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COMPACT MULTICELL SUPERCONDUCTING CRAB CAVITY FOR ILC*

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Abstract

We propose a novel design of a crab cavity for the ILC project with low parasitic High Order Modes (HOM) losses and preserving the beam emittance, which is critical for operation with high beam current intensity. Multiple electrodes immersed in the hollow waveguide form a trapped-mode resonator. The transverse components of the electromagnetic field of the trapped dipole mode induce a transverse kick and efficiently deflect charged particles passing through the cavity. We present a scalable design of a superconducting Quasi-waveguide Multicell Resonator (QMiR) seamlessly connected with a beam vacuum chamber. The cavity is completely open at both ends, which significantly reduces the maximum loaded quality factor of the higher order modes, avoids complex HOM couplers, and thus simplifies the mechanical design of the cavity. The same port is used to feed RF power to the operating mode and to extract the same order modes. Finally, we estimate the expected cryogenic losses, HOM impedance limits, RF input power required, and frequency tuning for a QMiR cavity designed to operate at 2.6 GHz.

INTRODUCTION

International Linear Collider (ILC), a proposed linear electron-positron collider, plans to utilize crab cavities to enhance its luminosity. By introducing a transverse kick to the beams, the crab cavities (CCs) rotate the beam bunches, allowing for increased overlap at the interaction points. High intensity of the beam current and limited transverse space along the beam pipe near the interaction point resulted in choosing superconducting technology for the ILC/CC. There are numerous approaches on the design of the SRF deflecting cavities including elliptical multi-cell resonator, the Double Quarter Wave (DQW) resonator and the RF Dipole (RFD) crab cavity [1]. While all the designs can provide a necessary transverse kick voltage, one the biggest problem is dumping the spectrum of HOM excitation below given threshold to preserve a beam emittance. The conventional HOM couplers complicate the cavity geometry and increase the outer space occupied by the cavity. In this paper we present a novel scalable design of the Quasi-waveguide Multicell Resonator (QMiR) deflecting cavity originally developed for Short Pulse X-Ray operation of the ANL APS Upgrade project [2]. The cavity is fully open at both ends and connected with the beam vacuum chamber. Proposed solution significantly reduces the loaded quality factor of trapped modes, eliminates the need of dedicated HOM couplers, and thus simplifies the mechanical design of the cavity. The prototype of QMiR cavity was build and successfully tested at 2 K in a vertical cryostat and demonstrated a record transverse kick of 2.6 MV [3]. We have re-optimized the cavity shape to comply with the requirements for the ILC crab cavity. The key specification parameters are listed in Table 1 for the baseline beam collision energy of 250 GeV (Higgs Factory) and for the ILC upgrade option of 1 TeV [4]. The cavity geometry with overall dimensions is illustrated in Fig. 1.

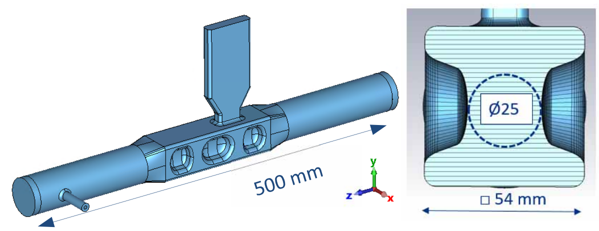

Figure 1: Geometry of the QMiR CC for ILC (left) and its cross-section showing the distance between opposite electrodes (right).

Table 1: Specifications for the ILC Crab Cavity

Parameter	250 GeV	1 TeV
Beam Energy (GeV)	125	500
Number of bunches	1312	2450
Repetition Rate (Hz)	5	4
Bunch Train Length (ms)	727	897
Bunch Spacing (ns)	554	366
Beam Current (mA)	5.8	7.6
Beam Size @CC (μm)	66, 300 (X,Y)	
Beta Function @CC (km)	23.2, 15,4 (X,Y)	
Cavity Frequency (GHz)	2.6	
Total Kick Voltage (MV)	0.92	3.7
Max surface E-field (MV/m)	45	
Max surface B-field (mT)	80	
Max Kick Factor (kV/pC/m)	1.6, 0.12 (X,Y)	
Max Impedance (MΩ/m)	49, 62 (X,Y)	
Min CC aperture (mm)	25	
Beam lines separation (mm)	200 (at center)	
Max installation length (m)	3.8	

The cavity frequency was chosen to be 2.6 GHz, the operating mode second harmonic, as good compromise to provide the necessary kick and fit into the available transverse and longitudinal installation space. In this paper, we present the results of the cavity RF design, wakefield simulation, and statistical analysis of the HOM excitation. The

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estimated cryogenic losses and RF input power requirements look feasible. We also propose a cavity mechanical design including an LHe vessel, a compact frequency tuner and a cryomodule concept. Finally, we discuss future R&D plans, as well as a prototyping and cavity testing schedule.

CAVITY RF DESIGN

Multiple electrodes immersed in a hollow rectangular waveguide form a trapped-mode resonator. The trapped dipole π-mode induces a transverse kick and efficiently deflect charged particles passing through the cavity. The single waveguide port is used to feed RF power to the operating mode and to extract the same order modes (SOM). The calculate maps of the electric field of the trapped dipole modes are shown in Fig. 2.

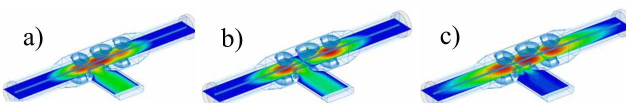

Figure 2: Electric field maps of trapped dipole modes in the QMiR cavity, two SOM (a) and (b) and operating π-mode (c).

The shape of the electrodes is optimized to lower the surface electric (E_s) and magnetic (B_s) fields. The distribution of surface fields is illustrated in Fig. 3 for the cavity operating at the nominal gradient. The operating mode parameters are listed in Table 2. Note that we use the accelerator definition of the normalized transverse shunt impedance, $(R/Q)_t = V_t^2/\omega W_0$, where V_t is the kick voltage and W_0 is the stored energy. The external coupling (Q_E) of the operating mode is chosen relatively large to minimize the microphonics and Lorentz Force Detuning (LFD) effects.

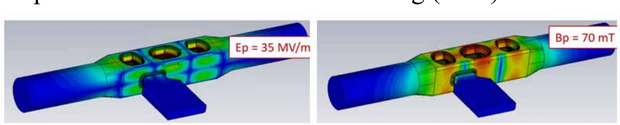

Figure 3: Distribution of surface electric (left) and magnetic (right) fields at nominal operating kick voltage.

Table 2: Parameters of the QMiR Crab Cavity for ILC

Frequency	2.6 GHz
V_t	0.92 Mv
$(R/Q)_t$	225 Ω
G-Factor	160
B_s, *max*	70 mT
E_s, *max*	35 MV/m
Q_E	1.3E6
W_0	0.24 J

Cryogenic operating mode losses can be estimated as $P_c = \omega W_0/Q0$, where $Q_0 = G/R_s$ is the intrinsic quality factor and R_s is the surface resistance. Typical measured values of Q_0 in 2.6 GHz elliptical cavities operating at high gradients are in the range $6\times 10^9 \dots 2\times 10^{10}$ and depend on the cavity treatment [5]. For continuous RF operation of a QMiR cavity with ILC pulsed beam, the 2 K cryogenic load can be as low as 0.5 W with nitrogen doping (N-doping) treatment of the niobium. The expected cryogenic loss budget of the operating mode is summarized in Table 3.

Table 3: Cryogenic Loss at Nominal Operating Gradient

Material	R_s, nΩ	Pc, W
Nb	50	< 1.3
Nb, N-dopped	20	< 0.5

The HOM spectrum was simulated numerically using the ANSYS HFSS code for a cavity with ports with matching boundary conditions [6]. Calculated normalized transverse shunt impedances for SOMs and HOMs with $Q_L > 100$ are shown in Fig. 4.

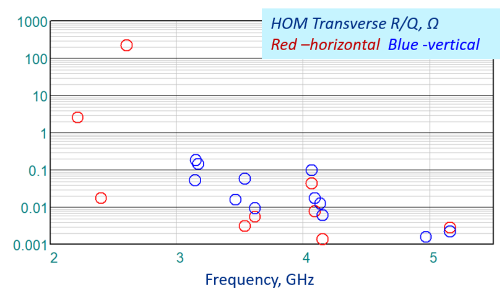

Figure 4: QMiR cavity dipole SOM and HOM spectrum.

The properties of HOM with the highest quality factor are given in Table 4, where the longitudinal impedance of the dipole modes is calculated at the offset of 1 mm from the cavity axis. The cavity is practically HOM-free with only few modes having $Q_L > 1\times 10^4$.

Table 4: Calculated Spectrum of SOM and HOM Modes

Freq. MHz	$(R/Q)_x$	$(R/Q)_y$	$(R/Q)_z$, Ω	Q_L
2120	2.5	-	6 E-3	6,0 E3
2400	0.02	-	1 E-5	8.4 E3
2600	225	-	0.68	1.3 E6
3145	-	0.05	7 E-3	5.2 E3
3620	-	-	16	4.3 E4
4085	-	-	20	1.2 E4
5110	1 E-4	-	1 E-4	5.5 E4
5955	2 E-4	-	2 E-4	6.3 E3

To maintain the crabbing voltage the cavity requires input RF power which should compensate the ohmic loss in the cavity walls (almost negligible, see Table 3) and a voltage induced by the beam going off the cavity axis. With a worst-case scenario of 1 mm beam offset and < 1 kHz combined frequency detuning due to the LFD and microphonics, the necessary RF input power can be estimated at 1.5 kW compared to the 740 W required to power an empty cavity. Thus, with 100% overhead, a 3-kW solid state RF amplifier would be sufficient to power a QMiR cavity working at nominal gradient.

HOM EXCITATION ANALYSIS

The incoherent losses are related to the wakefield emitted by a single bunch and as such are proportional to the

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integral of the cavity impedance over the frequency range. The ILC machine will operate with very short 0.3 mm bunches, and each bunch is effectively capable of driving frequencies up to about 160 GHz. Therefore, the incoherent effects of HOM excitation can be significant and should be carefully evaluated. To this end, we performed numerical simulations using CST Particle Studio to find the loss and kick factors for the QMiR crab cavity [7]. The results are presented in Fig. 5 for beams as short as 1 mm. Further modelling with sub-millimetre beams is time consuming and limited by available computer resources. Thus, we have extrapolated the calculated data to a nominal bunch length of 0.3 mm.

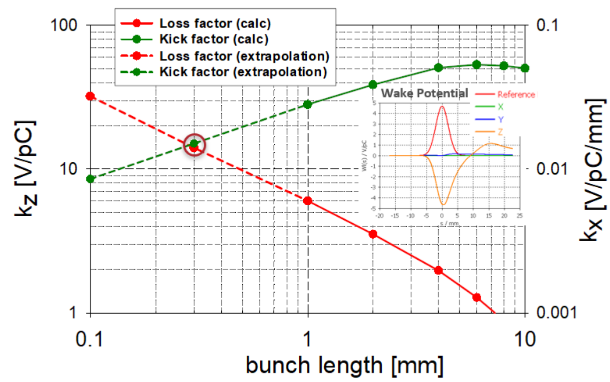

Figure 5: Loss and kick factors in the QMiR cavity operating with nominal ILC bunch length (inset shows wake potentials modelled with CST Particle Studio).

The calculated loss factor $k_z \approx 15$ V/pC which corresponds to the power of the radiated wakefield $P_{rad} = k_z q_0 N_b f_{rep} \approx 1$ W, where q_0 is the bunch charge, N_b is the number of bunches in the train and f_{rep} is the beam repetition rate. The estimated horizontal kick factor is 20 V/pC/m, and the vertical is negligible for the dipole mode. Both loss and kick factors are below the thresholds established for the ILC crab cavity (see Table 1).

The resonant excitation of HOM in the superconducting cavities by a pulsed beam has a probabilistic nature [8]. The idea is illustrated in Fig. 6, where the spread of HOM frequency is typically larger than the HOM bandwidth.

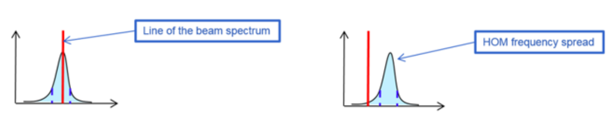

Figure 6: Stochastic HOM excitation by the pulsed beam, resonance (left) and off-resonance (right) case.

The probability that a single HOM will be in resonance with the beam harmonic depends on the statistical spread of HOM parameters, frequencies, Q-factors, and impedances. To estimate this probability, we first calculated 100,000 cavities with a normal deviation of HOM frequencies. The result is shown in Fig. 7 where the total HOM power loss, P_{loss}, is the sum of the losses of all individual modes in the given frequency domain (see Fig. 4). Note that the probability saturates if $\sigma_f > 1/t_b$, where σ_f is the rms value of the frequency spread and t_b is the bunch spacing. We conservatively consider $\sigma_f = 1$ MHz for further statistical analysis. The most uncertain HOM parameter is the quality factor, which can vary by an order of magnitude depending on the reflection of the radiated signal. The shunt impedance is more predictable, so we add only 20% variation, rms, to the calculated values.

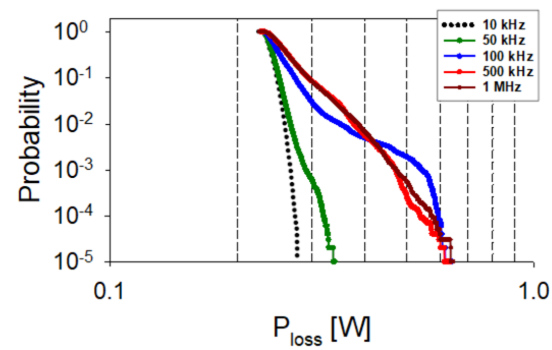

Figure 7: Probability of HOM losses on frequencies deviations, σ_f, rms.

Estimated probabilities of total power losses and transverse voltages for HOMs in the QMiR cavity exited by the pulsed ILC beam are shown in Fig. 8. Based on the above simulation data, we can conclude that with a probability of 99%, the HOM power radiated through the cavity ports will not exceed 0.7 W. The sum of expected coherent and incoherent HOM losses is about 1.7 W and can be easily absorbed in a stainless-steel beam vacuum chamber equipped with conductive cooling thermal straps. The overall parasitic kick voltage is expected to be less than 40 V, which is almost negligible compared to the nominal kick of 0.92 MV.

MECHANICAL DESIGN

The operation of a superconducting resonator at a high gradient requires both efficient cooling and mechanical stability since the operating mode frequency may deviate beyond a narrow bandwidth because of LFD and microphonics effects. Due to the poor thermal conductivity of Nb at 2 K, the typical cavity wall thickness is limited to 3...5 mm. In addition, a thicker wall may be difficult to deform, which complicates the design of the frequency tuner.

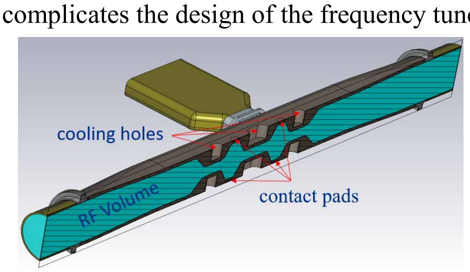

Figure 9: Mechanical 3D model of a bare QMiR cavity.

We plan to have six cooling channels in the electrodes and four contact pads on opposite sides in the middle of each cell to adjust the cavity deformation. Figure 9 shows a mechanical 3D model of a bare QMiR cavity. The relatively simple cavity geometry makes it possible to mill

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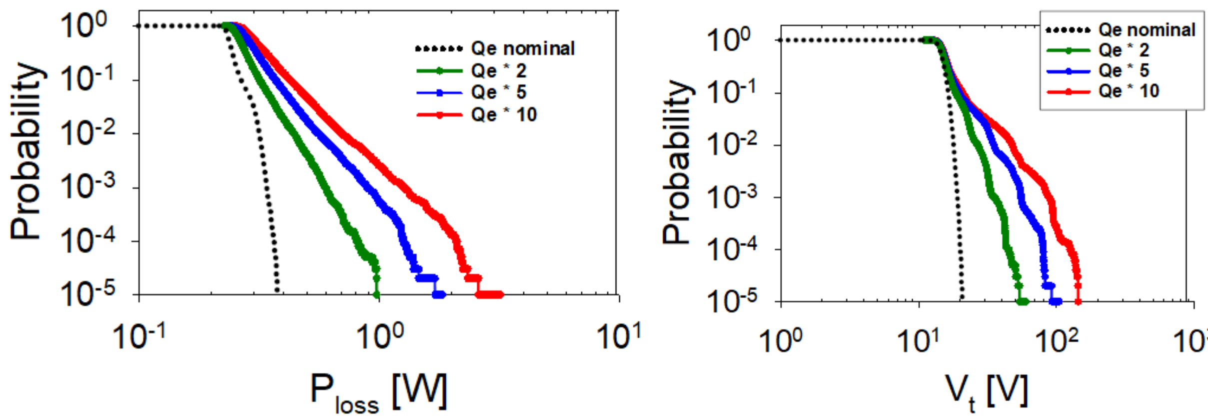

Figure 8: Probability of resonant excitation of HOMs in the QMiR crab cavity by the pulsed ILC beam as the total power loss (left) and the transverse voltage (right).

cavity parts with high precision from a solid Nb ingot.

The LHe vessel made of non-magnetic titanium is welded to the outer shell of the cavity through the transitional bellows to compensate for thermal and mechanical deformations (see Fig.10).

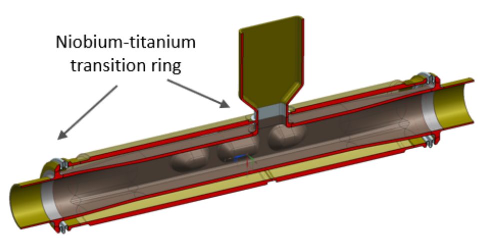

Figure 10: QMiR cavity with welded LHe vessel.

A slow frequency tuner is a mechanical device integrated with a dressed cavity to bring the operating mode frequency to its nominal value after the cavity cooldown. Because of the limited horizontal transverse space available for installation the crab cavity, we envision a compact design of the double 2-lever tuner driven by a stepper motor via a threaded titanium shaft. The idea is illustrated in Fig. 11. If required, the tuner can be equipped with fast piezo actuators for precise frequency tuning, similar to the design used in the LCLS-II cavities [9].

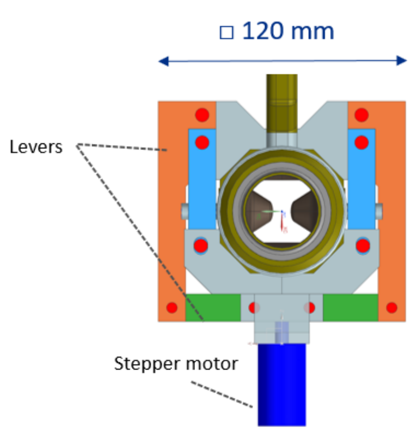

Figure 11: Compact double 2-lever frequency tuner.

A challenging problem is the transfer of mechanical forces to the cavity walls through the surrounding LHe vessel. A possible solution is to use short intermediate bellows to allow free movement of the inner contact fingers. The idea is illustrated in Fig. 12 and the full model of dressed QMiR cavity is shown in Fig. 13. The proposed design of the dressed ILC crab cavity fits into the intended transverse space and does not interfere with the backward beam line.

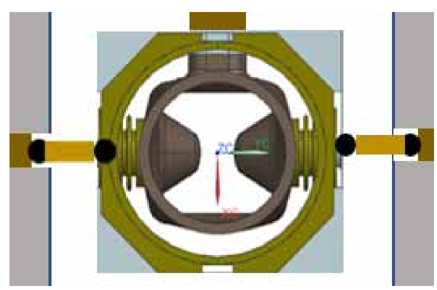

Figure 12: Scheme of transferring of mechanical forces from the tuner levers to the cavity walls.

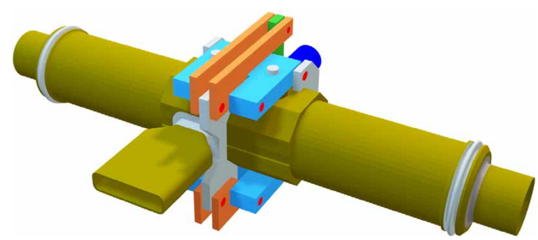

Figure 13: Dressed QMiR cavity with integrated compact frequency tuner.

To verify the cavity tunability and frequency tuning range, we performed a series of electromechanical analyzes of a bare cavity using the COMSOL software [10]. The dependences of the LFD coefficient and pressure variation (*dF/dP*) on the cavity wall thickness are shown in Fig. 13. Both coefficients, LFD and dF/dP, are smaller than the cavity bandwidth. Note that the LFD can be further reduced by adding stiffeners to the design, making it potentially possible for the QMiR crab cavity to operate without a fast frequency tuner.

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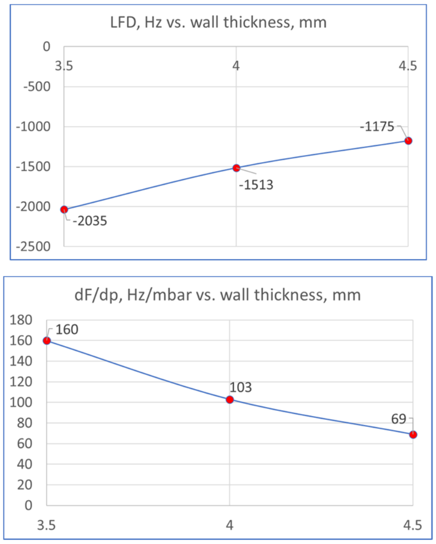

Figure 13: Calculated coefficients LFD (top) and dF/dP (bottom) of a QMiR cavity with different wall thicknesses.

Next, the deformation of the cavity walls was simulated for applied fixed external forces of 10 kN, uniformly distributed over two contact pads. The result is shown in Fig. 14 for the wall thickness of 4 mm. The found cavity sensitivities to frequency tuning and to external forces are -35 kHz/µm and -190 kHz/kN, respectively. This allows to have a frequency tuning range of up to 2 MHz.

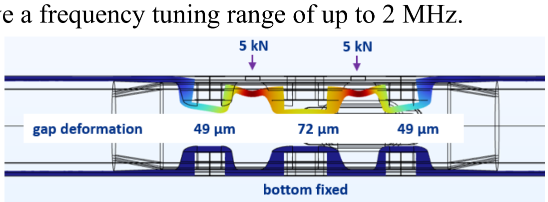

Figure 14: Mechanical analysis of the frequency tuning range in the QMiR cavity with 4 mm wall thickness.

The design of the crab cavity cryomodule is in progress. We assume to utilize a proven mechanical soliton based on existing 1.3 GHz capture cavity cryomodule installed and tested at FAST facility at Fermilab [11].

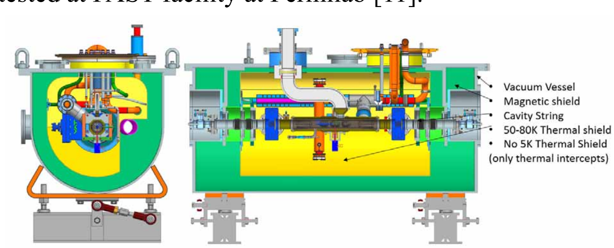

Figure 15: The design concept of CC cryomodule.

The key features of the proposed cryomodule are a) top plate support of the cryo-string, b) compact single window input power coupler, c) single 50 K thermal shield and 5 K thermal intercepts, d) magnetic shielding and e) external adjustable supports for the precise cavity position alignment with the beam. The design concept of the entire CC cryomodule is shown in Fig. 15. The design of the vacuum vessel and pipeline complies with pressure safety codes.

CONCLUSION

We propose a novel design of a compact and simple multi-cell SRF crab cavity, which fully complies with the ILC operational specifications. The design is based on the idea of the QMiR cavity earlier being developed and successfully tested at high operating gradient. The parameters of QMiR CC are confirmed by detailed electromagnetic and mechanical analysis. Cavity operation at nominal gradient has low cryogenic losses (<1.3 W) and requires about 1.5 kW RF input power. The QMiR CC does not have dedicated HOM couplers, and the broadband wakefield signal is radiated and absorbed in the beam vacuum chamber. The suggested concept of the cavity mechanical design includes a LHe vessel integrated with a compact frequency tuner providing a tuning range up to 2 MHz. The design of the CC cryomodule fits ILC technical requirements and environment limitations.

The QMiR CC is recommended for prototyping at a recent crab cavity technology down-selection meeting [1]. The near-term plan is to complete mechanical design of the cavity, manufacture, process and test it at high gradient operation at the Fermilab Vertical Test Stand (VTS).

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