Review of the Superconducting Approach to Linear Colliders*

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ABSTRACT

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 ! The superconducting (SRF) approach offers multiple relief from the many pressing challenges of achieving high luminosity. Collision energy spread and backgrounds can be reduced over normal conducting approaches. Because wall losses are low, SRF cavities can be filled slowly, drastically reducing the RF power demand. Presently available klystrons can be used. These and other attractive features of the SRF approach are discussed.

The major challenges for the SRF approach are to raise the gradients well above 5 MV/m possible today and at the same time to lower the costs. Progress in SRF technology on these fronts is presented.

Since the last EPAC, two international workshops[1,2] and several smaller meetings have been held to discuss issues connected with a TeV Energy Superconducting Linear Accelerator (TESLA). A collaborative venture on a TESLA TEST FACILITY is now taking shape. These activities are summarized.

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

INTRODUCTION

To expand the energy frontier of e^+e^- colliders beyond LEP II (200 GeV CM), a linear collider with CM energy > 0.5 TeV and Luminosity > 2.5×10^{33} is considered as the most desirable next step. To be affordable such a machine should have a capital cost substantially less than the SSC and operating power significantly less than 200 MWatt. Investment of this order would become further atractive if the machine could be scaled down in energy to run as a Z^0, W or Top Factory. The chosen approach should allow a future upgrade to 1 TeV in the center of mass. In these cases the luminosity for doing useful physics should scale as $10^{34}E(\mathrm{TeV})^2$ in cgs units.

The SRF approach to future linear colliders fights the main enemies of high luminosity, the short- and long-range wakefields, by permitting the use of a long RF wavelength and a long RF pulse length. By virtue of the high efficiency of conversion of wall plug power to beam power in an SRF linac, the approach to high luminosity is offered through use of high beam power, rather than through a miniscule spot size at the collision point, as is the case for the high frequency high gradient approaches. Ensuing physics benefits in the form of reduced beamstrahlung induced background and energy spreads are considerable.

It is true that an SRF linac could end up being several times longer than a high frequency 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 high frequency NC linac can be operated at the high gradients (100 MV/m) envisaged in the presence of the enormous field emission (dark) currents.

PARAMETER PHILOSOPHY FOR SRF LINEAR COLLIDERS

In the past, several different parameter philosophies have been used by Sundelin et al[3], Amaldi et al[4], Rubin et al[5]. In all the superconducting approaches, it is 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, the duty factor (~1 %) is still very high compared to proposed NC machines, so that many of the inherent advantages of the superconducting approach are retained.

The currently favored strategy (proposed by B. Wiik, DESY) is to optimize the design parameters for a highest possible luminosity 500 GeV CM machine, which could concevably be built when gradients of 25 MV/m are within reach. Using the same source and final focus systems, i.e the same emittances and final β^*s, the same machine could be operated at lower gradients in the Z^0, W and Top Factory modes, with parameters that meet the special requirements for each factory. The Z^0 factory should have a design luminosity of 10 x peak LEP. Resolution of the mass difference of the excited states of the toponium system, requires that the energy spread from beamstrahlung in a Top Factory be less than 1 GeV, and preferably smaller[6]. As gradients of 30 MV/m become available in the future, upgrades to 1 TeV CM can be envisioned.

A general parameter program[7] was developed based on equations given in [8], and design exercises were carried out guided by the above criteria. The main parameters for TESLA machines emerging from this strategy are presented in Table 1 More detailed parameters for each case are available[7]. Note that the luminosity for TESLA 500 is 5×10^{33} cgs units, which when lowered to the baseline (2.5×10^{33}) by lowering the rep rate, also lowers the AC operating power to 76 MWatts.

ATTRACTIVE FEATURES OF TESLA

Table 1: Main Parameters for TESLA machines

	Unit	Z	W	Top	Tesla	Tesla
		Fact.	Fact.	Fact.	500	1000
CM Energy	GeV	100	200	250	500	1000
Luminosity	10^{33} cgs	3.1	5.1	1.64	5*	10
Collision Energy Spread	%	0.1	0.5	0.16	3	12
AC Power	MW	94	129	133	137*	170
Emittance x,y	μm-rad	20,1	20,1	20,1	20,1	20,1
Final Focus beta x,y	mm	10,5	10,5	10,5	10,5	8,2.5
Beam size vertical	nm	226	160	143	101	50
Gradient	MV/m	14	15	15	25	30
Active Length	km	7.2	13.4	16.6	20	33.4
Bunch Separation	μsec	0.7	1	0.4	1	1
Vert. Align. Tol (Quads)	mm	> 1	0.43	0.78	0.3	0.13
Vert. Vibr. Tol. (Quads)	μm	>1	0.5	0.8	0.3	0.2

* For a Luminosity of 2.6 x 10^{33}, AC Power is reduced to 76 MWatts by reducing the rep rate to 4 kHz.

Table 2 reveals the promise of the superconducting approach by comparing some of the parameters for superconducting and normal conducting machines[9,10], each with 0.5 TeV CM energy and L ~ $2\mathrm{x}10^{33}$ in cgs units.

Beam Parameters and Physics Potential

By virtue of the higher linac efficiency (>20%) offered by the TESLA approach, the desired luminosity is envisaged with a high beam power rather than a small spot size at the interaction point. This relieves the requirements on source and final focus systems. Chosen beam parameters make it easier to generate, accelerate and bring beams into collision.

Thus it is possible to relieve the final focus spot size to 100 nm instead of 4 nm (NLC), using a vertical emittances of 10^{-6} m instead of 10^{-8} m (NLC), and final focus β^*y of 5 mm instead of 0.2 mm (NLC). The relatively large value of β^* and the long RF wavlength (23 cm) make it possible to accept rather long bunches (mm). Consequently, a smaller beamstrahlung induced energy spread and lower backgrounds greatly improves the physics potential.

Peak RF power

Because wall losses are so low, SRF cavities can be filled slowly, drastically reducing the peak RF power demand over the copper linacs from 10-100 MWatts/m to 200 kWatts/m. Presently available klystrons can be used, eliminating the major challenge of developing powerful new sources.

Table 3: Comparison between Normal and Superconducting Versions at 0.5 TeV CM, Luminosity~ $2\mathrm{x}10^{33}$ cgs units.

Parameter	Units	Supercon	Normal--	-->
		TESLA 500	DESY/ THD	NLC /JLC.
Linac Parameters				
RF Frequency	GHz	1.3	3	11.4
Gradient	MV/m	25	17	50
Active Length	km	20	30	10
Peak RF Power/m	Mwatts/ m	0.206	12	60
AC Power	Mwatts	76	110	70
Beam Power	MWatts	16.4	14.4	1.3
Linac Efficiency	%	22	13	1.8
No. of Bunches/ RF pulse		800	172	10
Beam on time/ RF pulse	μsec	800	2	0.08
Bunch separation	m	300	3.2	2.5
Quad Align. Tol	μm	300		70
Quad Vibr. Tol	μm	0.3	0.1	
Beam Parameters				
Luminosity	10^{33} cgs	2.6	2.2	2
Coll. Energy Spread	%	3	6	7.8
Beamstr. Parameter		0.07	0.13	0.18
No. of Incoh. Pairs*		182	5676	720
Vert spot size	nm	101	40	4
Spot size Aspect Ratio		6.3	8	45
Vertical β^*y	mm	5	0.8	0.22
β^*y/β^*x		2	6.3	20
Emittance y	μm-rad	1	1	0.02
Emittance aspect ratio		20	10	100
Bunch length	mm	1	0.5	0.105

Lower RF frequency and Lower Wakefields

Frequency scaling laws for achievable gradient, peak power and AC power for a NC collider push frequencies up. On the other hand, higher frequencies present severe disadvantages : transverse wakefields increase as f^3, longitudinal wakefields increase as f^2, the number of RF feed points increase as f and the RF pulse length decreases as $f^{1.5}$.

SRF cavites can store energy efficiently, allowing the use of low RF frequency. For TESLA the RF frequency chosen is

1.3 GHz. At these frequencies and large apertures (3.3 cm), transverse wakefield effects are substantially reduced, relaxing requirements on quadrupole alignment tolerances to several 100 μm and jitter to a small fraction of the beam size. With reduced longitudinal wakefields, the energy spread after acceleration is smaller ($5x10^{-4}$ for TESLA 500[11]), 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 ~ msec, many thousand times longer than for NC cavities. A large number (800) of bunches can then be spaced far apart from each other (> 300 m), reducing the long range wakefield effects. When combined together with the reduced wakefields from the large structure aperture, the damping requirements on the higher modes to avoid multibunch instabilities are considerably relaxed. Required Q values (~ 10^5) can be achieved with higher mode couplers similar to those presently used in storage rings SRF cavities. The large bunch separation (300 m) eliminates the possibility of wrong bunches running into each other at the collision point. At the close spacing of 3 m typical of NC machines, many bunches are present at the same time in the interaction region, making angle crossing with crabbing complications necessary. For TESLA, 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.

Several simulations analyzing multibunch stability have been completed[1,2] and a number are in progress. Prelimnary results suggest that for a bunch population of $5x10^{10}$ 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 ~ 10^5 - 10^6. A 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 computational tools to predict QL of such couplers, the expectation is that QL values of 10^5 can be provided for 9 cell cavities with similar couplers[1,2].

CHALLENGES FOR TESLA

The major challenges are to increase the gradients from today's levels of 5-10 MV/m to 20 - 30 MV/m, and to lower the costs to below $50,000/m.

Lowering the Structure Costs

Significant cost benefits to both cavities and cryostats will be realized if the number of cells per structure is doubled over the customary 4-5 cells used today. This helps reduce the number of couplers, the number of ends and costly cryostat penetrations.

Substantial progress has been registered in reducing cavity fabrication costs. In a cost cutting effort, four 9-cell 3 GHz and two 6-cell 1.5 GHz cavities have been fabricated using the simplest possible methods for forming, machining and electron beam welding. Careful records were kept of the all the stages of fabrication, tuning, and chemical etching. For the cavities alone (couplers excluded) it was possible to keep the cost below $10,000 /m[12]. This is a big step towards approaching the TESLA goal. Compact designs of coaxial HOM couplers are available[13].

For SRF systems in use today, a significant fraction of the linear cost resides in the cryostat and the helium distribution network, arising fom the high degree of complexity in both longitudinal and radial directions. For example there are cold-warm transitions every few meters, many penetrations per cavity, complex liquid helium and gaseous helium circuitry external and internal to the cryostat and many fixed points to room temperature, creating axial and radial stresses from thermal contractions. An economical cryostat design was worked out at the TESLA workshops to place 8 one meter cavities into a ~ 10 meter long cryostat, improving the packing fraction from 0.5 (typical of existing cryostats) to ~ 0.75, and bringing the static heat loss from 5 watts/m typical today to < 1 watt/m. Liquid helium distribution and cold gas recovery lines are incorporated in the cryostat design to yield additional savings.

When put together with economies of scale an overall cost reduction factor of 5 from presently quoted values can eventually be expected from these cost saving improvements.

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 MV/m. Key aspects responsible for this outstanding performance are the antimultipactor cell shape, high thermal conductivity Nb and clean surface preparation. Nb producing industry has responded admirably to SRF needs by increasing the purity and thermal conductivity of Nb by an order of magnitude in the last decade.

Field emission is recognized to be the main obstacle towards reliably achieving Eacc= 10 MV/m or higher. The emission is known to occur from isolated sites. Two new approaches to overcome field emission in SRF cavities have shown considerable promise. These are heat treatment (HT) and high power pulsed RF processing (HPP). By HT, emission sources are cleaned up by evaporation and dissolution into the bulk, and by HPP, emission sources are exploded in the high RF electric field.

Using 1-cell 1500 MHz Nb cavities, a substantial reduction in emission was shown for heat treatments between 1400 - 1500 C, even after subsequent exposure to clean air. An average accelerating field of 25 MV/m at Q values above 10^9, with 30 MV/m as the best value (Fig. 2)[14]. HT Tests on multicell cavities have started. In the five tests on 6-cell and 9-cell cavities, gradients of 15 - 20 MV/m accelerating were reached[15].

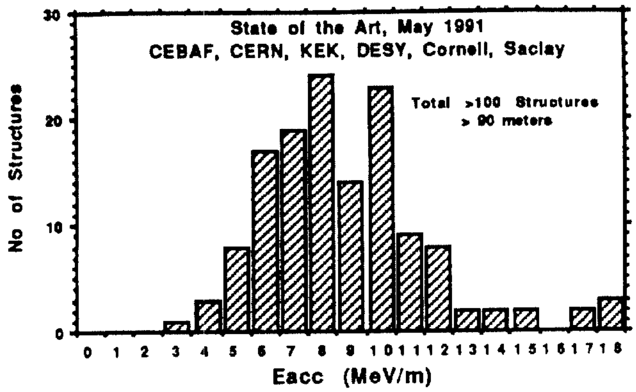

Fig. 1. State of the Art in Accelerating Gradients reached with standard chemical treatment.

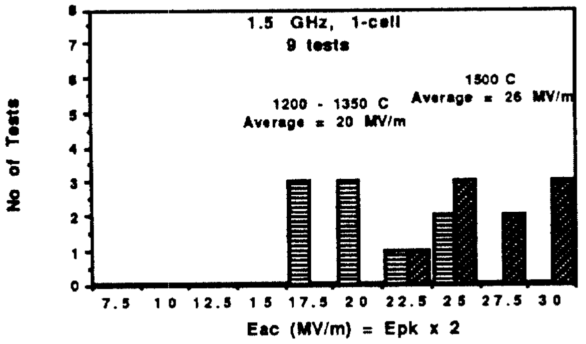

Fig. 2: A statistical comparison of results on 1-cell, 1500 MHz cavities at Cornell prepared by heat treatment.

The second promising technique (HPP) for overcoming field emission uses short pulses of high RF power to process emission. For many years in processing structures used for heavy ion accelerators at Argonne, Stony Brook and elsewhere, 1-2 kwatts of pulsed (msec) RF power was found more effective than the more usual cw method with 10-100 watts of cw power. A study conducted at SLAC[16] explored the use of 1-2 Mwatts of peak power pulses of 1-2 µsec duration using 3 GHz 1-cell Nb cavities. It was shown possible to reach surface fields of 54 to 70 MV/m, but it was never determined whether the benefits from the high power exposure would remain during long pulse or cw operation.

Based on these encouraging results, a wider exploration of HPP is being conducted[17]. The test set up is designed with variable input coupling without breaking the cavity vacuum. Results to date are very promising.

With pulses up to 1 msec long, and peak RF power between 2 and 50 kWatts, the onset of field emisison (as judged by first observation of X-rays) in 6 tests on several 1-cell 3 GHz cavites was moved up by 50%. The maximum fields reached after HPP were Eacc = 17-27 MV/m. Q values over 10^{10} at Eacc = 20 MV/m were found possible after HPP.

Tests on multicell cavities have also started using a 9-cell 3 GHz cavity. Five separate tests have been carried out, each time after preparing the cavity surface anew with standard chemical treatment. In all five tests, field emisison limited the initial performance of the cavity as shown in the examples of Fig.3 (lower graph). In each case the emission limitation was overcome using HPP up to 200 kwatts (Fig. 3- upper graph).

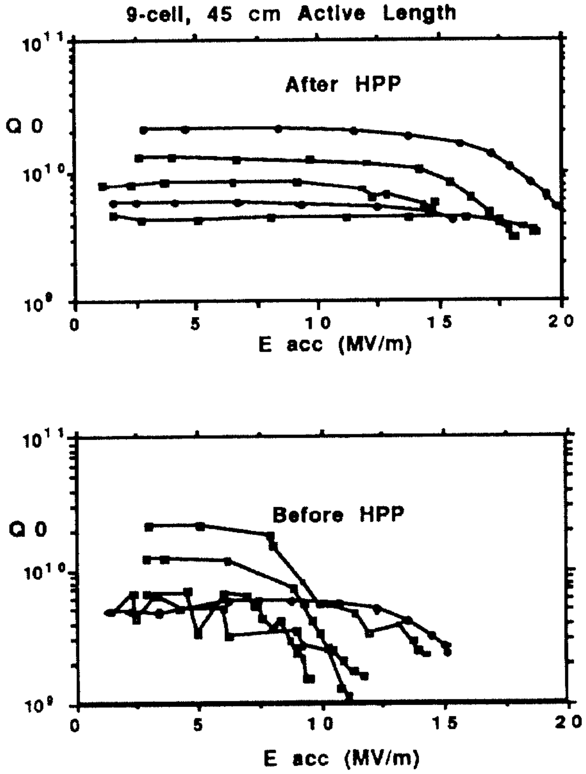

Fig.3: Results from separate tests on a 9-cell, 3 GHz structure before and after high power RF processing (HPP).

An understanding of the HPP solution to field emission is taking shape. Microscopic examination of dissected 1-cell cavities reveal molten crater-like structures 5-10 µm in diameter. Sometimes nearby regions of molten remnants of the contaminant, presumably responsible for emission are found, eg. In, Cu, Fe, stainless steel, Ti. In many cases no foreign elements are found, so the nature of these emitters are unknown. The features suggest the occurence of an RF spark and indicate that emitter extinction takes place by an explosive process. Presumably at a high enough electric field, the local field emission current density exceeds 10^8 amps/cm^2, as shown by calculations to be sufficient to reach melting temperatures near the emitter[18].

It appears then that the key to successful processing is to establish a high enough electric field at the emission site, even if for a short time (µsec), so that the local emission current density can be elevated to the intensity necessary to initiate the explosive process, which extinguishes the emission. Only those emitters that reach the explosive current density are likely to process. Others will continue to quiescently emit current. Q values over 10^{10} at 40 MV/m surface field are still possible in the presence of ~ 40 exploded emission sites, so that these small (5-10μm)craters do not present a serious degradation in performance. Fields reached during the processing stage are typically 50% higher than the maximum cw operating levels.

The limitation of HPP at 3 GHz tried so far has been shown, by careful thermometry measurements, to arise from a global thermal breakdown (GTB) at the high magnetic field region of the cavities[19]. Recently a 2-cell, 3 GHz cavity with a more favorable Hpeak/Epeak ratio was processed with HPP to reach a surface electric field of 100 MV/m. (Fig 4).

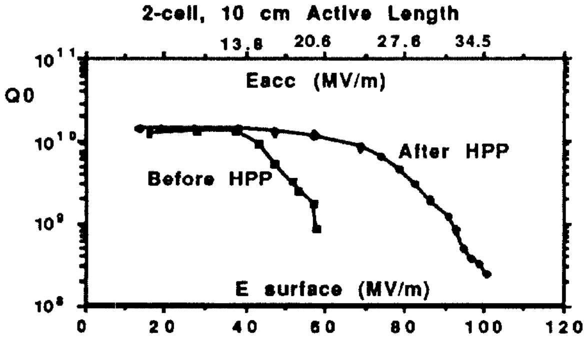

Fig. 4: HPP results on a 2-cell cavity

This result confirmed that if GTB is avoided, the HPP technique is inherently capable of processing emission to surface fields corresponding to Eacc = 50 MV/m in a well designed structure (Epeak/Eacc = 2). At the TESLA frequency of 1.3 GHz, the surface resistance is lowered by the square of the RF frequency, eliminating GTB as an obstacle to HPP effectiveness.

TESLA TEST FACILITY (TTF)

Encouraged by this progress, a collaborative proposal for a TESLA TEST FACILITY (TTF) is launched by DESY. Its long-term aims are to establish a technological base needed for TESLA, to demonstrate that the gradient and cost goals can be achieved, and to test a high gradient SRF section with beam. With the first cavities it is aimed to reach 15 MV/m accelerating gradient at $Q = 3x10^9$, and a static heat load, 1 watt/m. These values would represent a substantial improvement over presently quoted values.

It is proposed to build four 12 m long cryounits each with eight 9-cell cavities at 1.3 GHz. Cavities will be fabricated by industry and will be prepared and tested at the TTF site, which will include all SRF facilities for chemical treatment, dust-free assembly and RF cold tests, with heat treatment and high power RF processing. Each cavity will be surrounded by its own liquid He vessel, so that critical connections like cavity and coupler flanges, input coupler, HOM couplers, RF feedthrus, will be inside the insulation vacuum and not in contact with liquid helium. This constitutes cost reduction and increased reliability against leaks. All cold He feed lines and return lines will be integrated into the cryostat.

The cryounits will be incorporated into a small test accelerator, consisting of an injector, a low and high energy beam analysis system, an RF system and a 1.8 K Helium refrigeration plant.

As a first stage, a low bunch charge ($4x10^7$ e/bunch, 1.3 GHz bunch freqeuncy) injector at 5 MeV will be used to provide 10 mA beam current for 800 μsec RF pulse length. This mode will be used to test, under the full beam loading conditions, the pulsed operation at high gradient of a string of 16 SRF cavities connected to a common klystron. In the second stage a high bunch charge injector (>$2x10^{10}$ e/bunch) will be built, with a train of 800 bunches spaced 1 μsec apart to test wakefield related issues, such as multibunch stabliity and HOM losses. The design of such an injector is in progress.

Commercially available 4.5 MWatt, 2 msec pulse length klystrons will be used to distribute power to 16 cavities in a linear RF distribution network as used in HERA. A refrigerator/liquefier will be installed to provide 200 watts at 1.8 K, 600 watts at 4.4 K and 2000 watts shield cooling at 70 K for the test facility and the test linac operation .

CONCLUSIONS

With successful operation of SRF systems in TRISTAN, LEP and DESY, the importance of SRF to high energy electron accelerators is growing rapidly. Progress in SRF technology continues. Gradients are improving and costs are coming down. The SRF approach offers many compelling advantages to make the desired luminosity possible. The time is ripe to place increased effort into the SRF approach, as called for by the TTF proposal. The benefits to physics at the high energy frontier are likely to be considerable.

REFERENCES

[1] Proc. of the 1st TESLA Workshop, Cornell U, Ithaca, NY, CLNS 90-1029 (1990), Ed, H. Padamsee.
[2] Proc. of the SRF/TESLA Workshop, DESY, Hamburg, Aug 1991, Ed. D. Proch.
[3] R. Sundelin, Proc. of the 1987 PAC,p. 68 (1987).
[4] U. Amaldi et al, CERN/EF 86-8 (1986)
[5] D. Rubin et al, Proc. of the 1989 PAC, p. 721 (1989)
[6] U. Amaldi in refs [1], addendum (1990)
[7] H. Padamsee et al in refs [2], TESLA status and poster paper.
[8] R. Palmer, SLAC-PUB-4707 (1988)
[9] R. Ruth, SLAC-PUB-5405 (1990)
[10] T. Weiland et al, in refs [2].
[11] A. Mosnier et al, DAPNIA-SEA-92-01, CEN Saclay
[12] J. Kirchgessner et al in refs [1].
[13] E. Haebel et al in refs[2]
[14] H. Padamsee et al, Proc. of the 1991 PAC, p. 2420.
[15] J. Kirchgessner et al, 1991 PAC, p. 2426
[16] I. Campisi et al, SLAC/AP-16, Feb 1984.
[17] J. Graber et al, Proc. of the 1991 PAC, p. 2411 & in [2]
[18] D. Moffat et al, Proc. of the 1991 PAC, p. 21 & in [2]
[19] J. Graber et al , CLNS91/1061