# Status Report on TESLA Activities*

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## 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. 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. The energy spread 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 without invoking damping schemes designed to excessively load higher mode Q values to below 20. Most of the advantages of TESLA over TLC are retained in comparision with the 3 GHz Normal conducting Linear Collider under consideration by DESY/TH Darmstadt.

The first Workshop on a TeV Energy Superconducting Linear Accelerator (TESLA) was held at Cornell in July '90. Smaller meetings were held at DESY between March and August '91. Parameter sets for 5 machines were generated, from 0.1 TeV to 2 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 MV/m to 40 MV/m. The major challenges are to increase the gradients from 5 - 10 MV/m possible today and to lower the costs. With specially developed heat treatment techniques to reduce field emission, 1-cell Nb cavities regularly reach fields corresponding to Eacc = 25 MV/m. Similarly encouraging results are forthcoming from a high power processing technique recently under exploration. Application of both new techniques to multicell structures has started. When the advanced techniques are applied, gradients greater than 15 MV/m are more frequently the rule than the exception. Many ideas were studied at the TESLA workshops for lowering structure costs. Some of these are already put into practice. Encouraged by this progress, a collaborative proposal for a TESLA TEST BED is under preparation.

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

## 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 ! The SRF approach 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. Such an approach then must then be taken very seriously, even though the potential ultimate gradients are not as high as with normal conducting (NC) RF. Further, by virtue of the high efficiency of conversion of wall plug power to beam power in an SRF linac, an alternate 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 in the realm of physics potential can be 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 NC linac can be operated at the high gradients (100 MV/m) envisaged 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 these parameters were already demonstrated. Hence developmental efforts on these fronts would be unnecessary. 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. However, physics consideration demand higher luminosity at 2 TeV.

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

At the 1989 PAC, Rubin et al [3] adopted all the new advances in source and final focus that a normal conducting TLC [4] would count on, such as flat beams with aspect ratio = 100, a miniscule final vertical spot size = 2.2 nm, source emittance = 0.05 µm, $\beta^*y$ = 0.1 mm and a very short bunch length = 70 µm. Then with a beam power of 8 MWatts, a 1 TeV CM machine with L=8x$10^{33}$ 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, the high duty factor (few %) is still very high compared to proposed NC machines, so that many of the inherent advantages of the superconducting approach are retained as discussed below.

## CORNELL TESLA WORKSHOP & DESY MEETINGS

In July 1990, a 4-day workshop on TESLA was held at Cornell [5]. Between June and August 1991, several smaller TESLA meetings were held at DESY. The purpose of these meetings was to work on parameter lists 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 in the Cornell meeting 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. The DESY meetings were attended by scientists from Cornell, DESY, INFN, Frascatti, Saclay and Wuppertal.

The merits of a staged approach for TESLA, suggested by U. Amaldi [6] were recognized. 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. For the 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, and preferably smaller[6]. For such an application, use of SRF is imperative since a comparable machine built with NC RF would use prohibitively higher AC power. A W factory (200 GeV CM) could also be included as part of the staging.

A somewhat different strategy was proposed by B. Wiik for the DESY meetings. A 20 km long HALF TESLA (CM) machine could be built as a first step when gradients of 25 MV/m are within reach. Using the same source and final focus systems, ie same emittances and final ß*s, the same machine could be operated at lower gradients in the Z, W and Top Factory modes. As higher gradients become available in the future, upgrades to TESLA and TWO TESLA can be envisioned.

The main parameters for TESLA machines consistent with either strategy are presented in Table 1 for energies up to half TeV (CM), and in Table 2 for following upgrades at 1 and 2 TeV (CM). (More detailed sets of parameters for each case are given in Apendix 1.) In all cases:

Luminosity (cgs units) > $10^{34}$ x E (TeV)$^2$

Table 1: Main Parameters for machines up to 0.5 TeV CM Energy

| | Units | Z Factory | W Factory | Top Factory | Half TESLA |
|---|---|---|---|---|---|
| CM Energy | GeV | 100 | 200 | 250 | 500 |
| Luminosity | $10^{33}$ cgs | 3.1 | 5.1 | 1.64 | 5 * |
| Coll. Energy Spread | % | 0.1 | 0.5 | 0.16 | 1.76 |
| AC Power | MWatts | 99 | 135 | 149 | 152 * |
| emittance x,y | µm-rad | 20,1 | 20,1 | 20,1 | 20,1 |
| final beta x,y | mm | 10,5 | 10,5 | 10,5 | 10,5 |
| Beam size vert | nm | 226 | 160 | 143 | 101 |
| Gradient | MV/m | 14 | 15 | 15 | 25 |
| Active Length | km | 7.2 | 13.4 | 16.6 | 20 |
| Bunch Separation | µsec | 0.7 | 1 | 0.4 | 1 |

* For a Luminosity of 2.5 x $10^{33}$, AC Power is reduced to 85 MWatts

Table 2: Main Parameters for Upgrades to 1 and 2 TeV CM Energy

| | Units | Half TESLA | TESLA | TWO TESLA |
|---|---|---|---|---|
| CM Energy | GeV | 500 | 1000 | 2000 |
| Luminosity | $10^{33}$ cgs | 5 | 10 | 40 |
| Coll. Energy Spread | % | 1.76 | 12.2 | 16.7 |
| Linac AC Power | MWatts | 152 | 192 | 318 |
| emittance x,y | µm-rad | 20,1 | 20,1 | 10, 0.05 |
| final beta x,y | mm | 10,5 | 8,2.5 | 8.5,1 |
| Beam size vert | nm | 101 | 50.5 | 5 |
| Gradient | MV/m | 25 | 30 | 40 |
| Active Length | km | 20 | 33.2 | 50 |
| Bunch Separation | µsec | 1 | 1 | 0.35 |

The general parameter philosophy 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 so that focussing beams to very small sizes as for NC alternatives was unnecessary. Thus in Table 1, it was possible to relieve the final focus spot size to 100 nm, using a vertical emittances of $10^{-6}$ m instead of $10^{-8}$ m (NLC) and final focus $\beta^*_y$ of 5 mm instead of 0.2 mm (NLC). The benefits resulting from this approach are detailed in the next section along with the many other attractive features of the superconducting linear collider.

For the upgrades of TESLA and TWO TESLA (Table 2), in order to keep the AC power reasonable, it was found necessary to squeeze the vertical spot size, first to 50 nm and then to 5 nm.

These design exercises, which emerged from the work of parameters groups during the several TESLA workshops, are not yet optimized. A general parameter program was developed and is presented in detail in another paper at this workshop[7]. In this paper the choice of the RF frequency of 1.3 GHz for TESLA is also discussed.

## ATTRACTIVE FEATURES OF TESLA

Table 3 reveals the promise of the superconducting approach by comparing some of the parameters for superconducting and normal conducting machines[8,9], each with 0.5 TeV CM energy and L ~ $2x10^{33}$ in cgs units.

Table 3: Comparison between Normal and Superconducting Linear Colliders at 0.5 TeV CM, Luminosity ~ $2x10^{33}$ cgs units.

| Parameter | Units | Super 1/2 TESLA | Normal DESY/THD | Normal NLC |
|---|---|---|---|---|
| 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 | 85 | 110 | 49 |
| Linac Efficiency | % | 22 | 13 | 3 |
| Luminosity | $10^{33}$ cgs | 2.5 | 1.4 | 2.1 |
| Coll. Energy Spreqad | % | 1.8 | 6 | 7.8 |
| Beamstr. Parameter | | 0.038 | 0.13 | 0.18 |
| No. of Incoh. Pairs | | 251 | 5676 | 720 |
| Vertical spot size | nm | 101 | 40 | 4 |
| Spot size Aspect Ratio | | 6.3 | 8 | 45 |
| Vertical $\beta^*y$ | mm | 5 | 0.8 | 0.224 |
| $\beta^*y/\beta^*x$ | | 2 | 6.3 | 20 |
| Emittance y | µm-rad | 1 | 1 | 0.02 |
| Emittance aspect ratio | | 20 | 10 | 100 |
| Bunch length | mm | 2 | 0.5 | 0.105 |
| Bunch separation | m | 300 | 3.2 | 2.5 |
| No. of Bunches/ RF pulse | | 800 | 172 | 10 |
| Beam on time/ RF pulse | µsec | 800 | 2 | 0.08 |

### Beam Parameters and Physics Potential

By virtue of the higher linac efficiency offered by the TESLA approach, comparable luminosity is envisaged with substantially larger vertical beam size. Correspondingly, a significantly smaller beamstrahlung induced energy spread greatly improves the physics potential. 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 over the NLC. The smaller aspect ratio reduces coupling between the horizontal and vertical planes which can dilute emittance. Final focus quadrupoles have larger apertures. Although the number of incoherent e+e- pairs generated per crossing are comparable in all the machines, the time between collisions is 1 µsec for TESLA, judged sufficient to clear the detectors. In contrast the time between collisions for NC options is ~ 10 ns, so that the number of incoherent pairs must be multiplied by the number of bunches. This puts the 3 GHz NC option at a considerable disadvantage with respect to detector background.

## 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. Presently available klystrons can be used, eliminating the significant challenge of developing new sources.

## Lower RF frequency

Frequency scaling laws shown below for various dominant quantities of a NC collider push frequencies up.

| | |
|---|---|
| Achievable gradient | f |
| Peak Power | $1/\sqrt{f}$ |
| AC Power | $1/f^2$ |

On the other hand, higher frequencies present severe disadvantages on several fronts:

| | |
|---|---|
| Transverse wakefields | $f^3$ |
| Longitudinal wakefields | $f^2$ |
| No. of RF feed points | f |
| RF pulse length | $1/f^{1.5}$ |

SRF cavites can store energy efficiently, allowing the use of low RF frequency (1.3 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 (many hundreds) 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. 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. 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.

## CHALLENGES FOR TESLA

Whereas the capital cost of NLC is likely to be dominated by the RF sources, while that of the 3 GHz NC machine will be dominated both by structure and sources the cost of TESLA will be dominated entirely by the SRF structure. i.e the cavities and cryostats. Hence the major challenges are to increase the gradients from today's levels of 5-10 MV/m and to lower the costs.

### Lowering the Structure Costs

Significant cost benefits in both cavities and cryostats will be realized if the number of cells per structure is increased. This helps reduce the number of couplers, the number of ends and costly cryostat penetrations. The 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[3,10] and a number are in progress[11]. Prelimnary results suggest that for a bunch population of $5 \times 10^{10}$ 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 ~ $10^6$. 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 new computational tools to predict QL of such couplers, the expectation is that QL values of $10^6$ can be provided for 9-10 cell cavities with similar couplers[12]. A summary of the recent thinking on these subjects is included in these proceedings [13].

Substantial progress has been registered in reducing cavity fabrication costs. The wall thickness of 1.5 GHz cavities is reduced. 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. 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[14]. 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[15]. Compact designs of coaxial HOM couplers are available[16].

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 to ~ 0.7 and bringing the static heat loss to < 1 watt/m [17]. Liquid helium distribution and cold gas recovery systems are incorporated in the cryostat desing to yield additional saving factors.

## INCREASING THE GRADIENTS

The state of the art for gradients is shown in Fig. 1.

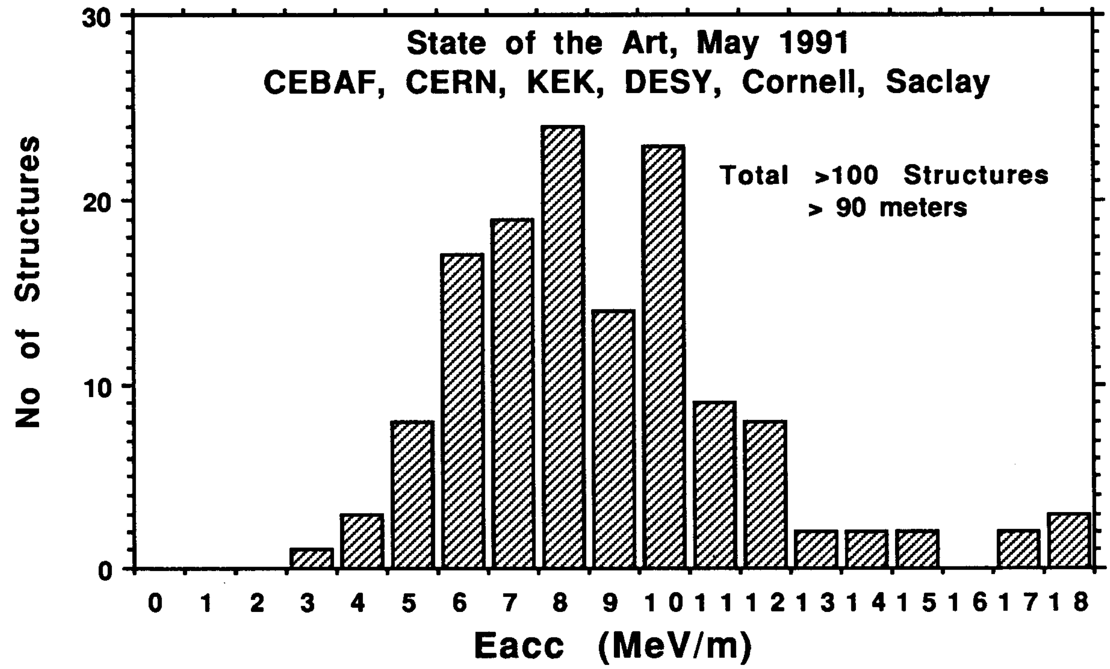



Figure 1. State of the Art in Accelerating Gradients reached with standard chemical treatment.

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. Studies in which sites are located by a dc probe and subsequently analyzed by a scanning electron microscope show that the enhanced emission is associated with superfiical μm size contaminant particles, or with inclusions. These studies confirm the importance of dust free environments, clean materials and clean test systems.

That it is occasionally possible to reach 18 MV/m with standard surface preparation techniques encourages us to expect that with better understanding and improvenmetns, even the standard techniques may in the future apporach the desired performance. The best structure tests from 4 different labs reached gradients of 15 - 18 MVm. (Fig.2)

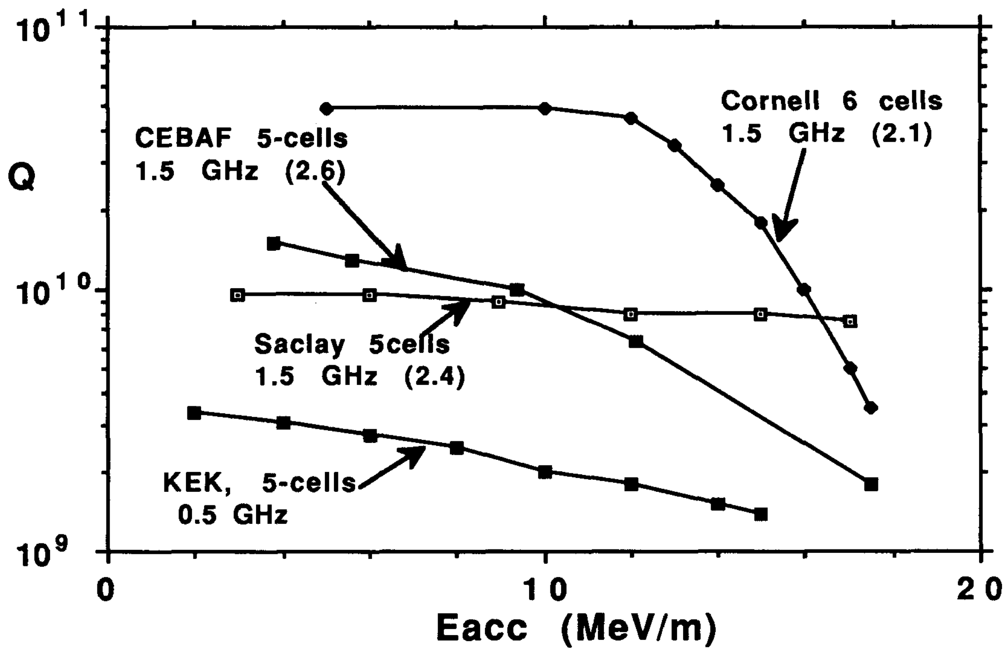


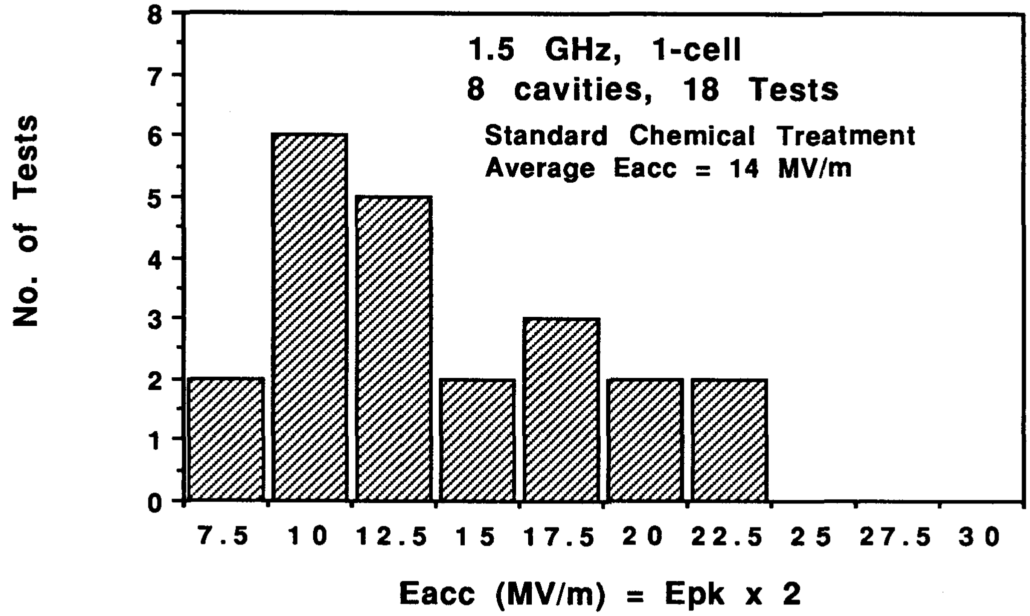

Fig. 2: Best results on chemically treated structures at 4 different labs. Values in parenthesis are Epk/Eacc

Recently at Los Alamos, 1-cell 3 GHz cavities have reached Epk = 78 MV/m with chemical treatment after incorporating the additional step of nitric acid soaking to remove indium debris left behind from earlier tests[18]. Several efforts are now underway to improve standard cavity preparation procdure: filtering of acids, (Saclay and CEBAF), treatments in a dust-free environment (Los-Alamos), high pressure (100 bar) rinsing after chemistry (CERN). Measures to improve the cleanliness of the RF cold test set-up are under consideration. These results are described in the status reports of the Laboratories cited.

Two new approaches to overcome field emission in SRF cavities have been studied and shown considerable promise. These are heat treatment (HT) and high power pulsed RF processing (HPP). Both are discussed more fully in other papers at this conference[19,20].

Encouraged by early results from DC field emission studies[21], there has been considerable exploration of the influence of high temperature annealing in a good vacuum for the final stage of surface preparation. In DC studies, Nb samples scanned for emisison sites were high temperature annealed and subsequently rescanned, all without removal from the UHV. Above 1200 C, the density of emitters was drastically reduced. Surfaces $cm^2$ which do not emit up to 100 MV/m were repeatedly obtained above 1400 C. Together with reduced emission, particles associated with emission were observed to disappear, presumably by evaporation or dissolution. Artificially introduced emitters such as graphite particles could also be elminated by heat treatment.

Using 1-cell 1500 MHz Nb cavities, a substantial reduction in emission was confirmed for heat treatments between 1400 -1500 C, even after subsequent exposure to clean air. During the heat treatment, the outer wall of the cavity must be coated with Ti to prevent the purity of the cavity wall from degrading in the furnace. With heat treatment at 1400 - 1500 C, 1.5 GHz single cells now reach an <u>average</u> surface field of 50 MV/m at Q values above $10^9$, with 60 MV/m as the best value (Fig. 3).



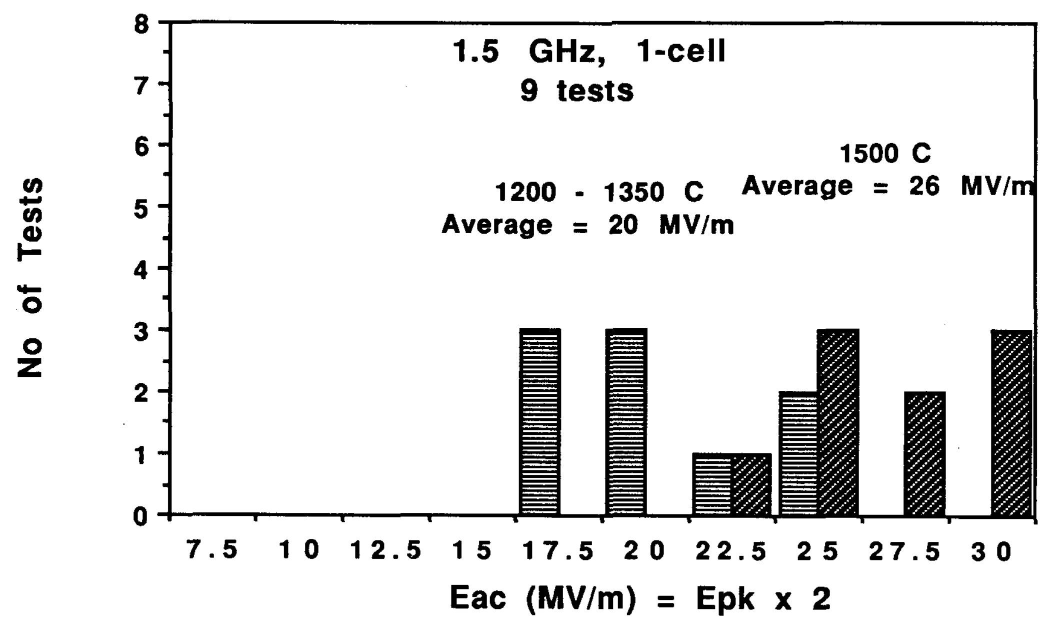




Fig. 3: A statistical comparison of results on 1-cell, 1500 MHz cavities at Cornell prepared by standard chemical treatment (upper) with those prepared by heat treatment (lower).

With the new heat treatment at Wuppertal, 3 GHz single cells have reached Esp = 70 MV/m[22]. Lower temperature treatments (1200 -1350 C) are also found beneficial but less substantially. More detailed studies that localize individual emisison sites and determine their emission characteristics are based on measurements of the cavity wall temperature increases caused by impinging electrons, i.e. temperature maps. Maps accomanying 1.5 GHz 1-cell cavity tests show an order of magnitude reduction in emitter density by heat treatment[23].

Important auxialiary benefits are derived from heat treatment. The Ti protection coating is found effective in improving the purity of the cavity wall, providing increased stabilization against thermal breakdown. As received Nb sheets from the supplier often suffer from a spatial variation in purity which heat treatment will homogenize, ensuring high thermal conductivity everywhere. Finally above 1000 C, any hydrogen trapped in the cavity wall during chemical cleaning stage is completely removed, so there is no risk of Q degradation from hydrogen contamination, a difficulty often observed after chemical etching.

HT Tests on multicell cavities have started. Two separate heat treatment tests on a 6-cell, 1.5 GHz cavity have been carried out at Cornell. In each case the cavity was freshly prepared with standard chemical treatment. These results along with other heat treated cavity results are presented in Fig. 4 and in other papers at this conference [19,24].

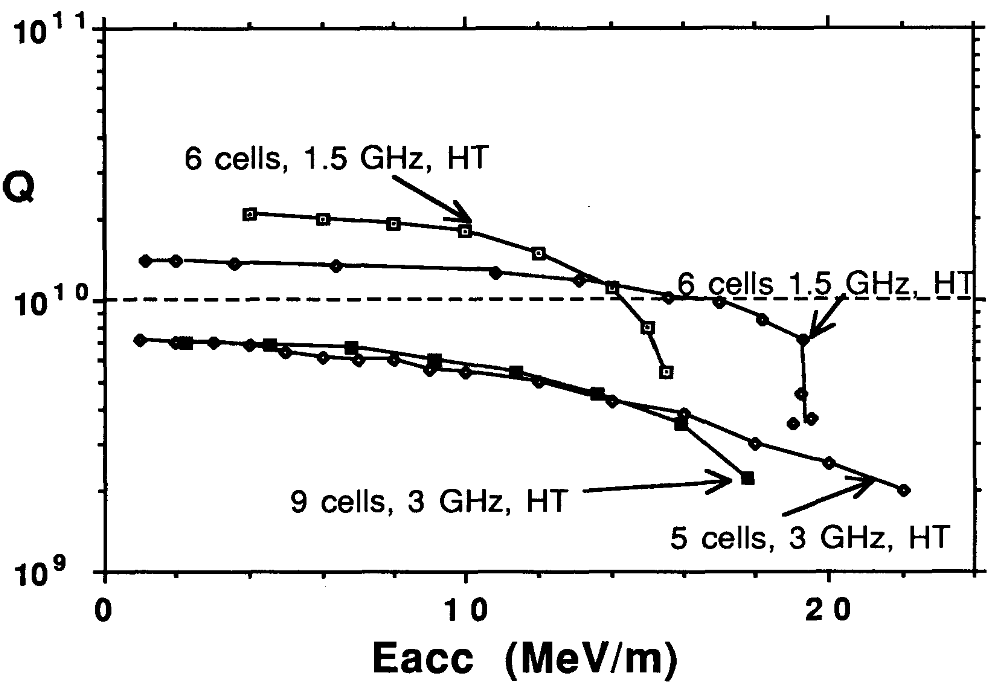


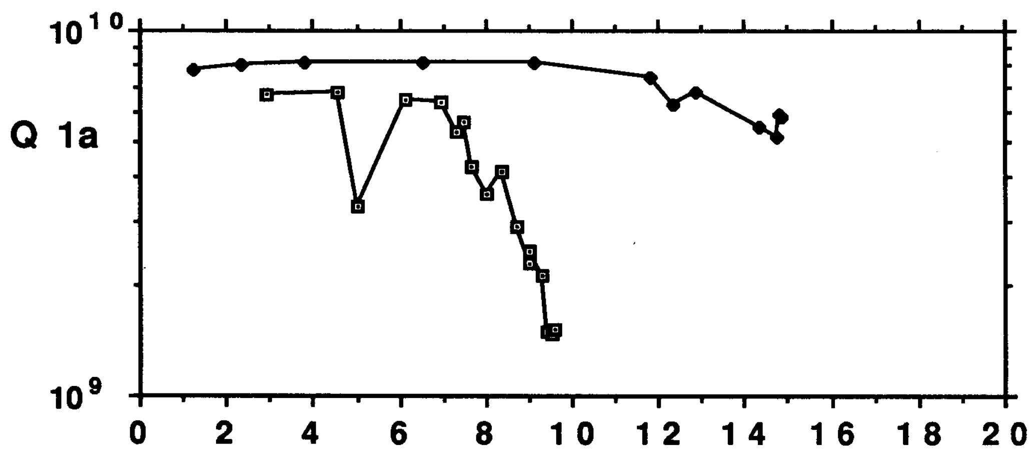

Fig. 4: Results on heat treated cavities at Cornell and Wuppertal.

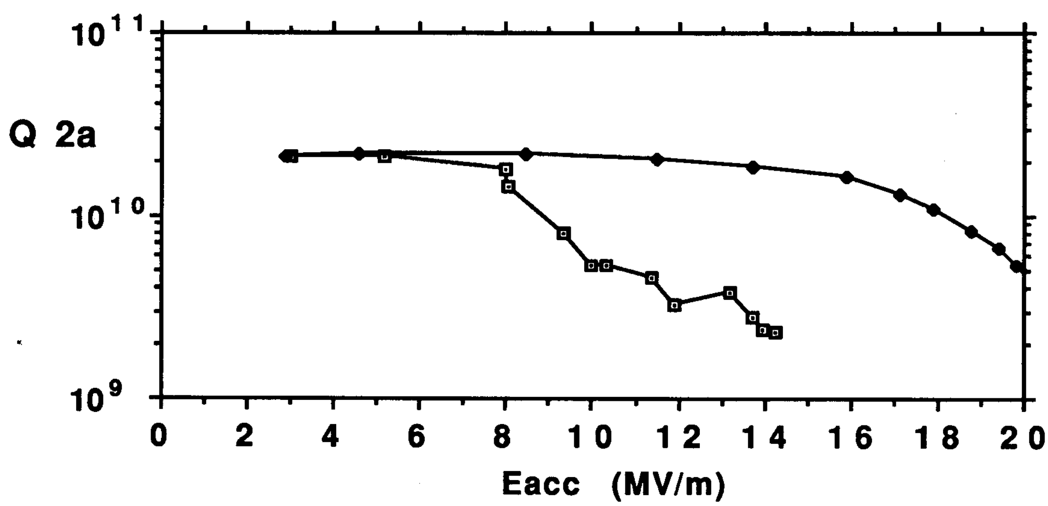
The second promising technique (HPP) for overcoming field emission uses short pulses of high RF power to process emission. In regular testing of SRF cavities with low RF power (10 -100 watts, cw) emission is often observed to reduce abruptly, especially when the RF is increased for the first time. Eventually however, emission becomes stable and no further progress is realized. 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. A study conducted at SLAC[25] 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 extend to long pulse or cw operation.

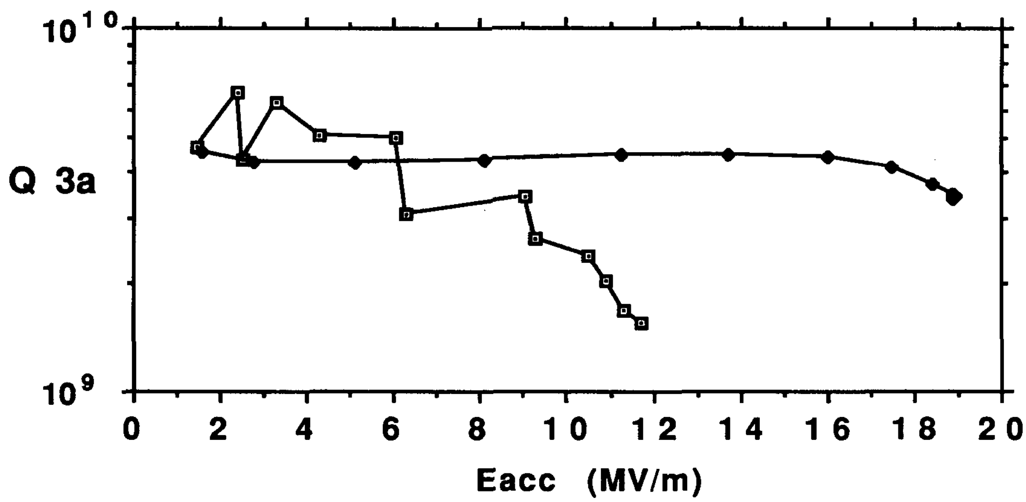
Based on these several encouraging results, a wider exploration of HPP is being conducted at Cornell[19,26]. The test set up is designed with variable input coupling without breaking the cavity vacuum. Strong coupling allows efficient transfer of short pulses of high power for processing, while weak coupling allows testing with low power to determine improvements in long poulse or cw behavior. Results to date are very promising.

With RF power between 2 and 50 kWatts, and pulses up to 0.5 msec, the onset of field emisison (as judged by first observation of X-rays) in 6 tests on several 1-cell 3 GHz caviites was moved up 50%, from the customary regime Epk = 20-30 MV/m to Epk=30-44 MV/m. The maximum surface field values recahed after HPP were Epk = 34 - 55 MV/m. At Epk= 55 MV/m, the surface magnetic field is near 1300 Oersted, close to the onset of global thermal breakdown of the RF surface from the BCS surface resistance and therefore the ultimate field level possible with cavity geometry used. In many cases, Q values over $10^{10}$ at Epk = 40 MV/m were found possible after HPP. Fields reached during the processing stage were typically 50% higher than the maximum cw operating levels. It is suspected that the maximum field accessible for processing was also limited by the global thermal breakdown effect.

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 inital performance of the cavity as shown in the examples of Fig.5.





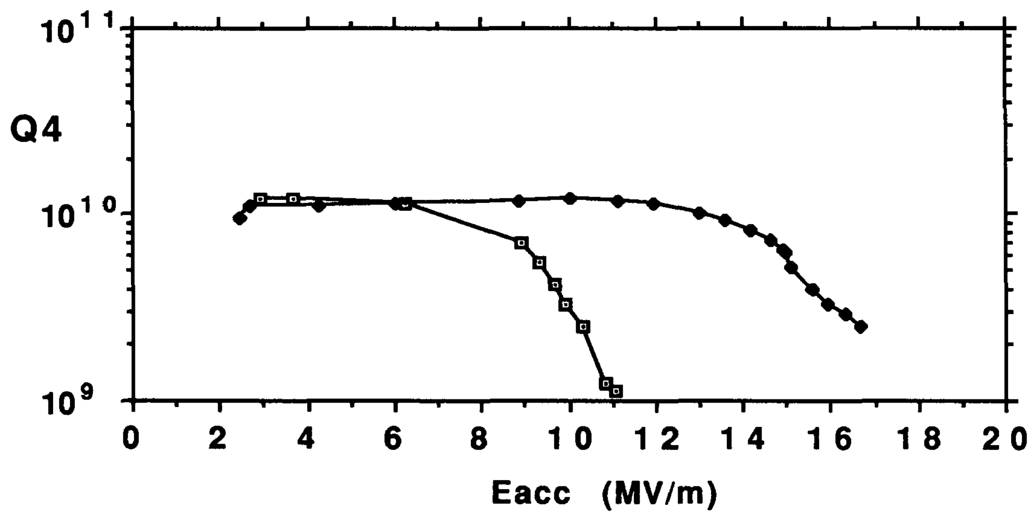




Fig.5: Results from separate tests on a 9-cell, 3 GHz structure before and after high power RF processing (HPP).

In each case the emission limitation was overcome using HPP up to 100-200 kwatts. The first test was limited to Eacc = 16 MV/m by thermal breakdown which was attributed to the low RRR = 200. After improving the RRR to over 400 at Wuppertal by a post-purification process, the next tests reached Eacc = 17-20 MV/m.

A better understanding of emitter processing in SRF cavities is taking place[27]. Microscopic examination of dissected 1-cell cavities reveal molten crater-like structures 5-10 µm in diameter. Often nearby regions of molten remnants of the contaminant responsible for emission is found. 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.

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 area craters do not present a serious degradation in performance.

Both HT and HPP techniques when appled to multi-cell structures permit accelerating gradients over 15 MV/m. The HPP technique offers the possibility of cleaning up residual emisison, which makes it more attractive than HT, considering the likelihood that a clean cavity surface may suffer contamination during installation or operation in an accelerator. The HT technique cleans up the surface before installation, but the onus of preserving the superior cleanliness reamains. However the HT technique should not be abandoned because the auxiliary benefits are very important.

## 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.

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## Appendix 1: Detail Parameters for Machines Up to 0.5 TeV (CM)

**Fixed Parameters for All Four Modes of Operation**

| | Units | |
|---|---|---|
| emittance x,y | μm-rad | 20,1 |
| final beta x,y | mm | 10,5 |
| No. of Bunches | | 800 |
| Injection Energy | GeV | 3 |
| RF Frequency | GHz | 1.3 |
| Aperture | cm | 4.6 |
| R/Q | Ohms/m | 832 |

| | Units | Z Factory | W Factory | Top Factory | Half TESLA |
|---|---|---|---|---|---|
| CM Energy | GeV | 100 | 200 | 250 | 500 |
| Luminosity | $10^{33}$ cgs | 3.1 | 5.1 | 1.64 | 5 * |
| Gradient | MV/m | 14 | 15 | 15 | 25 |
| Total Active Length | km | 7.2 | 13.4 | 16.6 | 20 |
| AC Power | MWatts | 99 | 135 | 149 | 152 * |
| No. of e/bunch | $x10^{10}$ | 3.8 | 4.6 | 2 | 5.14 |
| Collision Freq | kHz | 45 | 25 | 37 | 8 * |
| Bunch Length | mm | 0.9 | 1 | 1 | 2 |
| Bunch Separation | μsec | 0.7 | 1 | 0.4 | 1 |
| Beam size vert | nm | 226 | 160 | 143 | 101 |
| Disruption Dy | | 5.3 | 7.1 | 3 | 15.8 |
| Aspect Ratio | | 6.3 | 6.3 | 6.3 | 6.3 |
| Beamstr. Param. | | 0.0042 | 0.015 | 0.0056 | 0.038 |
| Coll. Energy Spread | % | 0.1 | 0.5 | 0.16 | 1.76 |
| No. of Coherent Pairs | | 0 | 0 | 0 | 0 |
| No. of Incoh. Pairs | | 314 | 322 | 18 | 249 |
| Beam Power | MWatts | 27 | 37 | 30 | 33 |
| Linac Efficiency | % | 28 | 27 | 19.9 | 22 |
| AC Power | MWatts | 99 | 135 | 149 | 152 |
| Q0 | $x10^9$ | 6.7 | 6.1 | 6.1 | 4.9 |
| Q Loaded | $x10^6$ | 1.9 | 2.4 | 2.3 | 3.7 |
| RF Pulse Length | msecs | 0.89 | 1.2 | 0.7 | 1.42 |
| Rep Rate | Hz | 56 | 31 | 46 | 10 |
| Eff. Duty Factor | % | 4.6 | 3.6 | 2.9 | 1.3 |
| Cryogenic Load Total | kWatts | 27.5 | 46 | 42 | 64 |
| Cryogenic load/meter | Watts/m | 3.8 | 3.4 | 2.5 | 3.2 |
| Peak RF Power/m | kWatts/m | 122 | 110 | 120 | 206 |
| Vert. Alignment Tol | mm | > 1 | ~ 1 | > 1 | 0.1 |
| Vert. Vibration Tol. | μm | 3 | 1.2 | 2 | 0.43 |

* For a Luminosity of 2.5 x $10^{33}$, the AC power is reduced to 85 MWatts and collision frequency is reduced to 4.1 kHz

## Appendix 2: Detail Parameters for Upgrades

**Fixed Parameters:**

| | Units | |
|---|---|---|
| Injection Energy | GeV | 3 |
| RF Frequency | GHz | 1.3 |
| Aperture | cm | 4.6 |
| R/Q | Ohms/m | 832 |

| | Units | Half TESLA | TESLA | TWO TESLA |
|---|---|---|---|---|
| CM Energy | GeV | 500 | 1000 | 2000 |
| Luminosity | $10^{33}$ cgs | 5 | 10 | 40 |
| Gradient | MV/m | 25 | 30 | 40 |
| Total Active Length | km | 20 | 33.2 | 50 |
| Linac AC Power | MWatts | 152 | 192 | 318 |
| No. of e/bunch | $x10^{10}$ | 5.14 | 5.8 | 1.48 |
| Collision Freq | kHz | 8 | 4.1 | 12.7 |
| No. of Bunches | | 800 | 800 | 3200 |
| Bunch Length | mm | 2 | 1.1 | 0.4 |
| Bunch Separation | µsec | 1 | 1 | 0.35 |
| emittance x,y | µm-rad | 20,1 | 20,1 | 10,.05 |
| final beta x,y | mm | 10,5 | 8,2.5 | 8.5,1 |
| Beam size vert | nm | 101 | 50.5 | 5 |
| Disruption Dy | | 15.8 | 16 | 15.8 |
| Aspect Ratio | | 6.3 | 8 | 41 |
| Beamstr. Param. | | 0.038 | 0.25 | 0.353 |
| Coll. Energy Spread | % | 1.76 | 12.2 | 16.7 |
| No. of Coherent Pairs | | 0 | 40 | 334 |
| No. of Incoh. Pairs | | 249 | 235 | 16 |
| | | | | |
| Beam Power | MWatts | 33 | 38 | 60 |
| Linac Efficiency | % | 22 | 19.7 | 18.8 |
| Linac AC Power | MWatts | 152 | 192 | 318 |
| Q0 | $x10^9$ | 4.9 | 4.9 | 11 |
| Q Loaded | $x10^6$ | 3.7 | 3.9 | 7 |
| RF Pulse Length | msecs | 1.42 | 1.46 | 2.3 |
| Rep Rate | Hz | 10 | 5.1 | 4 |
| Eff. Duty Factor | % | 1.3 | 0.69 | 0.8 |
| Cryogenic Load Total | kWatts | 64 | 91 | 125 |
| Cryogenic load/meter | Watts/m | 3.2 | 2.74 | 2.5 |
| Peak RF Power/m | kWatts/m | 206 | 278 | 270 |
| Vert. Alignment Tol | mm | 0.1 | 0.3 | > 1 |
| Vert. Vibration Tol. | µm | 0.43 | 0.4 | 0.7 |