Achieving the TESLA Gradient of 25 MV/m in Multicell Structures at 1.3 Ghz[1]

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Abstract

The challenges for the SRF approach to linear colliders are to achieve gradients of 25 MV/m or higher, and to reduce the cost of the structures, cryostats and peripheral devices, like couplers. We present here a breakthrough in the gradient goal. Using advanced preparation and processing techinques, three half-meter long units at the TESLA RF frequency of 1.3 GHz have achieved accelerating gradients between 25 - 28 MV/m.

1. INTRODUCTION

The present state of the art in superconducting cavities as well as the technological aspects of RF superconductivity discussed here are reviewed in Ref. [1]. There are two major field limiting mechanisms operative: thermal breakdown and field emission. A proven approach to avoid thermal breakdown is to raise the thermal conductivity of Nb by purification, which involves removal of interstitially dissolved impurities: oxygen, nitrogen, carbon and hydrogen. A convenient way to characterize the purity and thermal conductivity is the residual resistivity ratio (RRR). The RRR of sheet Nb delivered by industry today is about 300 and can be further improved by a factor of two (or more) by solid state gettering removal of the major impurity, oxygen.

Microparticle contaminants, most often micron and submicron size foreign particles of a conductive nature, are the culprits responsible for field emission. Increased vigilance in cleanliness during chemical etching, rinsing and assembly procedures has kept field emission under control up to the level Eacc = 10 MV/m. There are several new efforts underway to further improve cleanliness, such as UHV heat treatment[2], high pressure water rinsing[3] etc. There is evidence to show that with these clean treatments, emitter density is reduced[2].

While these efforts at supercleanliness have the potential to improve cavity performance, there are areas of concern. As is often observed, a single field emission site in an accelerating unit can limit the maximum field level, if this emitter will not "process" away. There is always some probability, high for large area cavities, that one or more such emitters will find their way on to the cavity surface. This shortcoming is especially clear in the light of the experience of all laboratories that there is a 20 - 25% decrease in the performance between the acceptance (or vertical cryostat) tests and the in-tunnel test results. It is also clear that due to the random nature of contamination, cavities with a large surface area show field emission limitation at lower fields.

Therefore a technique that processes (eliminates) emitters in-situ is highly desirable. Besides increasing the performance of a cavity prepared by existing cleaning techniques, such a technique would be effective against accidental contamination of the cavity in an accelerator, or during assembly of couplers and other components into a pre-cleaned cavity. Such a technique would also help to reduce the large spread typical in the performance of cavities.

A technique with just these desirable features has recently been demonstrated[4]. By applying High Pulsed RF Power (HPP) to 3 GHz superconducting cavities, emitters have been processed and operating field levels raised. With power levels between 5 and 150 kwatts, and pulse lengths between 5 msec and 1 msec, the CW operating field levels for several 1-cell, 2-cell and 9-cell cavities were raised consistently over a series of 25 separate tests. For example, in the 8 separate tests on 9-cell cavities, CW accelerating field levels improved from 8 - 16 MV/m before HPP to 15-20 MV/m after HPP. The HPP technique was also demonstrated to recover high gradient performance after delibertately introducing field emitting contaminants through cold and warm vacuum accidents.

The present level of understanding that has emerged from these studies is that, as the field is raised, the strongest emitters put out so much field emission current that a micro-discharge (RF spark) takes place, and the ensuing explosive event destroys (processes) the field limiting emitter. When the field level is raised further, the next strong emitters process, and so on. The essential idea of using high power pulses is to raise the surface field as high as possible. The processing is effective even if the fields reach high values for times as short as µsecs, because spark formation times are < µsec[5].

The goal of the present study is apply the HPP technique to multi-cell cavities at the TESLA RF frequency of 1.3 GHz.

2. NIOBIUM ACCELERATING STRUCTURES

Two 5-cell, 1.3 GHz cavities were purchased from industry (Cavities #1 and #2) and two 5-cell cavities were built at Cornell (Cavities #3 and #4). The important properties of the accelerating mode are listed in Table 1. During construction, one of the Cornell-built cavities (#4) had a weld hole which had to be repaired, but the repair was not very successful as judged from the premature thermal breakdown field. Results from this cavity will be omitted. Figure 1 shows one of the 5-cell cavities as it is set up for chemical treatment.

Table 1
Accelerating Mode Properties of the 5-cell, 1.3 GHz Cavities

Property	Industry Built	Cornell Built
R/Q(Ohm/m)	1012	1088
Epk/Eacc	2.5	2.0
Hpk/Eacc	41	43

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[2] Visiting scientist for Fermilab, Batavia, Illinois

[3] Visiting scientist from DESY, Hamburg, Germany

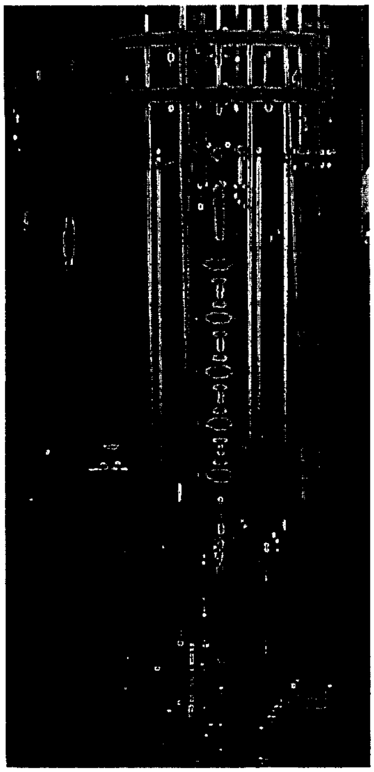

Figure 1: 5-cell niobium accelerating section set up for HPP

The starting sheet material for all cavities had a RRR = 250 - 300. After prelimnary RF tests, during which thermal breakdown limited the performance at Eacc < 14 MV/m, cavities #1 and #3 were further purified by solid state gettering. Both the inside and outside surfaces were exposed to Ti vapors at 1400 C. After RRR improvement, both the inside and outside surfaces were chemically etched to remove the Ti rich layers. Previous tests with samples treated in the same way have shown that the RRR improves to 500 - 600. The titanium diffuses into the bulk to the order of 100 μm, requiring removal of a comparable thickness of material by chemical etching, which was carried out.

3. HIGH POWER SOURCE AND TEST STAND

The high power klystron and modulator system available were capable of providing a maximum of 1 Mwatt of power at a pulse length of 150 μsec. The design of the high power test set-up is shown in Figure 2 We had to overcome several difficulties with the high power test stand before we could transmit 1 Mwatt of incident power to the cavity. After diagnosing and remedying these problems we could raise the power to 1.2 Mwatt without significant delays associated with the conditioning of the coupler.

5. FIVE-CELL TEST RESULTS

As mentioned, two of the cavities (#1 and #3) had their RRR improved by solid state gettering. Before RRR improvement,these cavities were limited by thermal breakdown

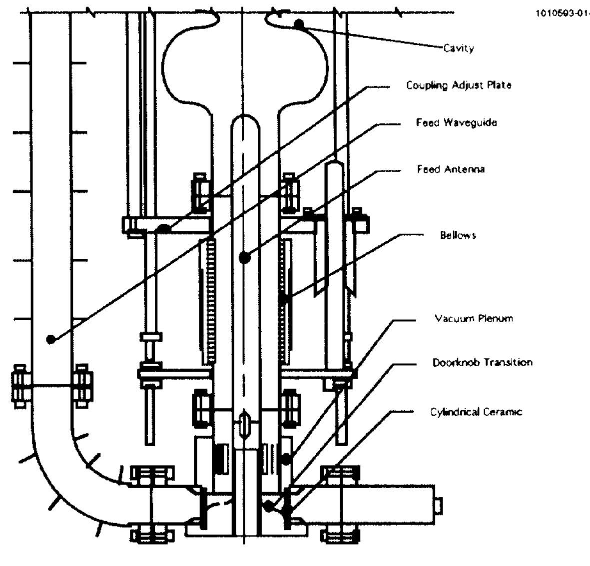

Figure 2: Schematic of High Pulsed Power RF test stand for 1.3 GHz cavities.

during CW operation at Eacc =14 MV/m (#1) and Eacc = 12.5 MV/m (#3). Cavity #2 did not show a low field breakdown and its RRR has therefore not yet been enhanced. As we shall discuss below, after RRR improvement the maximum CW field in our cavities improved to Eacc = 28 MV/m (#1, limited by field emission) and Eacc = 27 MV/m (#3, limited by thermal breakdown). Therefore the RRR improvement increased the field by a factor of 2 or more.

Figures 3 a-c show the performance of each of the three five cell cavities before and after HPP to process field emission. In these tests, before the application of HPP, the CW gradient for all three cavities was limited by field emission. In two cases the Q_0 had dropped substantially at Eacc = 10 MV/m, and in one case at Eacc = 22 MV/m. The spread in field emission limited performance is typical for the etching, rinsing and preparation techniques now in vogue.

In all three cavities, after HPP with 1 Mwatt of power, the field emission was substantially suppressed, so the maximum CW accelerating gradients reached were 27, 28 and 28 MV/m, all above the TESLA goal of 25 MV/m. During the pulsed processing stage, the surface electric fields reached were between 85 - 90 MV/m. After HPP at 1 Mwatt, the CW performances of cavities #1 and #2 were ultimately limited by field emission. Because of field emission loading, cavity #1 was limited by available CW RF power, and cavity #2 was limited by the radiation level safety trip point. The CW performance of cavity #3 was finally limited by thermal breakdown.

Our results show that the RRR improvement was effective in removing the thermal breakdown limitation of 12-14 MV/m level. Even if cavities are limited by field emission to CW Eacc =10 MV/m, they can be improved to Eacc = 28 MV/m with HPP. Therefore the HPP technique provides a way to reduce the spread in performance typical of field emission limited cavities.

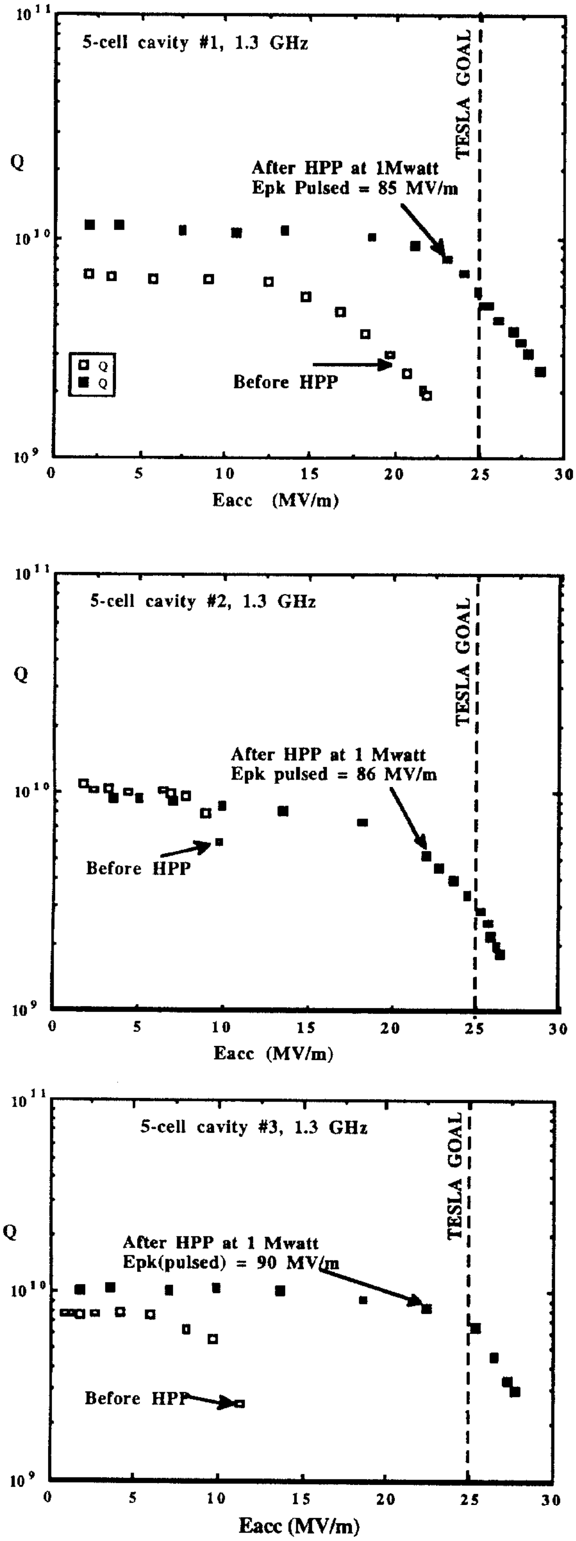

Figure 3: RF test results on 5-cell, 1.3 GHz cavities before (open squares) and after (filled squares) HPP.

Our results for the effectiveness of HPP are very consistent with 3 GHz HPP experiments. We find as before [4] that the

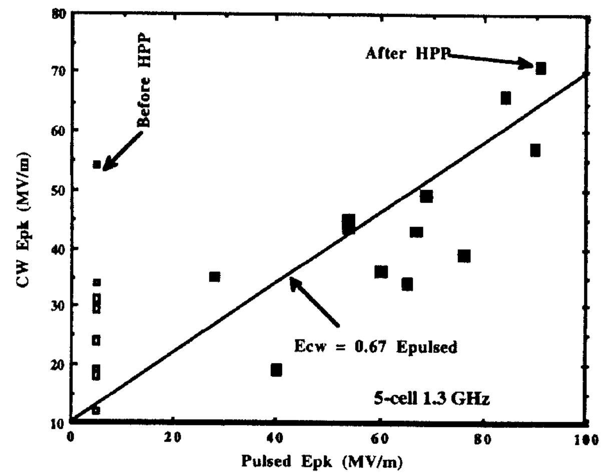

Figure 4: A summary of the benefits of HPP on 1.3 GHz cavities. The open squares are the CW results before HPP and filled squares are results after HPP.

most important parameter for successful processing of field emission is the value of the surface field reached during the pulsed conditioning stage. To demonstrate this we plot in Figure 4 the results from 5-cell 1.3 GHz cavities as the maximum CW surface field reached versus the pulsed conditioning field imposed on the RF surface. For both 1.3 GHz as well as for 3 GHz cavities we observe that

$$\text{Epk (CW)} = (0.6\text{-}0.7) \times \text{Epk (pulsed)}.$$

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