superconducting Linear Colliders at 0.5 TeV CM, Luminosity = 2×10^{33}

	Units	Super	Normal
Gradient	MV/m	25	100
Active Length	km	20	5
Particles/bunch	10^{10}	4.2	2.41
No. of Bunches/ Pulse		800	10
Beam Power	MW	27	2.5
Q0		5×10^9	10^4
Beam/Wall Plug Eff.	%	21	3.6
Vertical Emittance	µm	1	0.038
Aspect ratio		10	109
Bunch length	µm	2000	110
Final focus ß*y	mm	5	0.13
Vertical beam size	nm	100	4
Beamstr. energy spread	%	0.6	7
Beamstr. parameter		0.016	0.17
Total Peak RF Power	GW	3.4	1200
Peak RF Power/m	MW/m	0.168	240
RF Frequency	GHz	1.5	11.5
Vertical alignment tol.	µm	53*	34
Vertical vibration tol.	µm	0.3	0.027
RF Pulse length	µsec	1370	0.082
Bunch separation	m	300	2.5
Q HOM		10^6	<20

*Without any BNS Damping

<u>Beam Parameters and Physics Potential</u> By virtue of the large vertical beam size, the TESLA parameters provide an order of magnitude smaller beamstrahlung induced energy spread, improving the physics potential. The beamstrahlung parameter is also an order of magnitude lower, drastically reducing backgrounds from e+e- pairs generated by beamstrahlung photons. Chosen beam parameters make it easier to generate, accelerate and bring beams into collision. Vertical source emittance is relaxed by almost two orders of magnitude. A large bunch length eliminates the need for

bunch compression. The smaller aspect ratio reduces coupling between the horizontal and vertical planes which can dilute emittance. Final focus quadrupoles have large apertures, so dumping of higher beam powers will be possible.

Peak RF power Because wall losses are so low, SRF cavities can be filled slowly, drastically reducing the peak RF power demand over a copper linac, for eg from 240 Mwatts/meter to 170 Kwatts/meter in the above comparison. 100-200 kWatt klystrons are readily available, eliminating the significant challenge of developing new sources.

Lower RF frequency The need for higher efficiency in normal conducting linacs drives up the RF frequency, making the wakefield effects very serious, and the number of feed points per meter very large. SRF cavites can store energy efficiently, allowing the use of low RF frequency (1.3 - 3 GHz). At these frequencies, and large apertures, transverse wakefield effects are substantially reduced, relaxing requirements on alignment tolerances and jitter. With reduced longitudinal wakefields, the energy spread after acceleration is smaller, so that the energy bandwidth of the final focus can be made narrower.

RF Pulse Length and Bunch Spacing Because SRF cavities can store energy efficiently, the RF pulse length can be many thousand times longer than for NC cavities. A large number (several hundred) of bunches can then be spaced far apart from each other (> 300 m) eliminating the possibility of wrong bunches running into each other at the collision point. With the large bunch spacing and the lower wakefields, the damping requirements on the higher modes are considerably relaxed. To avoid multibunch instabilities, copper cavities require very heavy damping (QL < 20) because of the close spacing (3 meters) of the bunches within the very short rf pulse length. With such a close spacing, many bunches are present at the same time in the interaction region, making angle crossing with crabbing complications necessary.

TESLA PARAMETERS

In Table 3 we present selected TESLA workshop parameter sets for the Top Factory, the 0.5 TeV and 1 TeV machines [10]. These design exercises, which emerged from the parameters working group give encouraging scenarios for use of SRF in linear colliders. However, they are not yet optimized for capital and operating cost, the work of future meetings. Nearly all parameters are identical to those chosen at the workshop with the exception that the number of bunches is increased from 400 to 800 and the bunch separation is reduced to 1 - 2 μsec. It is possible in principle to use a ring of the size of HERA to fit 800 bunches spaced 7 meters apart to allow sufficient separation for kicker operation. Because of the tighter bunch spacing, the peak power demand is increased over the 50 kWatts/m used at the TESLA workshop, but the refrigerator load is decreased. Additional RF dissipation during the fill and decay of the cavity is included. Possible klystrons have been selected from available units. For longitudinal and transverse wakefields needed to estimate the tolerances and the wakefield induced energy spread, BCI calculations were carried out for a single cell 1.5 GHz cavity. The HOM power estimated from these results is higher than used at the workshop. Alignment and jitter tolerances were estimated following the procedures outlined in [11].

An important advantage of the TESLA strategy is that if one desires higher luminosity out any of these designs, then the vertical beam size can be squeezed further as confidence in operating final focus systems grows with tests envisioned[6]. To illustrate this point, the last column of Table 3 presents one additional parameter exercise for the 0.5 TeV CM case, where a vertical size of 50 nm is chosen to increase the luminosity by a factor of 4 to 7.7×10^{34} in cgs units.

CHALLENGES FOR TESLA

Whereas the capital cost of NC machines is likely to be dominated by the RF sources, that of TESLA will be dominated by the structure. ie the cavities and cryostats. Hence the major challenges are to increase the gradients from today's levels of 5-10 MeV/m and to lower the costs.

Lowering the Structure Costs A significant cost benefit in both cavities and cryostats will be realized if the number of cells per structure can be increased. This would help reduce the number of couplers, the number of ends and costly cryostat penetrations. A key issue is whether the damping needed to avoid multibunch instabilities can be achieved if the number of couplers per meter is reduced. Several simulations have been completed[3,12] and a number are in progress[13]. Prelimnary results suggest that for a bunch population of 4×10^{10} and separation of 1 μsec, both emittance growth from transverse wakes as well as beam energy width (bunch to bunch energy spread) from longitudinal wakes appear tolerable for QL of 10^6. Here the fundamental RF frequency is 1.5 GHz and the HOM mode frequency spread of 10^{-4} is assumed. For storage rings and recirculating linac SRF cavities, HOM couplers placed on the beam pipe past the end cell have been perfected to lower the QL of 5 cell cavities to 10^4. Based on new computational tools to predict QL of such couplers, the expectation is that QL values of 10^6 can be provided for 10 cell cavities with similar couplers[14].

Substantial progress has been registered in reducing cavity fabrication costs. The wall thickness of 1.5 GHz cavities is reduced by a factor of 2. Machined steps are eliminated at cavity weld joints, and parameters developed to allow multiple welds to be performed in one pump out of the weld chamber. Compact designs of coaxial HOM couplers are available[15]. Polarized cells have been developed to orient deflecting modes so that a single HOM coupler can do the job of two by damping both polarizations. Cavities have been built and tested to show that no multipacting occurs from the polarizing shape distortions[16]. After careful cost accounting during making of several multicell, Nb cavities with the above features, it is shown possible to keep the cost of the cavity, without coupling ports, to below 10,000 $/m[14].

An economical cryostat design was worked out at the TESLA workshop to place 20 one meter cavities into a 28 meter long cryostat, improving the packing fraction to 0.71 and bringing the static heat loss to < 1 watt/m [17].

Increasing the Gradients The state of the art for gradients is shown in Fig. 1. Achieved gradients in more than 100 structures (>90 meters) average 9 MeV/m. Key aspects responsible for this outstanding performance are the antimultipactor cell shape, high thermal conductivity Nb and clean surface preparation.

The best structure tests from 5 different labs reached gradients of 15 - 18 MeV/m. (Fig.2) These results can be considered as independent existence proofs that SRF technology can provide the gradients and Q's needed. That one can reach 18 MV/m shows that with better understanding and improvements, the standard preparation techniques may in the future approach the desired performance.

Field emission is recognized to be the main obstacle towards reliably achieving 20 MeV/m or above. Besides efforts to reduce emission by improving current practice, new approaches based on heat treatment[18] and pulsed high peak power processing[19] are beginning to show promise. These are discussed more fully in other papers at this conference.

With heat treatment at 1400 - 1500 C, 1.5 GHz single cells now reach an average surface field of 50 MV/m at Q values above 10^9, with 60 MV/m as the best value. With the new heat treatment at Wuppertal, 3 GHz single cells have reached Esp = 70 MV/m[20]. Tests on multicell cavities at both frequencies have started. Initial results are presented in Fig. 3 and in other papers at this conference [14,21].

With RF power between 3 and 50 kWatts, and pulses up to 0.5 msec , maximum surface field values were increased from Epk = 40 MV/m to Epk = 55 MV/m in single cell cavities. Tests on multicell cavities have also started. In a 9-cell, 3 GHz structure, pulsed processing was used to mitigate field emission from Eacc= 10 MeV/m ($Q = 2x10^9$) to Eacc = 15 MeV/m ($Q = 5x10^9$), also shown in Fig. 3.

CONCLUSIONS

An SRF linear collider offers multiple relief from the many pressing challenges of the high gradient, high frequency normal conducting approach. Progress in SRF technology continues. Gradients are improving and costs are coming down. The time is ripe to place increased effort into the SRF approach, as the ensuing benefits to physics at the high energy frontier are likely to be considerable.

REFERENCES

[1] R. Sundelin, Proc. of the 1987 PAC,p. 68 (1987)
[2] U. Amaldi et al, CERN/EF 86-8 (1986)
[3] D. Rubin et al, Proc. of the 1989 PAC, p. 721 (1989)
[4] R. Palmer, SLAC-PUB-4707 (1988)
[5] Proc. of the 1st TESLA Workshop, Cornell U, Ithaca, NY, CLNS 90-1029 (1990), ed. H. Padamsee.
[6] U. Amaldi in refs [5], addendum (1990)
[7] J. Rosenzweig, this conference
[8] M. Tigner et al, this conference.
[9] R. Palmer, SLAC-PUB-5195 (1990)
[10] J. Rosenszweig in refs [5], p. 180.
[11] D. Rubin et al, in refs. 5, p. 267.
[12] K. Thompson, in refs. 5, p.
[13] G. Krafft, this conference.
[14] J. Kirchgessner et al, this conference.
[15] A. Mosnier, Proc. of the KEK SRF Workshop, ed. Y. Kojima
[16] J. Kirhcgessner et al, Proc. of the 1989 PAC, p. 479 (1989)
[17] D. Proch et al in refs 5., p. 605.
[18] H. Padamsee et al, this conference.
[19] J. Graber et al, this conference.
[20] R. W. Roth et al, Proc. of the 1990 EPAC Conf., Nice, France
[21] R. W. Roth et al, this conference.

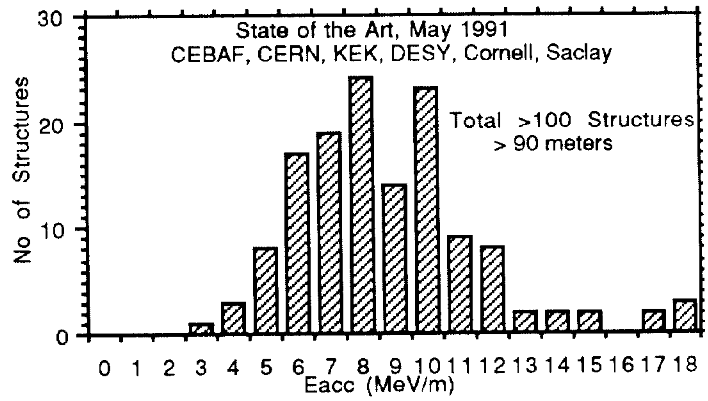

Fig. 1: State of the art in accelerating gradient

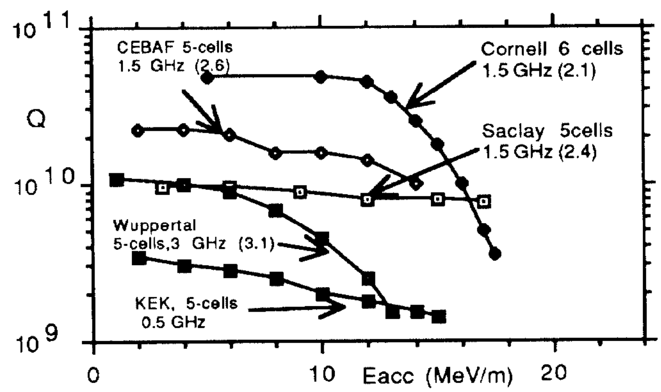

Fig. 2: Performance of the best structures of Fig. 1.. Numbers in parenthesis indicate Epk/Eacc for each cavity.

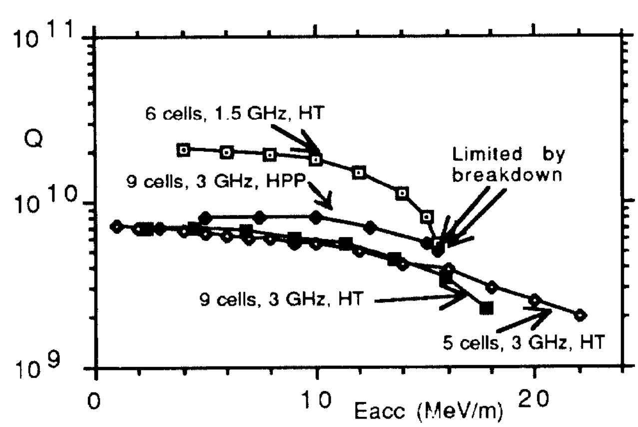

Fig. 3: All structures tested after high temperature firing (HT)) or pulsed RF high power processing (HPP).

Table 3: Parameters for example superconducting linear colliders.

Injection Energy = 3 GeV, No. of Bunches = 800, RF Frequency = 1.5 GHz, $Q_0 = 5x10^9$, Refrigerator Efficiency = 0.00137, Klystron Efficiency = 0.065, RF cell aperture = 4 cm

	Units	Top Factory	0.5 TeV CM	1 TeV CM	0.5 TeV CM High Lum.
General					
CM Energy	GeV	300	500	1000	500
Luminosity	10^33/cm^2sec^1	1.52	2	7.4	7.7
Length	km	15	20	33.3	20
Collision freq	kHz	8	8	3.5	8
Beam Power	MWatts	14.6	26.9	33.6	26.9
Source					
Particles/bunch	10^10	3.8	4.2	6	4.2
Bunch length	mm	2	2	1.1	0.8
Emittance x,y	μm-rad	30,1	25,1	30, 1	30, 1
Final Focus					
ß* x,y	mm	9.79, 2.93	19.5,5	8.16, 2.4	4, 1.2
sigma x,y	nm	1000, 100	1000, 100	500, 50	500,50
Dx,y		1.3, 13.3	0.88,8.7	1.38, 14	1.43,14.3
HD		1.65	1.79	1.83	1.68
δ	%	0.3	0.6	9.85	4.3
Υ		0.01	0.016	0.2	0.1
Linac					
Av Beam Current	μ A	49	54	33.6	54
Pk Beam Current	mA	6.08	6.72	4.8	6.72
Acc. Gradient	MV/m	20	25	30	25
QL	x10^6	3.43	3.9	6.5	3.88
Bandwidth	Hz	438	387	230	387
Rep Rate	Hz	10	10	4.38	10
Duty cycle	%	0.8	0.8	0.7	0.8
Eff. Duty Cycle		1.4	1.47	1.2	1.47
Beam on time	μsec	800	800	1600	800
RF on time	μsec	1300	1370	2560	1370
Filling time	μsec	364	411	690	411
Bunch spacing	μsec	1	1	2	1
Stored energy/L	Joules/m	44.2	69	99.5	69
Peak RF power/L	kWatts/m	122	168	144	168
Total RF power	MWatts	1824	3360	4800	3360
Ave. RF power	MWatts	23.8	46	53.7	46
Klystron	MWatts	3.2	3.1	2.17	3.1
No. of Klystrons	MWatts	568	1077	2206	1077
Refrigerator Load	kWatt	43.9	77	161	105
Static heat leak	Watts/m	1	1	1	1
RF dissip. in He	Watts/m	1.16	1.92	2.2	1.92
HOM diss. in He	Watts/m	0.76	0.93	1.6	2.32
AC Power	MWatts	69	127	199	147
AC- RF power	MWatts	36.6	70.8	82.6	70.8
AC-Refrig. power	MWatts	31.9	56	117	76.3
Overall Efficiency	%	21.3	21.1	17	18.3
Wakes, align., vibrations					
k ll - total	V/pC/m	7.42	7.42	12.03	15.1
k- hom	V/pC/m	5.15	5.15	9.8	12.87
ktransv.	V/pC/m^2	27.9	27.9	15.3	11.2
∂E/E- wake	%	0.45	0.45	0.77	0.81
Vert. align. tol	μm	75	53	135	834
Vert. vib tol.	μm	0.42	0.3	0.23	0.7