Options for the ILC Crab Cavity

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Requirements

Working assumptions:

theta_c = 20 mrad	Crossing angle (each cavity compensates half)
beam energy = 500 GeV	Assume a 1 TeV collider
R12 = 10 m	Transport element between cavity and IP
sigma_x_ip = 500 nm	Beam transverse size at IP
sigma_ x _crab = 500 microns	Beam transverse size at crab cavity

Required deflecting field: bunches centered about rf zero crossing so

kick voltage = V * sin(kz) ~ V k z where k = 2*pi / lambda_rf

(lambda_rf = 23.0 cm for 1.3 GHz)

position offset at IP = R12 * kick voltage / beam energy

want this to equal theta_c * z / 2

Thus V = theta_c * beam_energy * lambda_rf / (4*pi*R12) or

V = 18.3 MV for 1.3 GHz and 6.1 MV for 3.9 GHz

Tolerance on crab kick amplitude – if require the transverse beam offset relative to nominal to be less than 1/3 of the beam sigma at +/- 2 sigma in z, then 2*sigma_z * d_theta < sigma_x_ip / 3. With d_theta = d_kick / kick * theta_c/2, d_kick / kick < sigma_x_ip / (3 * sigma_z *theta_c) = 0.5 / (3 * 300 * 20e-3) or d_kick / kick < 2.8 %.

Required cavity-to-cavity phase stability. To keep beams in collision to sigma_x_ip / 3, the rms relative cavity-to-cavity timing error needs to be:

delta_t < (2/3) sigma_x_ip / (c * theta_c) = 0.06 ps

which corresponds to phase errors of

0.03 degrees at 1.3 GHz and 0.08 degrees at 3.9 GHz

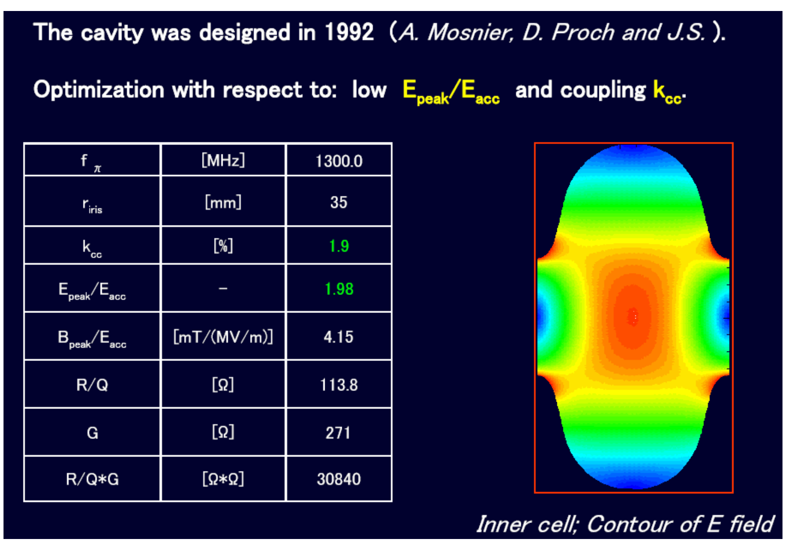
Would drive cavities from common source. The horizontal fast intratrain feedback would correct slow (> ~ 1 microsecond) time variations.

The choice of the frequency is open, but need to make sure that the cavity has a sufficiently large aperture – how large has yet to be specified. Also, want cavity length to be ~ 1 m or less.

Another possible constraint may be the transverse dimension of the cavity. If it is located 15 m from the IP, then the clearance to the outgoing beam is 30 cm (minus some margin).

Comparison of Accelerator and Deflecting Mode Field Strengths

The parameters of the 1.3 GHz TESLA baseline cavities are shown below. For a 25 MV/m gradient, the max B field is 4.15*25 = 104 mT and Epeak = 49.5 MV/m.



These values agree with those in the Linac04 paper on the 3.9 GHz, superconducting, deflecting-mode cavities being developed at FNAL, initially for the CKM project. Table 1 (see below) in this paper compares the TESLA cavities at 25 MV/m with the deflecting-mode design (called CKM) with 5 MV/m transverse fields. Thus, the critical magnetic field (~ 200 mT) should be the main limit to achieving high deflecting fields (as opposed to field emission).

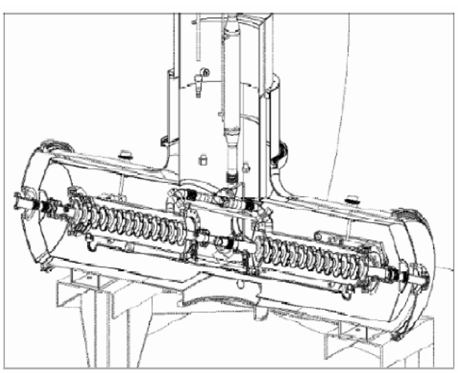
Cavity type	mode	Freq, GHz	$E_a/P_\perp$ MV/m	Bmax mT	Emax MV/m
TESLA	TM010	1.3	25	105	50
CKM	TM110	3.9	5	80	18.5

FNAL 3.9 GHz Deflecting-Mode Cavity Design

In a paper at PAC01, the design of a 13 cell deflecting-mode cavity for the FNAL CKM project is presented. It has the following parameters:

Frequency	3.9	GHz
mode	π, $\approx$TM110	
Equator diameter body, (end)	94.36 (95.10)	mm
Iris diameter	30	mm
Cell length	38.4	mm
cells/cavity	13	
Effective RF length/cavity	499.2	mm
$(R/Q)'$/cavity	351	Ohm
$(P = V^2/2(R/Q)' \times Q)$		
V_{trans}	5	MV/m
E_{peak}@ 5 MV/m	18.5	MV/m
B_{peak}@ 5 MV/m	0.077	T

Coupling factor $(f_0 - f_\pi)/f$	0.043	
$f_\pi - f_{\pi-1}$	1.0	MHz
polariz-tune-split.	10 . . . 40	MHz
tuning range	$\pm$ 1	MHz
G_1 =Q$\times$ R_{sur}	228	Ohm
R_{sur} @ 2K, T_c/T=4.6	1.1×10^{-7}	Ohm
Q@R_{sur}	2.1×10^{9}	
Power dissipated@5MV, 2K	8.5	W/m
Q_{ext}	6×10^{7}	
full bandwidth f/Q_{ext}	65	Hz
U (stored energy)	0.73	Joules/m



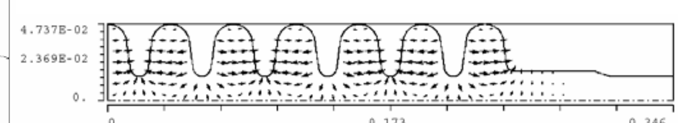


Figure 4: 13-cell cavity of shape C15, electric field of the π-mode (f = 3.8996 GHz).

Also, the fill time (Qext / omega) = 2.45 msec and input power is quoted as Pin = 300 W/m, which equals U / fill time. Since beam loading is essentially zero, Qext was probably chosen to match Pin to an available source. However, with Pin = U / fill time, one would operate with an input power = Pin for a period of 2 * ln(2) * fill time = 1.39 * fill time and then the power would be reduced by a factor of four (i.e. what Tesla does with no beam). Given the 1 second beam time, it would be easier to run with fixed input power = 0.25 * U / fill time and wait ~ 5-10 fill times to come to steady state before beam arrives.

The CKM deflecting-mode R/Q is 2*350 Ohm / .5 m = 1400 Ohm/m for the 30 mm aperture (the more standard R/Q definition is used here, which requires multiplying the value they quote by a factor of 2). For comparison, the 1.3 GHz Tesla cavity fundamental mode R/Q is 1000 Ohm/m for the 70 mm aperture. Scaling the Tesla R/Q value to the higher frequency (linearly) and to the corresponding CKM cavity aperture (assuming R/Q ~ 1/aperature) yields 1000 * 3 * (70/3)/30 = 2333 Ohm/m, which is 66% larger than the deflecting-mode value. So it takes 66% more power to produce the same deflecting field as accelerator field for the same cavity frequency, aperture and loaded Q.

From the above specs, using two 13 cell CKM cavities (1 m active length) would provide the necessary crab kick (6.1 MV) if they are operated at 6.1 MV/m. The peak magnetic (electric) surface field would be about the same (half) as that in the 1.3 GHz Tesla cavities at 25 MV/m – however, the 9 times higher surface resistance increases the sensitivity to thermal runaway and so makes achieving fields at these levels harder.

Choosing a higher cavity frequency would further increase the resistance, but the required gradient scales as 1/frequency for a fixed cavity length, so the local heating (H^2 * Rs) would remain constant. For a fixed fill time, the input power would scale as 1/frequency^4 assuming the aperture scaled as 1/frequency.

Choosing a lower frequency would require longer (> 1m) active cavity length to limit the surface magnetic field.

Beam loading

Assume fill time << bunch train length, then the steady state loading is

loading = kr * I * fill time * omega * R/Q

where I is the beam current (10 mA), fill time = Qext / omega (assume 160e-6 sec as discussed below) and r is the beam offset. Equating this to the 2.8% tolerance yields r = .028 * 6.1e6 * (.23/3) / (2 * pi * 10e-3 * 160e-6 * 2 * pi * 3.9e9 * 1400) = 38e-6. So if the beam is within 38 microns of the cavity center, can ignore loading. Given the 500 micron beam size at the crab cavity, the beam jitter would have to be < 8% of the beam size if no loading corrections were made. However, would use rf drive control and piezo-tuners to maintain constant cavity phase and amplitude as would be done in the linacs. Thus the beam jitter, which would likely be highly correlated bunch-to-bunch, could be compensated even if it were a large fraction of the beam size (a 500 micron offset would produce a 37% change in the deflecting field).

Other issues

Lorentz forces and microphonics: control by having high bandwidth (e.g., 1kHz which corresponds to a 160 microsecond fill time) and a long pulse (several msec) to damp transients before the beam arrival. Peak power, rf-to-beam efficiency and cryogenic cooling do not have to be optimized as with the 1.3 GHz accelerator cavities. The input power in this case would be (300/4) * 0.5 * (2450/160) * (6.1/5)^2 = 850 W.

For 0.08 degree phase stability and a bandwidth of 1 kHz, need to control cavity frequency to better than 1 Hz on a ~ 1 microsecond time scale (microphonics are probably ~ 30 Hz on a millisecond time scale – it would be useful to have spectral data for this analysis). For comparison, the piezo-tuners for the Tesla cavities correct about 0.7 Hz per microsecond during 35 MV/m operation.

Progress on FNAL 3.9 GHz cavities

PAC 2001 – Single cell deflecting-mode cavity achieved 10 MV/m deflecting field, 33.6 MV/m surface electric field and 109 mT surface magnetic field in CW test.

Applied SC Conference in 2004 – In a 3 cell longitudinal mode cavity with a 30 mm aperture, achieved 110 mT surface magnetic field at CW, but performance limited by field emission at 10 MV/m. Parameters of the cavity are:

Active Length	0.346 m
E_acc	14 MV/m
Phase	-179 deg
R/Q	375 Ohm
Epeak / Eacc	2.26
Bpeak / Eacc	4.84 mT/(MV/m)
Q_external	9.5e+5

Note R/Q = 2*375/.346 = 2168 Ohm/m – the value expected from scaling the Tesla 1.3 GHz design is 1000 Ohm/m * 3 * ((70/3)/30) = 2333 Ohm/m.

Also measured two 9-cell copper models for HOM damping: results good but not conclusive (see below).

Linac04 – Update of work on deflecting and longitudinal cavities:

Deflecting.
Latest CW test results from 3 cell cavity with increased wall thickness (2.2 mm instead of 1.6 mm) are shown below. Cavity treatment done at JLab.

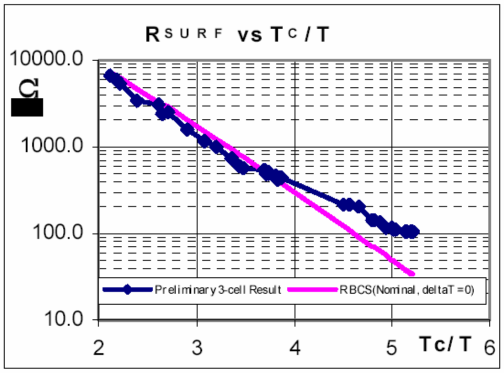


Figure 5: Surface resistance vs. T_c/T for CKM cavity.

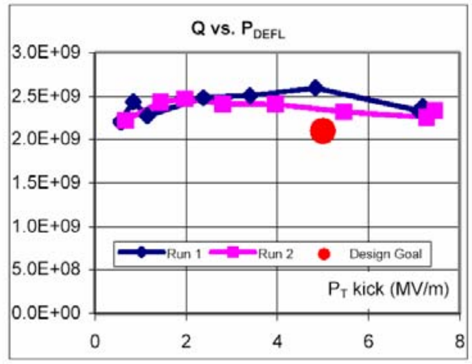


Figure 6: Q-value vs. kick gradient in CKM cavity.

A CKM cryomodule with two 13 cell cavities is being fabricated (currently have one cavity – see below – and will build one more plus a short cavity). Also building cryomodule for single cavity test in A0. The HOM couplers will be the same as those used in the longitudinal cavity, although an additional lower frequency coupler (2.8 GHz) is required to damp the lowest accelerator mode.

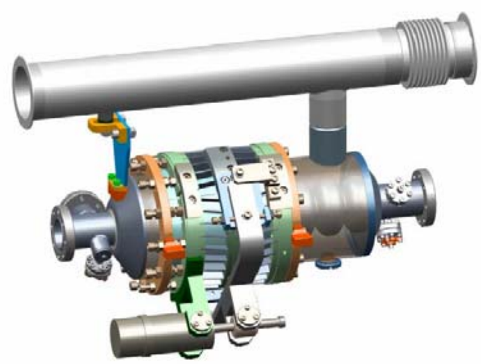


Figure 1: 3rd cavity, equipped with helium vessel and frequency tuner (design).

Figure 2: 13-cell CKM cavity, assembled with the helium vessel.

Longitudinal.

CW operation of 3 cell cavity still limited to 10-12 MV/m by field emission after several BCP treatments (design goal = 14 MV/m – note 3 cell cavity has 20% high peak electric and magnet fields ratios than 9 cell version). In process of building a cryomodule with a 9 cell cavity for test at A0 (see left-most figure above). The figures below illustrate results from HOM measurements on two copper prototypes to look for trapped modes.

Figure 7: HOM studies of assembly of the two copper cavities on the bead-pull set-up in clean room.

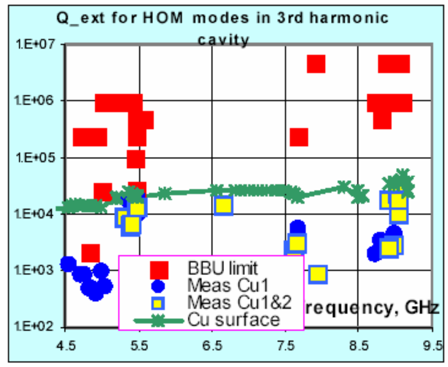


Figure 8: Q vs. frequency for HOM in TM_{010} cavity. Red-BBU limit, blue&yellow – measurements, green-Copper.

Normal Conducting Structure Possibilities

X-band TW

Scaling the X-band SW fundamental pi-mode R/Q, which equals 7850 Ohm/m for the 9.5 mm aperture (unloaded Q = 8700), to the CKM frequency and aperture yields R/Q = 7850 * (3.9/11.4) * (9.5*11.4/3.9)/30 = 2485 Ohm/m, which is 76% larger than the CKM deflecting-mode value. Assuming the same ratio applies to the H-type, X-band, 5*pi/6, TW structures (R/Q = 9100 Ohm/m, Q ~ 7000, 9.5 mm aperture), the deflecting field needed with one 0.6 m structure, 18.3*(1.3/11.4)/.6 = 3.5 MV/m, requires an input power of 60 MW * 1.76 * (3.5/65)^2 = 0.3 MW in a structure with the same iris size, group velocity and attenuation profile as in the X-band accelerator structures. The R/Q factor assumed here is consistent with that derived from the SLAC S-band deflecting-mode structure results, which are discussed below.

Pulse heating: Scaling the 20 degC result from the longitudinal X-band structure by gradient (3.5/65)^2 and accounting for the larger peak magnetic field to gradient ratio (16/4.2)^2 and the longer pulse length sqrt(1000/.4), yields a pulse heating of 42 degC (= 15 degC with 1 m of active length). The average heating would be 1.5 kW. The effect on the rf-to-beam phase from pulse heating needs to evaluated – with a ~100 ns fill time should be able to track any changes (both beams would be deflected by same amount if uncorrected).

Long range beam loading – make fill time of deflecting mode < 337 ns so energy flows to loads between bunches. Need to verify HOM's are sufficiently damped as well.

Short range beam loading – keep beam centered so differential wake kick is less than that from d_kick tolerance given above. That is, d_kick * k < Wt * dx * N where dx is the beam offset, Wt is the wakefield slope at center of bunch (= ½ single particle wake = 110 GV/m^3/1e10e assuming the longitudinal X-band structure value) and N is the bunch charge (2e10). With d_kick = 2.8% of 6.1 MV/m, dx = .028 *6.1 * 2 *pi * 3 / (.5 * 110e3 * 2 * .23) = 130e-6. Thus the beam needs to be centered to 130 microns or 26% of beam size. For correlated beam jitter, even larger amplitudes could be corrected by measuring the beam offset or the transmitted power from the cavity.

S-band TW

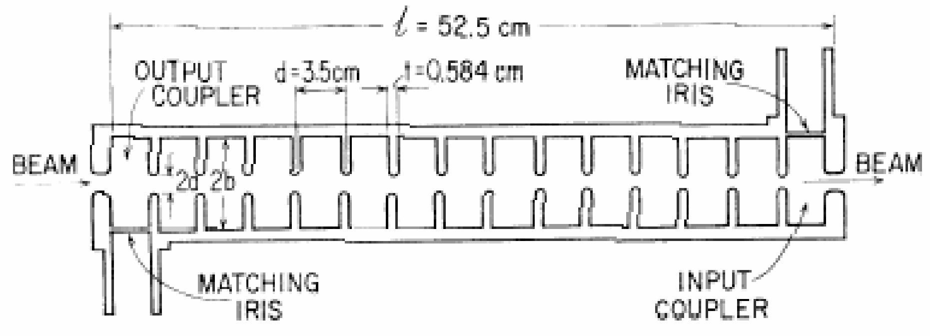


FIG. 11--Sketch of rf separator model with input and output couplers.

From the 1963 S-band deflecting-mode structure design report, infer R/Q = 1166 Ohm/m from measurements in figure 20 for the 3.1% c group velocity, 2*pi/3 phase advance per cell, 40.6 mm aperture, 0.52 m long, constant impedance (9% attenuation), TW structure (note that the analytical prediction using Eq 24 is 1600 Ohm/m, but as the conclusion notes, this is higher than measured). In Table I, they list the unloaded Q = 10,700 for the design without 'suppressor' holes (to suppress unwanted polarization ?). For comparison, the 2*pi/3, Mark IV S-band accelerator structure (page 129 of the 'Blue' book) has an R/Q of 4015 Ohm/m (Q = 13200) for a 21.8 mm aperture. So this R/Q, when scaled to the deflecting-mode structure aperture, is 4015*(21.8/40.6) = 2156 or 85% larger than deflecting-mode R/Q.

Scaling the SLAC deflecting-mode structure R/Q to 3.9 GHz with a 30 mm aperture yields 1166*(3.9/2.9)*(40.6*2.9/3.9)/30 = 1578 Ohm/m, compared to 1400 Ohm/m for CKM cavity, which is reasonable as one expects a larger R/Q value for a 2*pi/3 structure compared to a pi-mode structure. Scaling the S-band R/Q to 11.4 GHz with a 9.5 mm aperture yields 1166*4*(40.6*/4)/9.5 = 4983 Ohm/m, compared to 9100 Ohm/m for the H-type X-band accelerator mode (i.e. the accelerator mode is 83% is larger).

For the 0.52 m long S-band deflecting-mode structure, the deflecting field (in MV/m) equals 1.5 times the square-root of input power (in MW), so if used one structure to produce the required deflecting field, 18.3 MV * (1.3/2.856) / .52 m = 16.0 MV/m, would require 114 MW of input power. Thus this S-band structure, which is of comparable in length to the H-type X-band structure, requires ~ 400 times more input power. The major factors in this difference are the larger required gradient (factor of [16/3.5]^2 = 21) and the smaller elastance (factor of ~16) of the S-band structure.

If used two of these structures (1.04 m total active length), the required deflecting field is 8 MV/m and the structure input power is 29 MW. The pulse heating would be 42 * (8/3.5)^2 * (1/2) = 110 degC, which is over the safe limit.

Note unloaded Q of S-band 2pi/3 deflecting-mode is around 10,000 so expect Q = 10000*sqrt(2.856/1.3) = 14,800 at 1.3 GHz, 8600 at 3.9 GHz and 5000 at 11.4 GHz (the unloaded Q of the 2pi/3 X-band fundamental mode is ~ 6800).

3.9 GHz Cavity

If used a NC version of the 3.9 GHz CKM deflecting-mode cavity with a loaded Q around 4300, the required power level for a 6.1 MV/m deflecting field would be 300/4 W/m * (6.1/5)^2 * (6e7/4.3e3) = 1.6 MW/m. The pulse heating would be around 74 degC which is fairly high and may change the mode pattern in the pi-mode structure.