A REPORT ON FERMILAB SRF ACTIVITIES AND PROPOSALS

H. T. Edwards*, DESY and Fermilab#
MS306, PO Box 500, Batavia IL 60510, USA

Abstract

Three areas of SRF application underway or proposed at Fermilab will be discussed. The operation of the A0 Photoinjector using a TESLA cavity after the gun to accelerate the electron beam to 17 MeV has been ongoing for some months. A proposal to construct an RF separated kaon beam using transverse deflecting mode cavities has been developed and R&D initiated. Design study efforts on a neutrino factory and the use of low frequency cavities in the recirculating linac has just been started.

1 OVERVIEW

Fermilab has become a minor player in the use and design of superconducting RF cavities. Activities are in three diverse areas with rather different specifications and time scales. 1) An electron injector identical to that at TESLA TTF (TESLA Test Facility) of 17 MeV has been assembled and is in operation with beam characterization studies underway. 2) Design work is underway for construction of 3.9 GHz deflecting mode cavities to be used to provide a pure kaon beam for experiments in the Fermilab external beam area. 3) A design study of a 50 GeV muon storage ring is underway. The ring would provide neutrino beams. The potential benefit of superconducting RF to provide acceleration in the low energy linac and recirculating linacs is being considered.

2 THE PHOTOINJECTOR

The first superconducting RF application at Fermilab has been in the construction and operation of an electron photoinjector with the design parameters of the TESLA TTF Injector 2 [1]. The injector consists of a laser driven normal conducting 1.6 cell RF gun followed by a 9 cell superconducting TESLA cavity, a magnetic chicane for bunch compression, and various beam line components and diagnostics. The photo injector produces a 16-17 MeV beam with bunch charge of 1 to 10 nC and bunch length of 2 mm σ before compression, and expected normalized emittance 3 to 20 π mm mrad depending on bunch charge. Bunch spacing is one microsec and pulse length can be up to 800 microsec though typically 1 to 20 bunches are used during measurements. An identical gun and superconducting cavity system is in operation at TTF. Fig. 1 shows the injector layout.

Studies are underway [2] to investigate the transverse beam emittance at different beamline z locations as a function of the various parameters: charge, bunch length, gun gradient, phase, and solenoid field. Understanding, characterizing and minimizing the emittance at 1 nC is critical to the FEL operation at TTF and can be best done at Fermilab where other operational demands do not conflict as much as in the complex TTF.

The gun operates at 35 to 40 MV/m on the cathode to provide 4.5 MeV beam and the 9 cell cavity at 10-12 MV/m accelerating gradient. The 1.3 GHz RF peak power used is about 2.5 MW for the gun and less than 100 kW for the superconducting cavity, clearly reflecting the different technologies. The low level RF system of a TESLA design [3] provides phase and amplitude control of the gun and superconducting cavity and a phase stable oscillator reference to the laser.

The construction, commissioning and operation of the photoinjector has given Fermilab its initial experience with superconducting cavity technology as well as lasers, high gradient normal conducting RF, high vacuum and particle-free assembly, and the coordinated operation of the diverse systems.

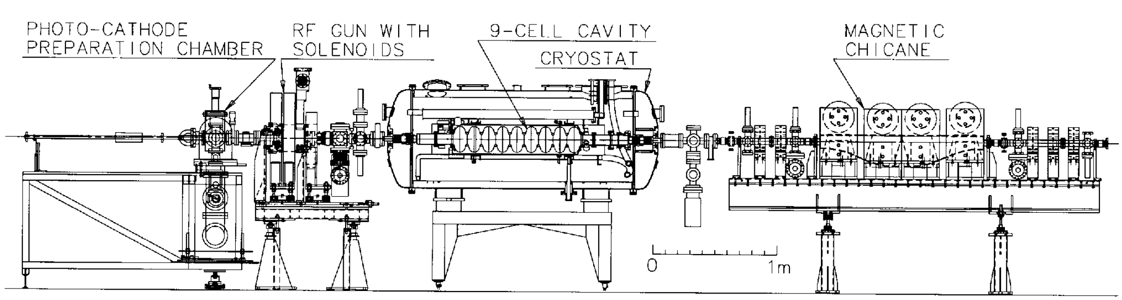

Figure 1: Elevation view of the photoinjector showing the gun, superconducting cavity and chicane.

#Operated by Universities Research Assoc under contract with the U.S. Dept of Energy.
*E-mail: hedwards@fnal.gov

2.1 Superconducting Cavity Experience

The superconducting cavity provided by DESY is one of several built early on which had a low quench field attributed to contamination in the equator welds [4]. The performance of the cavity has not been an issue in our application. The fact that it was not one of the very best made it ideal for us to proceed with gaining experience with its installation and operation.

The cavity was prepared and measured at DESY with both vertical dewar and horizontal "Chechia" cryostat. After removal from Chechia special beam tube extensions and gate valves were mounted to the "dressed" cavity and the assembly (under slight pressure) was sent to Fermilab in Sept. 1997 for assembly into its cryostat. The cryostat itself is a copy of that fabricated at Orsay for TTF [5]. The connection of the beam tube vacuum assembly to the cryostat end caps, and the final installation of cryostat-cavity assembly in the beam line were performed in portable cleanrooms.

In the beam line the cavity can be isolated by gate valves external to the cryostat which are in addition to those mounted inside the cryostat. It was found that the internal valves were very unpredictable and possibly vented the cavity with (cleanroom) air, not filtered dry nitrogen. These valves are no longer operated. It was necessary to remove the cryostat end after beam line installation in order to repair the tuner and fix a cryo hose. This work required that the cavity be vented twice.

The cavity is cooled by saturated 1.8K helium II supplied from a dewar system, heat exchanger, JT valve, and pumped to 12 torr [6]. Typical operation consists of cooling down early in the morning, operating during the day and evening, then letting the system drift up in temperature over night or weekend. An automatic procedure has been implemented and works effectively. Many thermal cycles from 1.8K to 50-70K have taken place. Additionally thermal cycles to higher temperature have happened a number of times, and room temperature warmups with pumpout of evolving gas has been done 4 times.

Measurements have been made of the calibration of the field gradient by measuring the forward power going to the cavity and the Q during decay [7]. The probe calibration does not agree very well with the DESY calibration. The probe Q_{ex} was calibrated at 1.5e10 at DESY and 2.2e10 at Fermilab.

Cryogenic measurements have also been carried out to determine the point of onset of high loss with gradient. The Fermilab measurements are compared with those from Chechia in Fig. 2 [6]. It would appear that some degradation has occurred though calibration of gradient in each case is probably no better than 10%. High peak power processing has not yet been attempted.

Additional information on the gradient calibration can in principle be gained by measurements of the beam energy from the gun and after the 9 cell cavity. These results [7] indicate agreement between the RF gradient calibration and beam energy measurements to typically 5%.

Operation so far has been without major difficulty. More running time for beam characterization, wakefield measurements, and experiments in plasma wakefield and channeling acceleration are planned.

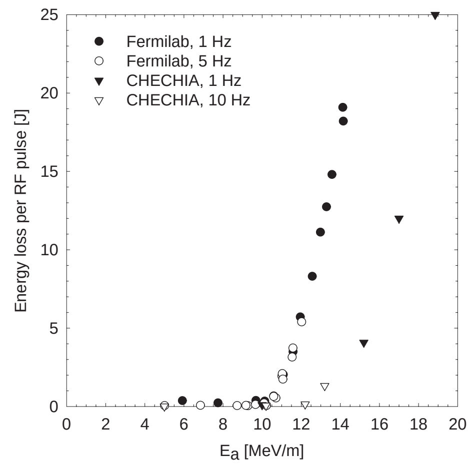

Figure 2: Superconducting cavity performance at DESY and at Fermilab after installation. Flat top duration 800 microsec.

3 THE KAON SEPARATED BEAM CAVITIES

A high purity kaon beamline is being planned at Fermilab [8, 9]. The key system for this beamline is two stations of superconducting cavities operating in the transverse deflecting mode. The present schedule calls for the beamline to be operational in 2006. Superconducting cavities are required because of a beam duty cycle of 1 sec beam time in a 3 sec cycle time.

The beamline concept is outlined in [9]. This concept is as follows. In a secondary beam of mixed pions, protons, and kaons the kaons can be "separated" from other particle types of the same momentum (in our case 22 GeV) by their relative time of flight between two deflecting mode RF stations. With transverse optics between the stations of +- I the deflection of the beam particles emerging from the second RF station will depend on: the phase at which the particles enter the first station, the relative phase of the two stations, the RF frequency (f), the distance between the stations (L), and the speed of the particles (β) relative to c. It is possible to choose a particular fL product such that for a specific β, a “closed" beam bump is produced so that there is no resultant deflection after the second station independent of the particle arrival phase at the first RF station. Particles of other velocities will arrive at a different time at the second station so the resultant bump will not be closed and they will have a net deflection dependent upon their arrival phase relative to the first station. If the RF deflection takes place all in one plane (h or v), the result will be that one particle species will have no resultant kick whereas others will be swept into a fan. For this case the purest kaon beam is obtained if the kaons are produced in a fan and the unwanted protons and pions are directed straight ahead into a stopper plug.

Circular polarized RF deflection is also possible (say by each station having horizontal and vertical deflection 90 degrees out of phase) then one species again has no deflection and other species will exit in a cone about this central trajectory. The cone angle will be dependent on the relative β of these other species. Here the station to station RF phase is chosen so kaons are undeflected and the protons-pions would be stopped in a collimator with a hole.

Because of the relatively short kaon lifetime the overall beam line and the distance between separator stations should be kept as short as possible. The frequency-separator distance product, $fL = 2c\gamma^2(\Phi/2\pi)$ is chosen so that protons arrive at the second station 2π after the pions and kaons arrive with a phase delay of about $\pi/2$ (a convenient result of kaon mass being about half that of the proton). For the 22 GeV beam fL is 330 GHz-m.

An RF cavity frequency of 3.9 GHz (TM110, π mode) has been chosen as the upper limit to be acceptable from the point of surface resistivity, thermal conductivity and experience with superconducting cavities. This leads to a station to station distance of 85 m for a 22 GeV/c kaon beam. The overall beam line is about three times this length. The 3.9 GHz frequency is also easily compatible with beam tests using the A0 photoinjector and its 1.3 GHz RF frequency. Alternatively, 3.25 GHz could be used with 102m L. Of the order of 30 MV equivalent transverse deflection is needed total for both stations.

Other applications of similar transverse deflection mode cavities are emerging, for instance splitting of linac beams for multiple FEL stations.

Table 1. Provisional parameters for transverse mode 3.9 GHz separator cavity system

frequency	3.9 GHz
mode	π, TM110
equator diameter	94 mm
iris diameter	30 mm
cell length	38.4 mm
cells per meter	26
cells per cavity	13
$(R/Q)'$	55 ohm/cell
$(r/Q)'$	1430 ohm/m
V_{trans} @ 0.1 T	5.7 MV/m
E_{peak}	22 MV/m
B_{peak}	0.100 T
U (stored energy)	0.92 J/m
coupling factor	0.051
$G_1 = Q \times R_{sur}$	236 ohms
R_{sur} @ 2K, T_c/T=4.6	$1.04 \times 10^{-7}\Omega$
Q @ R_{sur}	2.2×10^9
Power dissipated @ 5.7MV/m, 2K	10 watts/m
System Requirements for 30 MV/m total kick	
Total cryogenic power	48 watts @ 1.8K
	115 watts @ 2K
Q_L (loaded Q)	6×10^7
RF power @ 5.7 MV/m	380 watts/m
RF power including factor of 2 for regulation	760 watts/m
Total RF power	4 kilowatts

3.1 Provisional Cavity and System Parameters

Parameters considered for the point design [8] are given in Table 1. and the half cell geometry in Fig. 3. (See [10] for definition of transverse mode parameters.) The cavities would be polarized by using slightly elliptical dies. The 13 cell cavity has an active length of 1/2 m and at an equivalent operating gradient of 5 MV/m of deflection would have a Bpeak of 880 gauss, not far below the TESLA cavity Bpeak of 1000 gauss at 25MV/m in the accelerating mode. If 5 MV/m gradient can be achieved then of order 12 cavities would need to be installed.

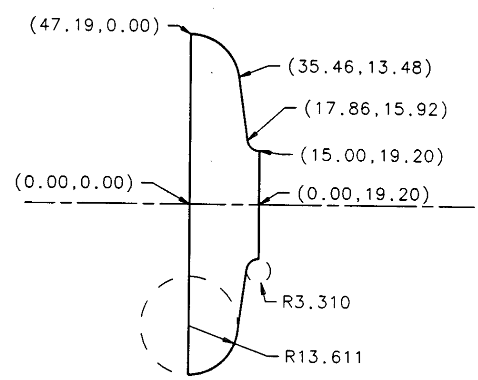

Figure 3: Geometry of the separator half cell. Dimensions in mm.

Conceptual drawings of the cavity in a demountable helium vessel and of a two cavity module are shown in Fig. 4 and Fig. 5.

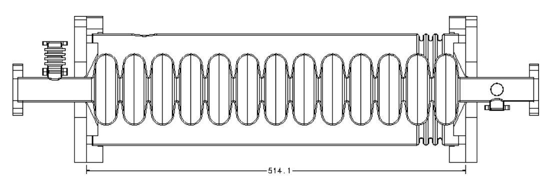

Figure 4: Conceptual drawing of the separator cavity in a demountable helium vessel.

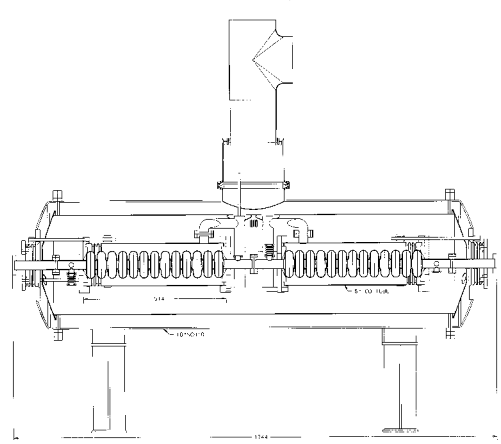

Figure 5: Cryostat module with two cavities.

3.2 Cavity Shape investigations

End cell geometry has been worked out to keep the equator and iris diameters fixed by making a squashed elliptical rather than a circular contour at the equator curvature.

The dispersion curve of the provisional cavity shape, Fig. 3 showed rather a small frequency separation between the π and π-1 modes of 900 kHz (df/f = -2.3 e-4) and led us to modifications in the cavity shape. In addition the small curvature of 3.31mm at the iris was found to be difficult in the die drawing and welding process. Contour radii at the iris and equator of (3.31, 13.6 mm) and of (4.5, 12.0 mm) have been investigated for different iris openings [11]. Fig. 6 shows the dispersion curve for the provisional shape, 15 mm R_{iris} and for a 19mm R_{iris} with 4.5 mm curvature. The 19 mm iris has a df/f of 6.5 e-4, however Bmax has increased 12% and (R/Q)' decreased by a factor of 0.67. In addition the modes appear to go from TM to TE as the band frequency is increased suggesting coupling between the M and E pass bands. Because of these results it has been decided to keep with the 15 mm R_{iris}, and to investigate the 4.5 mm curvature there.

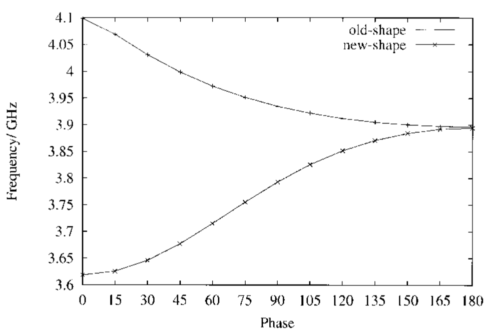

Figure 6: Dispersion curve of the prototype shape (old shape) and 15 mm iris radius and of a new shape with a 19 mm iris radius. The 15 mm iris radius will be used.

3.3 Status

A 5 cell Nb cavity has been fabricated from 1/16" material. Bead pull measurements are underway and tuning about to start. A vertical dewar setup has been supplied by Cornell and vertical dewar tests will be carried out first with a 3 GHz (acc mode) Cornell cavity, then with the 5 cell 3.9 GHz cavity.

4 POTENTIAL OF SRF FOR MUON STORAGE RING

A design study of a muon storage ring- neutrino source is underway at Fermilab as part of the Neutrino Factory and Muon Collider Collaboration. The study is to evaluate the technical feasibility and potential cost of a 50 GeV muon storage ring with intensity of 2.5e12 muons per pulse. Such a device should be less technically challenging and costly than a high energy muon collider while still confronting many of the issues and also providing an exciting physics tool for long baseline neutrino experiments.

The accelerator consists of: a proton driver, target station, pion decay channel and bunch rotation, ionization cooling of the muons at 190 MeV, a muon linac with acceleration to 1 GeV, two stages of recirculating linac, and the storage ring orientated at a dip angle out of the horizontal plane so as to direct decay neutrinos at some distant laboratory.

Of interest here is the potential use of superconducting RF which could be used in the proton driver [12] but more importantly in the muon linac and recirculating linacs. As the design study is only just underway parameter numbers given here reflect only initial input [13] to start a point design and the author's opinions, not official information from the collaboration.

The design has 2.5e12 muons in a pulse length of 150 nsec. Low frequency RF is necessary because of the large beam emittance both transversely and longitudinally. A frequency of 200 MHz is chosen for the reference design and would have 30 bunches of 8e10 per beam bunch or 2.7 amp current during the pulse. For some reasonable number of recirculation passes (3-5 each ring) in two rings of order 10-15 GV acceleration voltage could be required.

If one takes the parameters of a TESLA cavity as reference scaled to 0.2 GHz then an estimate of comparison of normal and srf can be made. The Q_{nc} of a normal conducting cavity would be ~70,000. If a gradient of 10 MV/m is assumed, the Q_b of the beam during the pulse is 24,000. For a recirculating time of 3.3 microsec (1000 m circumference ring) the duty factor is .045 leading to an average Q_b of 5.3 e5 and about 0.8% of the cavity energy is extracted with each pulse crossing. Peak RF power and fill time for the normal conducting case is 9.3 MW/m and 77 microsec. Equivalently for the sc case would be 1.2 MW/m and 580 microsec. RF energy per pulse would be about the same and result in 12 KW/m average power at 15 Hz rep rate.

The case for srf must be made through a comparison of the relative engineering difficulities of the two cases and the potential gradient advantage of the srf case. A major difficulity for the normal conducting case may be the very high peak power needed at 200 MHz where there is at present only limited potential power sources.

The main difficulity is that a frequency as low as 200 MHz is unatractive for either normal or superconducting systems and probably will be very expensive. It will be interesting to see the design as it matures.

5 ACKNOWLEDGEMENT

Special thanks to N Barov, L. Bellantoni, R. Carrigan, J.-P. Carneiro, M. Champion, E. Colby, D. Edwards, M. Fitch, S. Fritzler, A. Fry, W. Muranyi, J. Fuerst, W. Hartung, K. Koepke, M. Kuchnir, A. Melissinos, M. McAshan, and R. Wanzenberg.

6 REFERENCES

[1] D. A. Edwards (Ed.), TESLA Test Facility Linac Design Report, DESY Report TESLA 95-01.

[2] J.-P. Carneiro *et al.*, Beam Dynamics Studies in a High-Brightness Photo-Injector, Proceedings FEL'99, DESY Aug 99, NIM A to be published.

[3] A. Gamp et al., Experience with the Control of the Vector Sum at the Tesla Test Facility, Proceedings EPAC 98, Stockholm, Sweden, 1998.

[4] M. Pekeler, Experience with Superconducting Cavity Operation in the TESLA Test Facility, Proceedings PAC99, New York, 1999.

[5] S. Buhler *et al*., Status Report of the TTF Capture Cavity, Advances in Cryogenic Engineering, Vol. 41, Plenum Press, New York (1996), p. 863.

[6] J. D. Fuerst and W. H. Hartung, Dissipated Power Measurements in the A0 SRF Cavity System, Cryogenic Engineering Conference, July 1999, Advances in Cryogenic Engineering, Vol. 45, to be published.

[7] W. Hartung *et al*., Beam Test of a Superconducting Cavity for Fermilab High-Brightness Electron Photo-Injector, Proceedings PAC99, New York, 1999.

[8] R. N. Coleman, *et al*., An RF Separated Kaon Beam from the Main Injector: Superconducting Aspects, Fermilab Technical Memorandum TM-2060, October 19, 1998.

[9] T Koeth, Superconducting RF Cavity R&D for a Separated Kaon Beam at Fermilab, Proceedings PAC99, New York, 1999.

[10] H. Padamsee, *et al*., Proc. IEEE Particle Accelerator Conference, San Francisco, May
1991, p. 2426.

[11] R. Wanzenberg private communication. M. McAshan and R. Wanzenberg, RF Design of a Transverse Mode Cavity for Kaon Separation, paper under preparation.

[12] CERN is at present working on a proton driver design. B. Autin, H. Haseroth.

[13] N. Holtkamp, private communication.
www.fnal.gov/projects/muon_collider/nu-factory/