FY2006 ILC Request $320k
January 4, 2006

PROJECT DESCRIPTION
FY2006 ILC University Accelerator R&D

Half-Reentrant SRF Cavity Development for the ILC

Personnel and Institution(s) Requesting Funding
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Project Overview

We propose an advanced half-reentrant cavity design that has the potential to increase the accelerating gradient to >50 MV/m and to decrease the cryogenic load by over 20%.

CONCEPT FOR HALF-REENTRANT CAVITY

The baseline design for the International Linear Collider (ILC) is the superconducting, 1.3 GHz, 9-cell, TESLA structure [1]. The cavity uses elliptical arcs in the high electric and magnetic field regions that are connected on the radial sidewalls with a straight section whose angle is maintained steep enough to allow chemicals, gas and water to drain, and to adequately clean the surface during high-pressure rinsing. The peak surface magnetic field, B_p, attainable in niobium superconducting cavities is about 180 mT at 2 K that for the TESLA cavity corresponds to an accelerating gradient, E_a, and peak surface electric field, E_p, of 42 and 84 MV/m, respectively. During recent tests at DESY, a few multi-cell TESLA cavities have reached this limit, but a significant fraction of the cavities only achieved lower values implying that better performance could be obtained through improved processing and clean room procedures.

Beyond improved processing, further gradient gains can be achieved by advanced cavity designs with lower ratios of B_p/E_a. The design variables are not linearly independent. A smaller aperture will decrease B_p/E_a, but will lower the cell-to-cell coupling, k_c, and increase the number of trapped higher order modes. The tapered wall angle can be decreased and even made reentrant to decrease B_p/E_a, but this will increase E_p/E_a and make processing more difficult since the surface is harder to reach at normal incidence with the high pressure water jets and more likely to trap water with entrained particulate.

These techniques have been employed for the low-loss (LL) and reentrant cavities that have been prototyped in the last few years [2,3]. Recently, single-cell reentrant cavities have demonstrated accelerating gradients above 50 MV/m at Cornell and KEK, but serious concerns still exist about the ability to reliably process and achieve high performance for multi-cell versions [4-6].

A technique that is being pursued at Michigan State University and is the focus of this proposal, is to make one side of the cell reentrant and leave the other side non-reentrant. The concept for this cavity was first presented at the Applied Superconductivity Conference in 2004, and a preliminary design was presented at the Workshop on RF Superconductivity in 2005 [7,8].

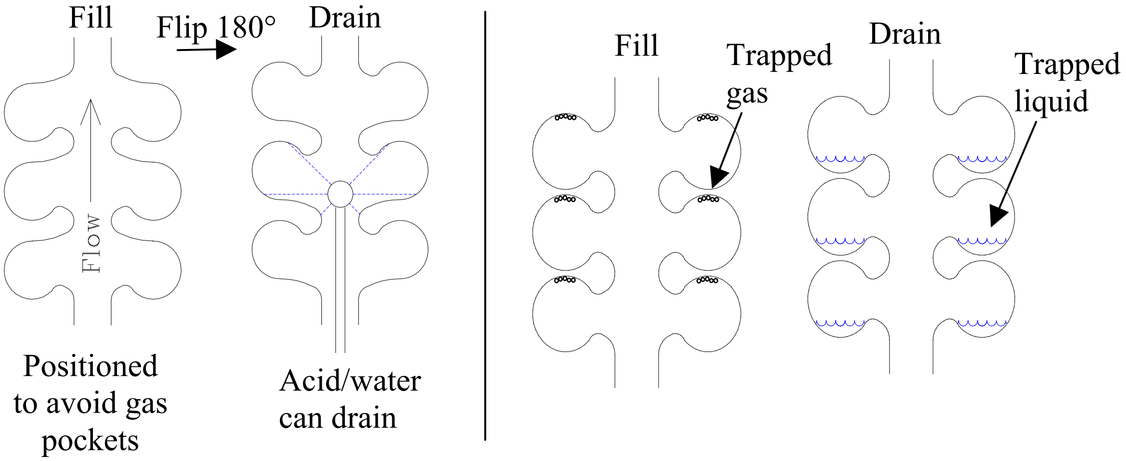

Figure 1. Processing steps for half-reentrant (left) and reentrant cavities (right).

By making the cavity shape reentrant, the surface magnetic field can be reduced, which allows for a reduction in the cryogenic load and a higher accelerating gradient. With a half-reentrant shape instead of a fully reentrant shape, liquids can still drain out easily during chemical etching and high pressure water rinsing, and there is no risk of trapped gas pockets in the acid. Figure 1 shows conceptually how the half-reentrant cavity is etched in one orientation and then rotated by 180º to drain the acid and rinse, and it also shows the problem encountered by reentrant cavities.

DESIGN

The electromagnetic performance of the half-reentrant cavity is nearly identical to that of the reentrant cavity and better than that of the low loss (LL) cavity. Therefore the half-reentrant should be better suited to multi-cell performance at accelerating gradients approaching 50 MV/m.

Table 1 shows the electromagnetic parameters of the potential candidates for the ILC, which are the TESLA (baseline design), low-loss, reentrant, and the half-reentrant cavities. The last type is the focus of this proposal. Figure 2 shows the half-reentrant cross section compared to the other types. Figure 3 shows the electric and magnetic field contours, and Figure 4 plots the surface fields along the perimeter of the half-reentrant cavity.

Table 1. Comparison of electromagnetic performance of candidate ILC cavities.

		Low Loss		Reentrant		Half Reentrant		
Parameter	TESLA [1]	CEBAF [2]	ICHIRO [3]	Small [4]	Large [5,6]	Small	Large	Prototype
Iris radius (mm)	35	30.5†	30	30	35	29	35	29
Wall angle	13°	8°	0.16°	--	--	2°	2°	8°
k_c (%)	1.87	1.49	1.55	1.57	2.38	1.52	2.43	1.47
B_p/E_a [mT/(MV/m)]	4.26	3.74	3.60	3.55	3.78	3.51	3.82	3.55
E_p/E_a	2.0	2.17	2.31	2.26	2.40	2.40	2.39	2.41
G × R/Q (Ω^2)	30510	36103	37900	38350	33768	39363	33719	38797
R/Q (Ω)	113	129	134	136	121	137	119	136
G (Ω)	270	280	283	282	280	286	284	285
Equator radius (mm)	103	100†	98.1	--	98.7	96.9	98.4	97.6

† Radii scaled from 1.5 GHz to 1.3 GHz for comparison (values at 1.5 GHz are 26.5 and 87 mm)

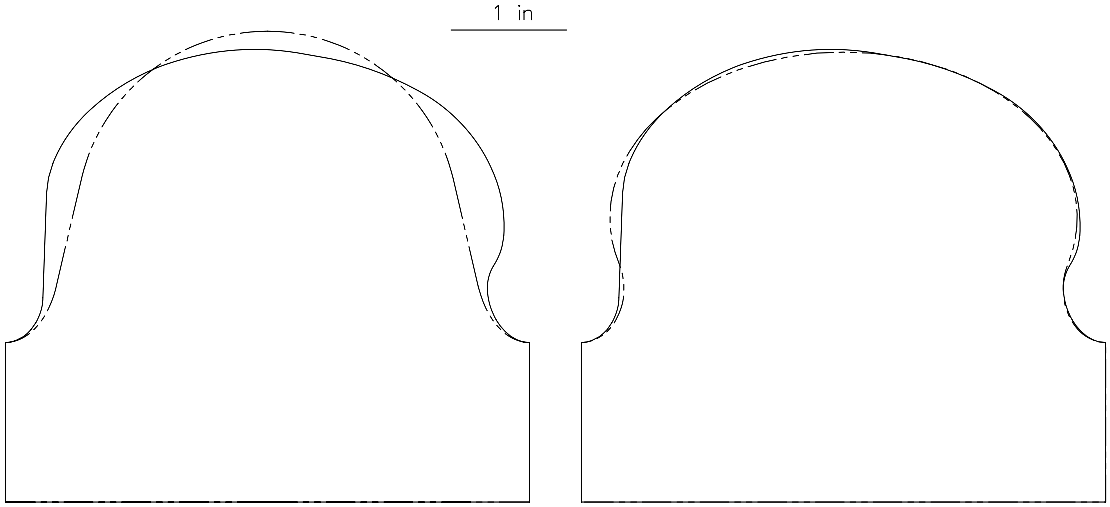

Figure 2. Half-reentrant cross section compared to TESLA (left) and reentrant (right). The large aperture half-reentrant and reentrant designs are shown.

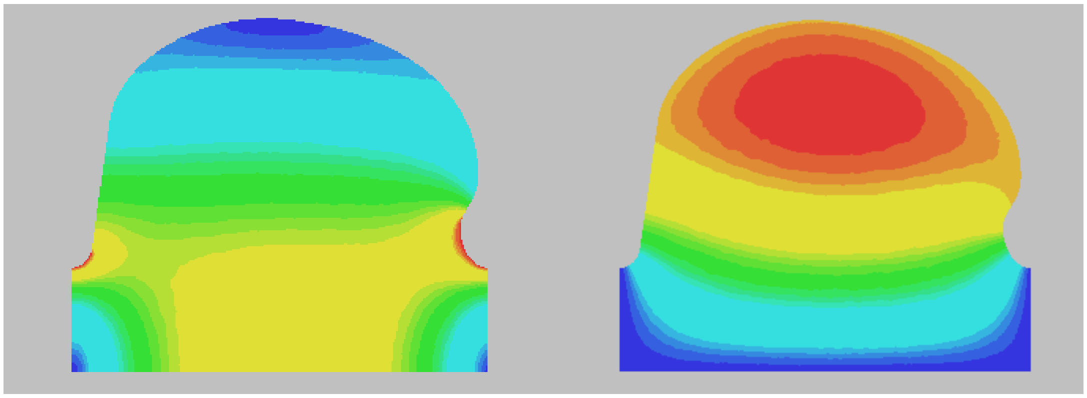

Figure 3. Electric (left) and magnetic (right) field contours of the small aperture 8° half-reentrant central cell.

For the low-loss cavity, two types are shown in Table 1 with decreasing wall angle. Both have smaller apertures than TESLA which decreases k_c from 1.87 to about 1.5. The smallest side angle low-loss cavity has been nicknamed ICHIRO and has gone to the extreme limit of a flat sidewall. This significantly decreases B_p/E_a from 4.26 mT/(MV/m) for the 13° sidewall of TESLA to 3.60 mT/(MV/m).

By taking the sidewall angle negative, the cavity becomes reentrant and further improvement is possible. Two reentrant designs are shown in Table 1; a design with a small aperture and low k_c and one with the same aperture as TESLA, which presumably gives similar HOM characteristics since the cutoff frequency is the same for both cavities.

Both reentrant designs give significantly lower B_p/E_a than TESLA. But, comparing the small aperture low-loss and small aperture reentrant shows only a small improvement in B_p/E_a from 3.60 mT/(MV/m) to 3.55 mT/(MV/m). The increased difficulty of trapped gas and liquid during processing of multi-cell structures may negate the small improvement over low-loss designs.

The parameters of three half-reentrant designs are given in Table 1. The first two use a small side angle of 2° to obtain the best performance assuming that the processing and draining do not limit performance, which is the same assumption used for the low-loss designs. The 2° half-reentrant designs are a small aperture with E_p/E_a~2.4 and k_c~1.5, and a large aperture that is the same as TESLA.

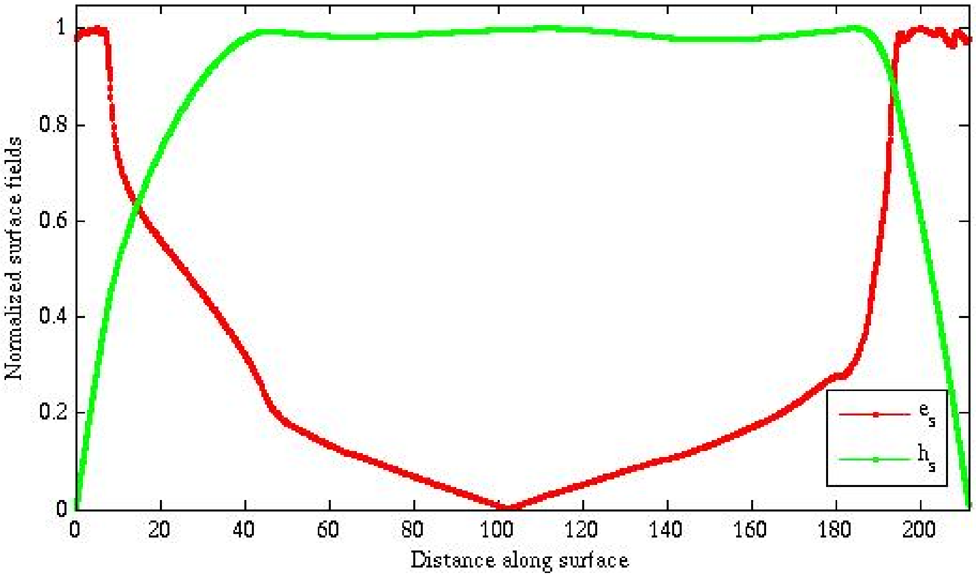

Figure 4. Normalized surface electric (e_s) and magnetic (h_s) fields of the small aperture 8° half-reentrant central cell.

Both 2° half-reentrant designs give significantly better performance than TESLA, and are nearly identical to the reentrant designs. But, the small aperture half-reentrant does have a lower B_p / E_a of 3.51 mT/(MV/m) and therefore has the potential to obtain higher fields than the world record setting reentrant cavity. The cryogenic load of the small aperture half-reentrant cavity, which scales inversely with (R/Q)G is 22% lower than the TESLA design and is even lower than the reentrant cavity. Also, the processing of a half-reentrant cavity is much more straightforward using existing techniques and more likely to be applicable to industrial production of multi-cell cavities and cryomodules than the reentrant cavities.

The final half-reentrant design shown in Table 1 uses a larger side angle of 8°, which is closer to the TESLA design. With the steeper angle on the non-reentrant side this cavity should drain quicker and be easier to process. The electromagnetic performance is only slightly degraded from the 2° design and is still comparable to the reentrant design. The first half-reentrant prototype, which is discussed in the next section will use the 8° design as a conservative step in demonstrating the concept.

SINGLE-CELL HALF-REENTRANT PROTOTYPE R&D

The central cell's electromagnetic design is complete. The first prototype will be a single-cell cavity to prove the concept works and show that multipacting does not limit the achievable gradient. During single-cell testing, the design and plans for a 9-cell prototype can be advanced. The single-cell work will occur during the first year and will include:

1. Single cell mechanical design
2. Mechanical analysis (Lorentz detuning, df/dp)
3. Multipacting simulations
4. Design and fabrication of half-cell and beam tube dies
5. Cavity fabrication and electron beam welding
6. Fixed coupler design and fabrication
7. Chemical etch (BCP) and high pressure rinse in Class 100 cleanroom
8. Installation on insert for cooldown to 1.5-2 K
9. High gradient rf test
10. Post purification at 1400° C and electropolish (these steps are needed to achieve the highest gradients and reduce the high-field Q-slope.
11. Repeat the high gradient rf test

Three (3) single-cell cavities will be fabricated to increase the likelihood of a successful test and allow rapid turnaround of processing and testing. This also increases the statistics of achieved gradients, which helps to diagnose weaknesses in the processing and testing systems. High RRR niobium with either the standard fine grain or single crystal will be used depending on material availability.

NINE-CELL HALF-REENTRANT PROTOTYPE R&D

During testing of the single-cell prototypes, the 9-cell cavity's design and test plans will be finalized. The end cells will most likely use the same beam pipes with couplers as the TESLA cavity. The two ends will have different shapes to reduce the chance of trapped higher-order modes. The 9-cell prototype R&D program will include:

1. Nine-cell mechanical design
2. Mechanical analysis (Lorentz detuning, df/dp, stiffening rings)
3. Multipacting simulations
4. Higher-order mode analysis
5. Design and fabrication of end half-cell and beam tube dies
6. Cavity fabrication and electron beam welding
7. Fixed coupler design and fabrication
8. Chemical etch (BCP) and high pressure rinse in Class 100 cleanroom
9. Installation on insert for cooldown to 1.5-2 K
10. High gradient rf test
11. Post purification at 1400° C and electropolish (these steps are needed to achieve the highest gradients and reduce the high-field Q-slope).
12. Repeat the high gradient rf test

The 9-cell program will begin during the second half of the first year and last for about 1.5 years. Three (3) cavities will be fabricated without radial coupling ports, helium vessel, HOM dampers or stiffening rings to quickly and inexpensively prove the concept. This will also address field flatness and frequency measurements and tuning. High RRR niobium with either the standard fine grain or single crystal will be used depending on material availability.

During the second year the 9-cell cavities will be fabricated, chemically etched (BCP) and tested as shown above in steps 1-10. The final year will also see the cavities post purified and electropolished. Upon completion of this R&D program, a fully dressed (radial coupling ports, HOM dampers, helium vessel and stiffening rings) 9-cell half-reentrant cavity can be fabricated and tested as a follow on project.

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[1] B. Aune, et al., “Superconducting TESLA Cavities”, Phys. Rev. STAB, Vol. 3 092001 (2000).
[2] J. Sekutowicz, et al., “Cavities for JLAB’s 12 Gev Upgrade", Proc. of the 2003 IEEE Particle Accelerator Conference, Portland OR (2003).
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[7] T.L. Grimm, A. Aizaz, M. Johnson, W. Hartung, F. Marti, D. Meidlinger, M. Meidlinger, J. Popielarski, R.C. York, “New Directions in Superconducting Radio Frequency Cavities for Accelerators”, IEEE Transactions on Applied Superconductivity, 15, No. 2, p. 2393-2396 (June 2005).
[8] M. Meidlinger, T.L. Grimm, W. Hartung, “Design of Half-Reentrant SRF Cavities”, Proc. of the 12th Workshop on RF Superconductivity, Ithaca NY (2005).

Broader Impact

The half-reentrant cavity offers the improved performance of the reentrant cavity, while continuing to use the standard chemical processing and high pressure rinsing techniques. This cavity with its higher accelerating gradient and lower cryogenic loss can be applied to any future accelerator that uses elliptical SRF cavities. The improvements are anticipated to be even greater for cw applications with smaller k_c, as well as proton and heavy ion reduced beta linacs.

Results of Prior Research

Several advanced designs are being pursued such as the low-loss (LL) and reentrant cavities that have been designed and prototyped in the last few years [2,3]. Recently, single-cell reentrant cavities have demonstrated accelerating gradients above 50 MV/m at Cornell and KEK, but serious concerns still exist for the processing and performance of multi-cell versions [4].

The half-reentrant concept was first presented at the Applied Superconductivity Conference in 2004, and a preliminary design was presented at the Workshop on RF Superconductivity in 2005 [5,6].

Facilities, Equipment and Other Resources

This research can be completed using the existing facilities and infrastructure at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. The NSCL facilities include an electronics shop, fully integrated mechanical design department and machine shop, cryogenics plant (1.75 kW), computer department, welding department and fabrication and assembly group. The superconducting radio frequency division at the NSCL has additional specialized facilities to manufacture, process, and test the superconducting cavities. The infrastructure includes a class 100 and a class 10,000 cleanroom, ultra pure water system (>17 MΩ·cm), chemical etching facility with 500 CFM scrubber, sub atmospheric pumping system (1.5-4.5 K), two shielded (magnetic and radiation) vertical test Dewars, and RF testing equipment.

FY2006 Project Activities and Deliverables

SINGLE-CELL HALF-REENTRANT PROTOTYPE R&D

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During testing of the single-cell prototypes, the 9-cell cavity's design and test plans will be finalized. The end cells will most likely use the same beam pipes with couplers as the TESLA cavity. The two ends will have different shapes to reduce the chance of trapped higher-order modes. The 9-cell prototype R&D program in 2006 will include:

1. Nine-cell mechanical design
2. Mechanical analysis (Lorentz detuning, df/dp, stiffening rings)
3. Multipacting simulations
4. Higher-order mode analysis

FY2007 Project Activities and Deliverables

NINE-CELL HALF-REENTRANT PROTOTYPE R&D

During testing of the single-cell prototypes, the 9-cell cavity's design and test plans will be finalized. The end cells will most likely use the same beam pipes with couplers as the TESLA cavity. The two ends will have different shapes to reduce the chance of trapped higher-order modes. The 9-cell prototype R&D program in 2007 will include:

5. Design and fabrication of end half-cell and beam tube dies
6. Cavity fabrication and electron beam welding
7. Fixed coupler design and fabrication
8. Chemical etch (BCP) and high pressure rinse in Class 100 cleanroom
9. Installation on insert for cooldown to 1.5-2 K
10. High gradient rf test

11. Post purification at 1400° C and electropolish (these steps are needed to achieve the highest gradients and reduce the high-field Q-slope).
12. Repeat the high gradient rf test

The 9-cell program will begin during the second half of the first year and last for about 1.5 years. Three (3) cavities will be fabricated without radial coupling ports, helium vessel, HOM dampers or stiffening rings to quickly and inexpensively prove the concept. This will also address field flatness and frequency measurements and tuning. High RRR niobium with either the standard fine grain or single crystal will be used depending on material availability.

During the second year the cavities will be fabricated, chemically etched (BCP) and tested as shown above. The final year will also see the cavities post purified and electropolished. Upon completion of this R&D program, a fully dressed (radial coupling ports, HOM dampers, helium vessel and stiffening rings) 9-cell half-reentrant cavity can be fabricated and tested as a follow on project.

Budget Justification

	FY06	FY07
Design		
Single-cell	0.4 FTE	
Nine-cell	0.5 FTE	0.9 FTE
Vertical test setup	0.3 FTE	
HOM analysis		0.6 FTE
Mechanical analysis		0.6 FTE
Prototype (3) single-cell cavities		
Dies and fixtures	20 k	
Material	25 k	
Machine and form	15 k	
Electron beam	5 k	
BCP and test	0.2 FTE	
Post purify, EP and test		0.2 FTE
Prototype (3) nine-cell cavities		
Dies and fixtures		20 k
Material		80 k
Machine and form		60 k
Electron beam		30 k
BCP and test		0.3 FTE
Post purify, EP and test		0.36 FTE
Analyze and document results	0.3 FTE	0.6 FTE
Materials and supplies	10 k	20 k
Travel	5 k	7 k
Subtotal manpower	1.7 FTE	3.56 FTE
Subtotal manpower	240 k	502 k
Equipment	65 k	190 k
Materials, supplies and travel	15 k	27 k
TOTAL	320 k$	719 k$

FY06-FY07 TOTAL 1039 k$

Two-year budget in then-year $

Item	**FY2006**	**FY2007**	**Total**
Other Professionals	$83,623	$203,955	$287,578
Graduate Students	$21,395	$22,037	$43,432
Undergrad Students	$8,840	$9,105	$17,945
Total Salaries and Wages	**$113,858**	**$235,097**	**$348,955**
Fringe Benefits	$34,814	$82,387	$117,201
Total Salaries, Wages and Fringe Benefits	**$148,672**	**$317,484**	**$466,156**
Equipment	$65,000	$190,000	$255,000
Travel	$5,000	$7,000	$12,000
Materials and Supplies	$10,000	$20,000	$30,000
Other direct costs	$7,805	$8,429	$16,234
Total direct costs	**$236,477**	**$542,913**	**$779,390**
Indirect costs	$83,473	$175,687	$259,160
Total direct and indirect costs	**$319,950**	**$718,600**	**$1,038,550**