Snowmass WG5: Superconducting Cavities and Couplers
(Draft August 12, 2005 Rong-Li Geng)

Topic 1: Cavity Shape

Overview

The cavity shape determines the fundamental mode as well as the higher order modes properties. The aperture of cavity cells determines the loss factor of wakefields. There are several options under consideration for ILC BCD and ACD. These options differ in terms of the following cavity parameters,

- The ratio of the peak magnetic field to the accelerating gradient (Hpk/Eacc).
- The ratio of the peak electric field to the accelerating gradient (Epk/Eacc).
- The product of the geometry factor G and R/Q (G·R/Q).
- The cell-to-cell coupling factor (k_c).
- The loss factors of longitudinal ($k_{\parallel}$) and transverse ($k_{\perp}$) wakefields.
- The Lorentz detuning factor (K_L).

The choice of a specific shape has profound impact on the cavity performance, beam quality and beam stability. The mature TESLA shape has a favorable low Epk/Eacc, a large cell-to-cell coupling and small wakefield loss factors. It has lower risk of field emission and dark current. Two major new shapes, the Cornell re-entrant shape and the DESY/KEK low-loss shape, are under initial developments. Both new shapes have a lower Hpk/Eacc and a higher G·R/Q. They have a higher gradient reach and lower cryogenic losses. The iris aperture is a major geometrical difference between the two new shapes. The DESY/KEK low-loss shape has a smaller iris aperture, whereas the Cornell re-entrant shape has the same aperture as that of the TESLA shape.

Options under consideration

The following options exist and are under consideration for ILC BCD and ACD,

- TESLA shape
- Cornell Re-entrant shape
- DESY/KEK Low-Loss shape

A comparison of major cavity parameters is given in the following table.

Parameter	Iris Dia.	Epk/Eacc	Hpk/Eacc	G·R/Q	k_c	$k_{\parallel}$	$k_{\perp}$	K_L
Unit	Mm	-	Oe/(MV/m)	Ω·Ω	%	V/pC	V/pC/cm^2	Hz/(MV/m)^2
TESLA	70	1.98	41.5	30840	1.90	1.46	0.23	-0.74
Re-entrant	70	2.40	37.8	33762	2.38	1.45	0.23	-0.81
Low-loss	60	2.36	36.1	37970	1.52	1.72	0.38	-0.83

Note: 1) Loss factors assume bunch length σ_z=1mm. 2) Lorentz force detuning assumes 2.8 mm cavity wall thickness and optimal stiffing.

Modifications/variants of these shapes also exist, such as the smaller aperture (60mm) re-entrant shape and the half re-entrant shape.

BCD choice: TESLA Shape (assuming BCD goal gradient ≤ 35 MV/m)

Pros & Cons of BCD *(technical, cost, reliability/risk)*
The TESLA cavity is the benchmark that all other designs must be compared to.

Pros:
It has low Epk/Eacc, large cell-to-cell coupling and small wakefield loss factors.

It has been studied and tested extensively: It has achieved ≥ 35MV/m gradient at Q ≥ 8×10^9 for a number of cavities, as well a one cavity in a module with beam. Over 80 cavities have been constructed. Wake fields have been thoroughly investigated. Cavities and modules have operated in TTF for considerable time. The cost basis for limited quantity is well established and a number of vendors have produced these cavities. Cavity Data base, processing and test history is extensive. Industrialization studies of fabrication and processing have been carried out. These cavities are planned for the XFEL. These cavities are closest to meeting ILC requirements at this time.

Pro & Con:
35MV/m is close to the ultimate gradient (42MV/m) for this cavity shape. This points to the maturity of the R&D program.

Cons:
This shape has a higher Hpk/Eacc and a higher risk of premature quench induced by a higher surface magnetic field for gradients > 35 MV/m. These cavities do not have the ultimate gradient potential that some of the other ACD designs have. However other designs reduce Hpk/Eacc at the expense of Epk and/or iris diameter. These new shape cavities have not yet been proven as a module operating at 35MV/m with a beam.

Potential cost impact
Cost optimization models indicate a potential cost increase of the ILC of 3-5% if this gradient (35MV/m) is used relative to a higher one (40-45MV/m). However other intangibles are not reflected in this estimate. (e.g. reliability, dark current)

Potential Mods to BCD

Impact (tech, cost, difficulty /time scale).
A number of minor modifications and improvements could be implemented without impact to the basic cavity design. These include:

- Slight modifications to the HOM, and pickup design for ease of fab, fundamental power rejection, and thermal stability.
- Design modification to the helium vessel end walls for more strength.
- Shortening the beam tube lengths to their acceptable minimum
- Review of the overall mechanical design, including flanges, and end group fabrication, with an eye toward industrial production.

Technical advantages, increased tech potential:

Savings in cavity length (and interconnect) will shorten the tunnel required. HOM's would have better power margin.

Potential cost impacts:

If a 5% cavity slot length reduction could be realized, this would impact the tunnel length and cost (but probably less than or ~ 1% of total cost.) Greatest cost impact is probably in the design for industrial production if good ideas emerge.

Risk and Reliability impacts:

Better design with more margins should decrease risk and improve reliability. This is especially true if a reliable and simple flange design (or weld) can be developed.

R&D necessary (at different levels)

Most critical R&D is the establishment of proof of principle of 35MV/m modules. And the ability to get adequate gradient safety margin and get reproducible high gradient results from cavity processing and test.

ACD Choices prioritized

Overview

1) A number of different cavity shapes are being proposed. These shapes tend to decrease Hpk/Eacc (Pro) and increase G·R/Q (Pro), but increase Epk/Eacc and may have smaller iris diameters (Cons). The most work to date has been done on the DESY/KEK low-loss.
2) The "superstructure" concept is different in nature in that it is an idea that can be applied to any of the cavity shapes including TESLA.

ACDs

Pros & Cons of specific ACD

1) New cavity shapes
<u>DESY/KEK low-loss shape - priority 1 ACD</u>
Pros:

Most work done to date.

Successful test of 40 MV/m with 1.3 GHz single cell cavity (45 MV/m with 2.2 GHz single cell cavity).

Computational analysis of wakefields underway.

Test of 9 cell cavity underway.

Lorentz force detuning analysis underway.

Cons:

Has smaller iris than TESLA.

May have less mechanical strength.

Needs much development and testing to reach maturity of TESLA.

Cornell Re-entrant shape

Pros:

Has expectation of higher gradient with TESLA like iris diameter.

Single cell tested to 47 MV/m.

Successful HPR with single cell done to give record Epk (> 100 MV/m).

First order HOM analysis of multicells complete.

Lorentz force detuning analysis underway.

9 cell cavity fabrication plans underway.

Cons:

Weaker mechanical strength.

HPR maybe problematic because of re-enterent design. (there is a similar idea with reentrant only on one side).

Needs much development and testing to reach maturity of TESLA.

Modifications/ variants of re-entrant: smaller aperture re-entrant and half-re-entrant.

Other shape designs

Pros $ Cons similar to above but mush less developed ideas

Summarize status -

Generally for new shapes

Technical advantages, increased tech potential

Reduced risk of premature quench due to lower Hpk/Eacc for gradient > 35 MV/m.

Higher gradient – possibly up to 45-50 MV/m.

Has higher G·R/Q – so lower cryogenic power loss.

Needs shorter tunnels.

Gradient improvement could be used for operating margin.

Potential cost impacts

Cost model estimates 3-5% for total cost (is this correct?).

Risk and Reliability impacts

Has higher Epk/Eacc.

Dark current (exponential with Epk) may be a greater problem.

Operating at higher gradient implies greater reliability issues, and greater risk, especially during commissioning and early operation.

R&D necessary (at different levels)

Considerable R&D will be required and different check points:

Wake fields:

a) The allowed iris diameter must be specified from theoretical analysis. This is a trade off between allowable emittance growth (luminosity) and cost.

b) Complete wake field analysis must be carried out computationally and checked with measurements.

c) Cold tests of wake fields must be carried out on two or more adjacent cavities.

d) Wake fields must be checked in modules with beam.

Gradient and Q:

a) Gradient and Q expectations up to at least 35MV/m must be achieved first in single cavity tests then in modules with beam.

Time scales for R&D

a) Specification of iris diameter should take place ASAP (2-3 months).

b) Initial single cavity test results should be expected within a year.

c) Full program to bring one of these cavity ideas to the state of understanding of the TESLA cavity may be of order 5 years with funding at ~ 25M$/y???

d) The rules for when the ACD would be considered to replace the present BCD should be proposed. Such a point might be when ~6 cavities have achieved gradients in excess of 35MV/m with Q >??, and when HOM damping has been checked in at least a 2 cavity string without beam.

<u>2) Superstructure</u>

Pros:

Super structure has possibility for significant cost savings through the use of only one input coupler per two cavities.

Significant design work has been carried out.

A two superstructure module (with two pair of 7 cell structures) has been tested with beam at DESY.

Wake fields have been investigated and the mode analysis understood.

Cons:

A main drawback of the superstructure is how to process and test such a long assembly, either with BCP or EP processing. This would take significant infrastructure development beyond that needed for single cavity structures.

Alternatively a superconducting joint might be developed to join the superstructure pair after processing. This has been attempted recently at DESY without success.

Pros & Cons of specific ACD

Technical advantages, increased tech potential

The main technical advantage would be the reduction in the number of input couplers by a factor of two. These couplers would need to carry double power.

Wake fields are less????

Potential cost impacts

The cost saving might be the cost of ½ the couplers. Assuming couplers are ¼ the module cost, and modules 1/3 of the over all cost then saving might be ~ 8%. However if coupler fabrication cost is reduced significantly then the impact would be less.

Risk and Reliability impacts

R&D necessary at different levels and check points

The most important R&D that could be undertaken immediately is work on a superconducting seal joint. (This is being started at JLab).

Time scales for R&D