BEAM TEST OF A SUPERCONDUCTING CAVITY FOR THE FERMILAB HIGH-BRIGHTNESS ELECTRON PHOTO-INJECTOR

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1 INTRODUCTION

An electron photo-injector facility has been constructed at Fermilab for the purpose of providing a 14–18 MeV electron beam with high charge per bunch (8 nC), short bunch length (1 mm RMS), and small transverse emittance [1]. The facility was used to commission a second-generation photo-cathode RF gun for the TeSLA Test Facility (TTF) Linac at DESY [2, 3]; in the future, the Fermilab electron beam will be used for R & D in bunch length compression, beam diagnostics, and new acceleration techniques. Acceleration beyond 4 MeV is provided by a 9-cell superconducting cavity (see Figure 1). The cavity also provides a longitudinal position-momentum correlation for subsequent bunch length compression. We report on the RF tests and a first beam test of this cavity.

2 SYSTEM DESCRIPTION

2.1 Cavity

The accelerating cavity is a 9-cell superconducting Nb structure of the TeSLA Test Facility (TTF) type. The shape is optimised for a smaller ratio of surface electric field to accelerating gradient and larger iris diameter for better propagation of higher-order modes (HOM's); RF parameters are given in Table 1. The cavity and He tank were built by industry for TTF. The cavity is one of a batch with low quench field, attributed to contamination in the welds at the equator.

2.2 Couplers and Tuner

The input coupler was developed for TTF by Fermilab [4]. It is designed for 200 kW of peak power for normal operation (1.3 ms pulses, 10 Hz repetition rate), as well as 1 MW of peak power in short pulses for high peak power pulsed processing (HP^4). The coupling strength can be varied over an external Q range from $1 \cdot 10^6$ to $9 \cdot 10^6$. This coupling range is appropriate for heavy beam loading; in the absence of a beam, the cavity is highly over-coupled.

The coaxial HOM couplers were designed at DESY [5]. They provide strong coupling to the non-propagating HOM's and have a notch filter to inhibit damping of the accelerating mode. The 2 couplers are about 90° apart azimuthally, one on each beam tube, in order to couple to both polarisations of the dipole HOM's. There is also an antenna on one of the beam tubes to monitor the field level in the cavity.

The TTF cold tuner was designed at Saclay [6]. It changes the resonant frequency of the cavity by changing the overall length of the cavity, which is done by winching on the beam tube relative to the helium tank. It provides a tuning range of about ±400 kHz.

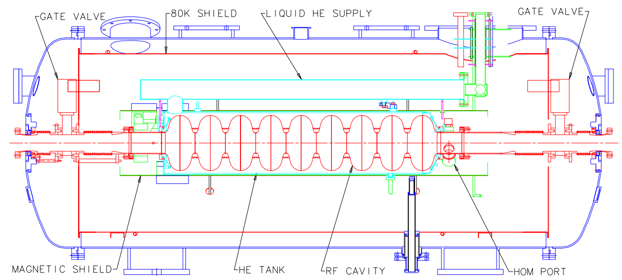

Figure 1. Side view of the cavity and cryostat for Fermilab.

Table 1. Cavity parameters [2, 3]. In the following, E_a is accelerating gradient, E_p and B_p are the peak electric and magnetic field on the surface of the cavity, respectively, and R_s is the shunt impedance (linac definition).

Mode	$TM_{010}\pi$
Resonant frequency f	1.3 GHz
Cell-to-cell coupling	2.0 %
E_p/E_a	2
cB_p/E_a	1.3
R_s/Q per cell	114 Ω
df/dL	315 kHz/mm
Cavity active length L	1036 mm
Aperture	70 mm
Operating temperature	1.8 K

2.3 Helium Tank, Cryostat, and Cryogenics

The titanium helium tank is electron-beam welded directly to the Nb cavity. It is intended to minimise the volume of liquid helium in the cryostat. The cryostat is nominally identical to the TTF capture cavity cryostat designed and built at Orsay [7], albeit with some differences, for example, in the cavity support rods and their attachment to the helium tank, as well as the presence of a 5 K radiation shield. The vacuum vessel was built by industry.

Cryogens are supplied from dewars of liquid He and liquid N_2. Roots blower pumps are used to pump down to 1.8 K. The pressure and liquid level in the He tank are regulated by control loops which actuate variable flow valves on the supply and exhaust lines.

2.4 Beam Tube

The beam tube inside the cryostat was redesigned for use at Fermilab (see Figure 1). A larger aperture (59 mm diameter or more) is maintained through it, in contrast to the 35 mm aperture through the original Orsay cryostat. The Fermi-

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lab scheme incorporates 2 gate valves inside the cryostat, which take the place of demountable valves outside the Orsay cryostat. The gate valves are always open when the cavity is cold.

2.5 Drive RF

High peak power RF drive is required due to the strong input coupling. At the design beam current, the power goes into accelerating the beam; in the absence of beam loading, the power is reflected by the coupler. The pulsed RF power is provided by a klystron and modulator with an RF pulse length of up to 2 ms, peak power ∼150 kW, and variable repetition rate.

The RF control system was developed for TTF [8]. It incorporates digital control of the amplitude and phase of the RF field. The monitor probe signal is used for feedback. The klystron drive RF is controlled by a vector modulator.

3 PREPARATION AND INSTALLATION

3.1 Cavity Preparation at DESY

A total of 135 μm was chemically etched off the inside surface of the cavity. The cavity was fired in vacuum at 800°C before the final etch to inoculate it against the "Q virus" associated with hydrides on the RF surface. The last preparation step was a high-pressure water rinse to eliminate particulates from the RF surface. Vertical RF tests were done before the He tank was installed; a horizontal test was done in the CHECHIA test cryostat after the He tank was welded on. After the CHECHIA test, the cavity was bled up with clean Ar gas and sent (in its He tank) to Fermilab.

3.2 Cavity Installation at Fermilab

At Fermilab, the cavity was leak-checked and installed in its cryostat. During the process, critical operations were carried out in a small mobile Class 100 clean room. An effort was made to maintain laminar flow in the vacuum system when pumping down and bleeding up the cavity. Precautions were taken to ensure cleanliness of beam line components downstream (all the way to the beam dumps) and upstream (up to and including the RF gun) of the cavity. Using hand-held particle counters, we confirmed that valves and flanges are a major source of particulate contamination.

4 CRYO AND RF MEASUREMENTS

4.1 RF Tests at DESY

In the best vertical test at DESY, the cavity quenched at E_a = 13 MeV/m in CW; the Q exceeded 10^{10} below the quench level [2].

In the horizontal test in the CHECHIA cryostat, the field was limited by cryo capacity. The attainable fields under different conditions are summarised in Table 2. The cryo losses as a function of E_a were measured (the Q cannot be measured with RF after the input coupler is installed, due to the strong input coupling), as shown in Figure 2. The power was deduced from the flow rate of He gas into the vacuum pumps.

Table 2. Maximum field values at 1 Hz repetition rate.

RF test in CHECHIA			
Fill Time [μs]	Flat Top Duration [μs]	Forward Power for Fill [kW]	Max E_a [MeV/m]
500	800	∼100	18.8
1100	0	150	26.5
200	0	1000	27.4

RF tests at Fermilab			
Fill Time [μs]	Flat Top Duration [μs]	Max E_a [MeV/m]	Cryo
500	800	17.4	overloaded
		15.3	okay
800	0	25.7	overloaded
600	0	22.5	okay

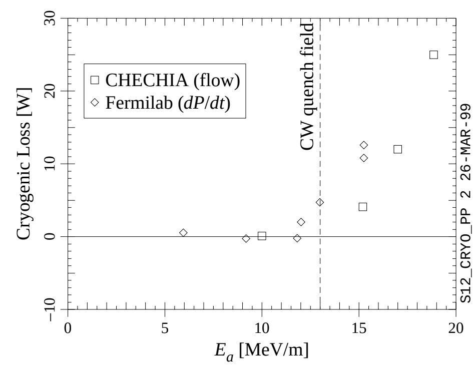

Figure 2. Cryogenic loss measurements with 500 μs fill time and 800 μs flat top at 1 Hz.

4.2 Cryo Measurements at Fermilab

The static heat leak into the He tank at 4.2 K was measured via the rate of decrease in liquid level with the supply valve closed: 3.6 W ± 0.3 W, which is equivalent to 5.8 litres/hour of He consumption. This is larger than values measured at Orsay for the TTF cryostat (2.3 W at 4.2 K, 3.2 W at 1.8 K), but still tolerable. The static He consumption of the cryo system at 1.8 K is typically 25 to 30 litres/hour. This high consumption is believed to be due to a significant heat leak in the transfer lines and inefficient operation of the JT heat exchanger (optimised for 100 to 200 W) at low flow rates. The capacity of the system is limited by the vacuum pumps. Static fluctuations in the bath pressure are typically ±1.3 mbar; the time scale is about 6 minutes.

4.3 RF Tests at Fermilab

The field level in the cavity is determined from the monitor probe signal after measuring the strength of the coupling between the cavity and the probe. Iteration was required to obtain a reliable coupling calibration. Our present value (Q_{ext}= $2.2 \cdot 10^{10}$) is somewhat different from what was measured in CHECHIA at DESY (Q_{ext}= $1.5 \cdot 10^{10}$).

As was the case at DESY, the cavity field in tests at Fermilab was limited by the cryo capacity. The attainable field levels are given in Table 2. Measurements of the cryo losses vs. E_a were repeated. The method was to close the supply and exhaust valves and measure the rate of pressure increase in the He tank, as done at the accelerator facility formerly known as CEBAF [9]. The rate of pressure rise was calibrated with a resistance heater in the bath. Our main difficulties with this measurement were in getting reliable and repeatable operation of cold valves; our technique is not yet very satisfactory. Our preliminary results are compared to the measurements at DESY in Figure 2.

With feedback on, the typical fluctuations in the amplitude and phase during the flat top portion of the RF pulse are $\pm 1\%$ and $\pm 0.5°$, respectively. Figure 3 shows a detail of the amplitude and phase of the monitor probe signal during the flat top. We measured the change in resonant frequency with bath pressure to be about 28 Hz/mbar. This is 1.4 times larger than predicted [3], but the feedback can still compensate for the pressure fluctuations.

5 FIRST BEAM TESTS

So far, we have operated the cavity with beam only long enough for beam energy measurements with a spectrometer. Measurements were done with the RF gun for TTF (in October 1998, just before the gun was shipped to DESY) and the RF gun for the Fermilab photo-injector (in March 1999).

The phase of the gun relative to the laser pulse was chosen to maximise the photo-current at the exit of the gun. The phase of the 9-cell cavity was then varied relative to the gun phase to maximise the beam energy as measured with the spectrometer. Results are given in Table 3. The agreement between the spectrometer measurement of the beam energy and the beam energy expected based on RF measurements for the gun and 9-cell is reasonable, given the uncertainties in both measurements.

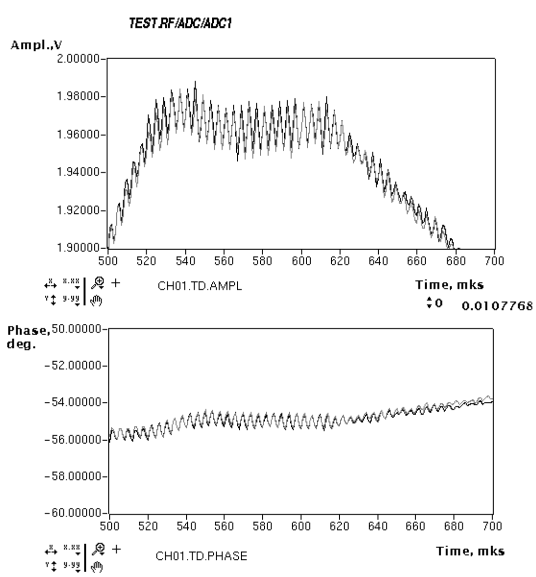

Figure 3. Detail of the amplitude and phase of the transmitted power during a 100 μs flat top, with feedback on.

Table 3. Beam energy measurements.

Conditions	Oct 1998	Mar 1999
Fill time	500 μs	
Flat top	$\sim$200 μs	100 μs
Bunches per train	1	70
Charge per bunch		$\sim$0.25 nC
Rep rate	1 Hz	
RF Results	Total Energy	
From Gun	4.3 MeV	4.3 MeV
From 9-cell	15.0 MeV	8.1 MeV
Total from RF	19.3 MeV	12.4 MeV
Spectrometer	Total Energy	
Dark current	19.9 MeV	
Photo-current	18.5 MeV	13.7 MeV

6 CONCLUSION

A TTF superconducting cavity has been installed and operated at Fermilab without severe degradation in its RF performance. We have accelerated beam with the RF gun and the superconducting cavity. The measured beam energy in the first beam tests is consistent with RF power measurements. Future plans for the machine, after it has been understood and optimised, include longitudinal compression with a chicane and experiments in fast diagnostics, plasma wake field acceleration, and channelling acceleration.

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