QMiR Crab Cavity for ILC

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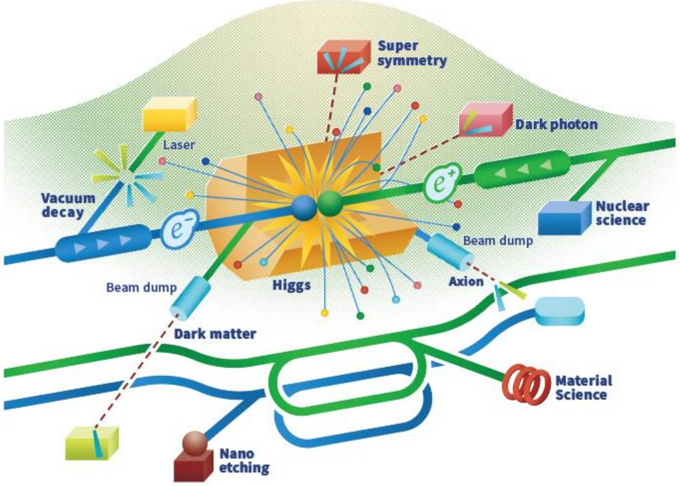
WP3 Crab Cavity Design Review Workshop #2



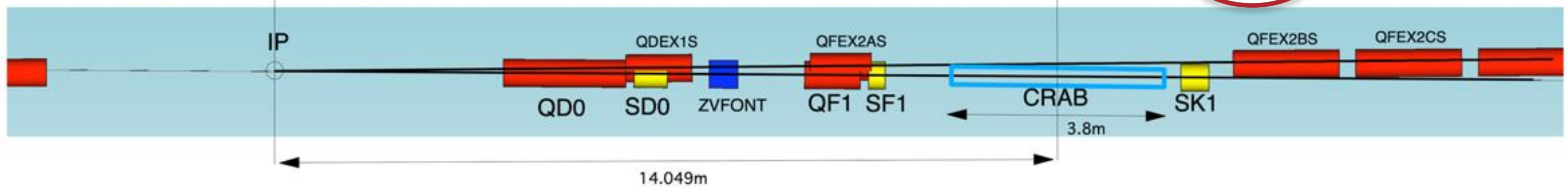
Outline

- General Requirements for the ILC deflecting cavities
  - HOM impedance limitation due to resonance excitation
  - Transverse wakefields effects
- QMiR (2.6 GHz) re-optimized version for ILC
  - CC aperture limit
  - HOM and Wakefields Analysis
  - RF Power Requirements
  - Cavity Detuning Requirements
  - Mechanical Analysis (LFD and dF/dP)
  - Frequency Tuner and Dressed Cavity Design
- Conclusions

Requirements for the ILC Crab Cavities (CC)

Crab cavity location (present ILC optics deck)

two beamline distance
14.05m x 0.014rad = 197mm



T. Okugi, ILC Crab Specification Final Discussion meeting, 08/08/21

Beam energy	E = 250; 500; 1000 GeV
Beam current (pulsed, average)	I_p = 5.8 mA , I_{av} = 20 μA
Pulse width	t_p = 727 μs
Beta function at the CC position (X,Y)	$\beta_x = 2.3\times10^4$ m , $\beta_y = 1.5\times10^4$ m
Bunch charge	q = 3.2 nC
CC kick voltage @2.6GHz	U_0= 0.92; 1.84; 3.68 MV
Normalized emittance (X,Y)	ε_x = 10 μm , ε_y = 35 nm
Beam size at CC location (X,Y,Z)	σ_x = 0.97 mm, σ_y = 66 μm, σ_z = 300 μm

- **The kick voltage is inverse proportional to frequency ($V_t \sim f^{-1}$)**
- **The CC space is limited by a close beamlines distance (< 0.2 m)**
- **Too small CC aperture results in large HOM transverse kicks**
- **Crab cavity @2.6 GHz looks a good compromise**

Crab Cavity HOM Impedance Limits

Resonant HOM Excitation ($U_{HOM} = k_0 x_0 I_p\, r_\perp$) can cause:

a) Crabbing voltage distortion

$$\left(\frac{r_\perp}{Q}\right) \equiv \frac{\left|\int_{-\infty}^{\infty}\left(\frac{\partial E_z(x,0,z)}{\partial x}\right)_{x=0} e^{i\omega z/c} dz\right|^2}{W k_0^2 \omega_0} \equiv \frac{U_{kick}^2}{W\omega_0} \quad [\Omega]$$

- HOM kick voltage should be less than the crabbing voltage (*U_0*)

$$U_{HOM}\sigma_z k_0 \ll U_0\, \sigma_z \omega_{RF}/c \quad \text{or} \quad r_\perp \ll \frac{U_0\, \sigma_z \omega_{RF}/c}{k_0^2 x_0 I_p}$$

b) Beam emittance dilution

- HOM kick should be less than the transverse momentum spread

$$U_{HOM}\sigma_z k_0 \ll \frac{\sigma_{p_\perp} c}{e} = \frac{p_\parallel c}{e}\sqrt{\frac{\varepsilon}{\gamma\beta}} \quad \text{or} \quad r_\perp \ll \frac{E}{k_0^2 x_0 \sigma_z I_p}\sqrt{\frac{\varepsilon}{\gamma\beta}}$$

For max beam offset @CC: $x_0 < \sigma_x$ and $y_0 < \sigma_y$

- Horizontal Shunt Impedance Limit

$r_x f_{HOM}^2 \ll$ 9.6 GΩ·GHz^2

- Vertical Shunt Impedance Limit

$r_y f_{HOM}^2 \ll$ 0.7 GΩ·GHz^2

250 GeV is the most demanding regime for HOM damping

Crab Cavity Transverse Wakefields Limits

Incoherent CC excitation (single-bunch effect) can cause:

a) Crabbing voltage distortion

- Transverse kick should be less than the crabbing voltage

$$U_{kick} \ll U_0\, \sigma_z \omega_{RF}/c \quad \text{or} \quad k_\perp \ll \frac{U_0\, \sigma_z \omega_{RF}/c}{q x_0}$$

b) Beam emittance dilution

- Transverse kick should not increase the bunch emittance

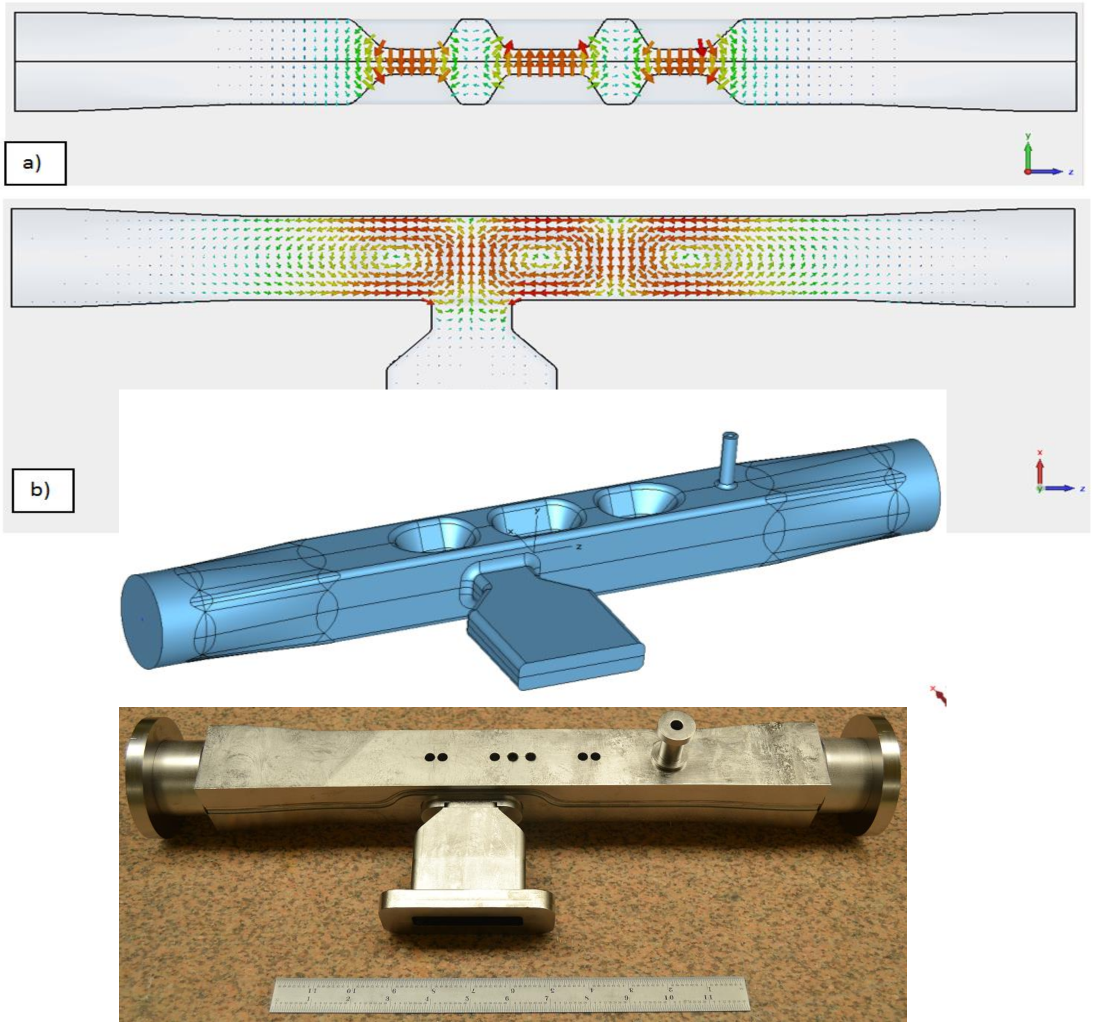
$$U_{kick} \ll \frac{\sigma_{p_\perp} c}{e} = \frac{p_\parallel c}{e}\sqrt{\frac{\varepsilon}{\gamma\beta}} \quad \text{or} \quad k_\perp \ll \frac{E}{q x_0}\sqrt{\frac{\varepsilon}{\gamma\beta}}$$

For max beam offset @CC: $x_0 < \sigma_x$ and $y_0 < \sigma_y$

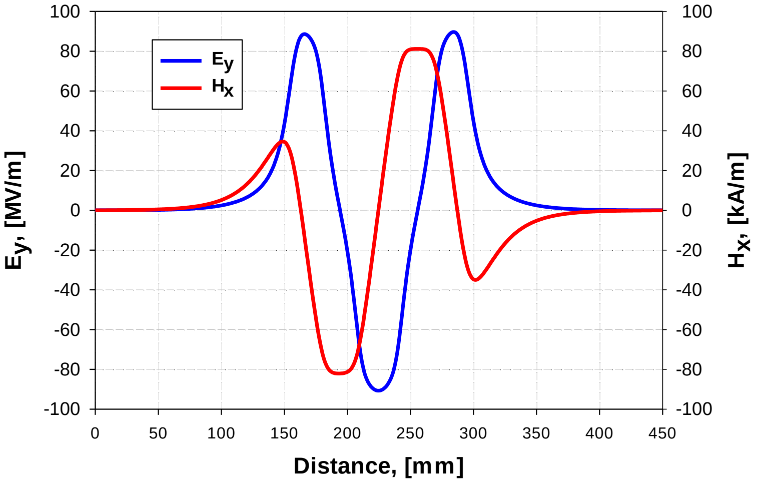
Horizontal Kick Factor Limit	**k_x << 2.3 V/pC/mm**
Vertical Kick Factor Limit	**k_y << 0.2 V/pC/mm**

Compact HOM-free Deflecting Cavity QMIR

Operating Mode

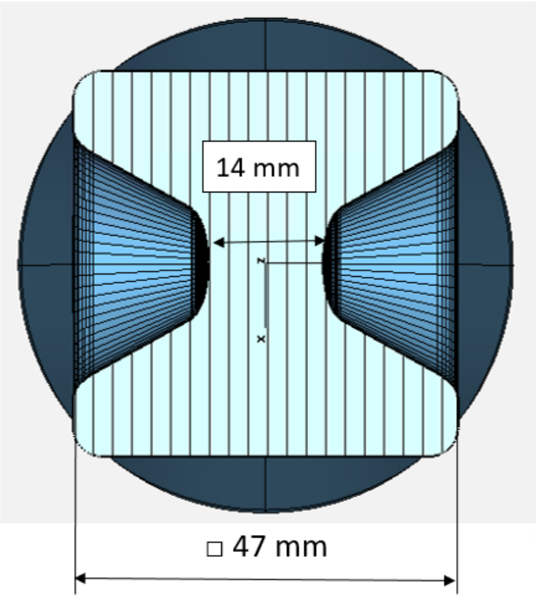


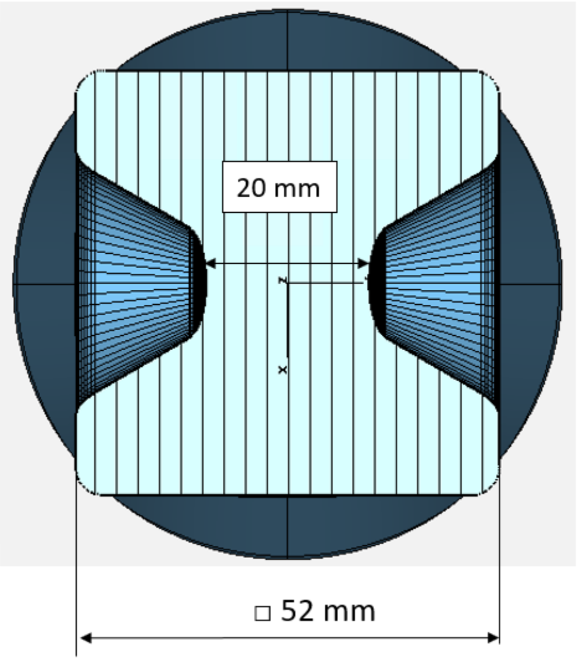
Transverse electric (blue) and magnetic (red) field components along the cavity axis.

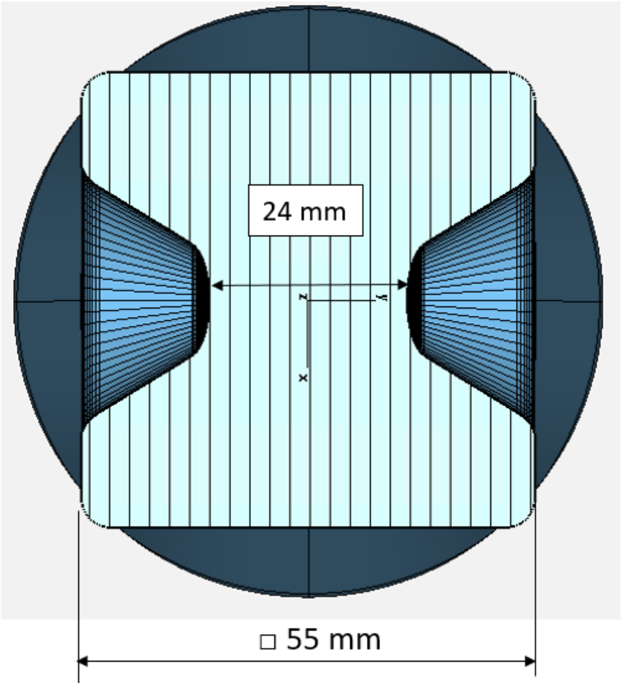


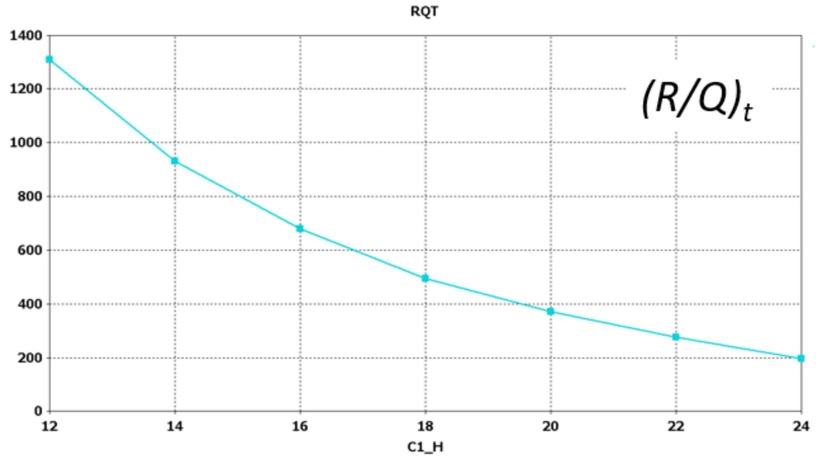
Freq	2815 MHz
V_{kick}	2 MV
E_{max}	55 MV/m
B_{max}	76 mT
$(R/Q)_Y$	1040 Ω (acc. def.)
G	130
W_{STOR}	0.23 J
Length	450 mm

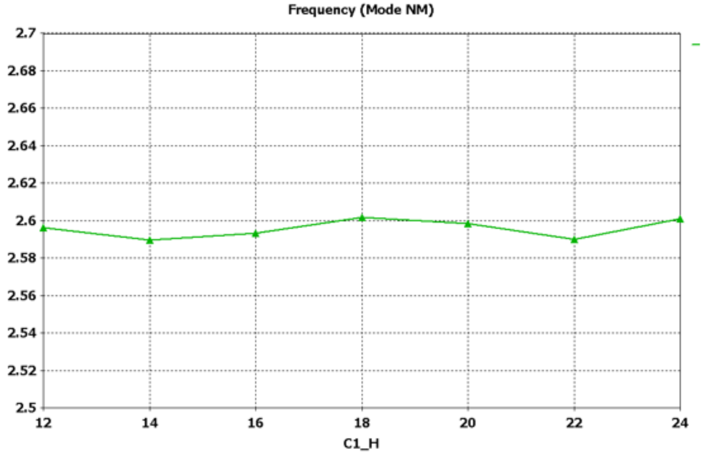
Scaling of QMiR Crab Cavity for ILC







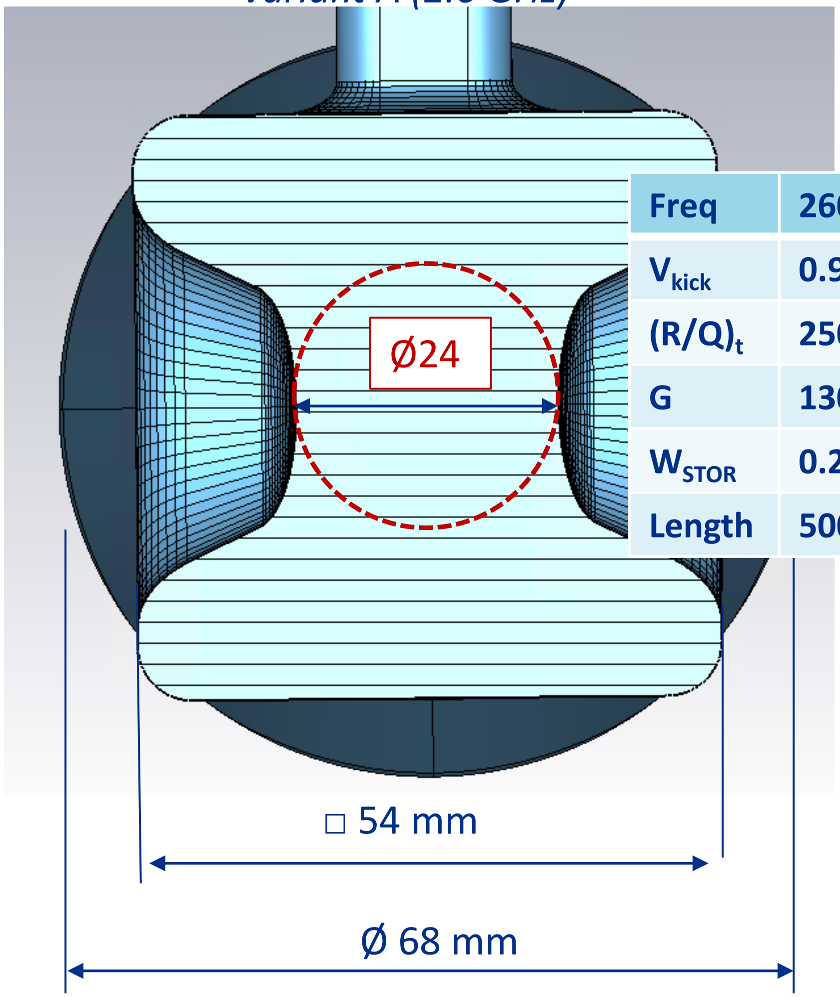




QMiR Cavity for ILC (re-optimized to 2.6 GHz)

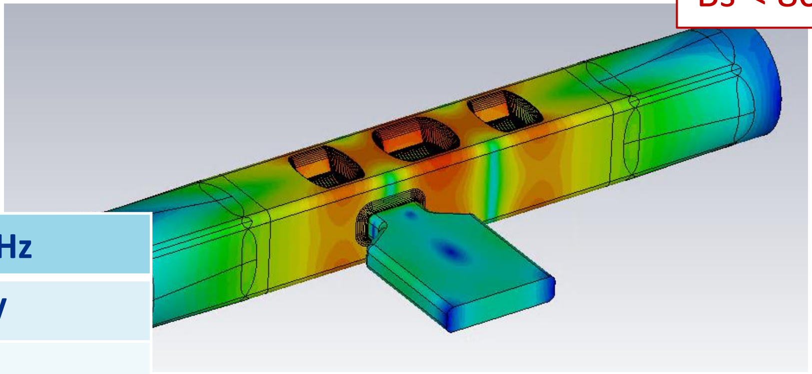
ILC CC Aperture Limit: < Ø25 mm

Variant A (2.6 GHz)



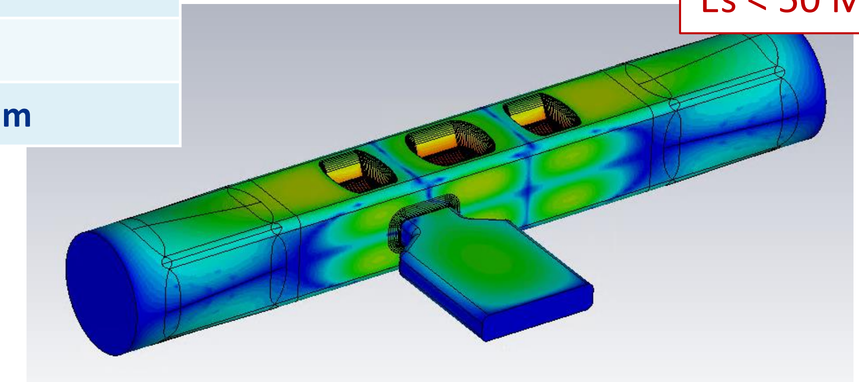
Freq	2600 MHz
V_{kick}	0.92 MV
$(R/Q)_t$	250 Ω
G	130
W_{STOR}	0.2 J
Length	500 mm

Magnetic Field



Bs < 80 mT

Electric Field

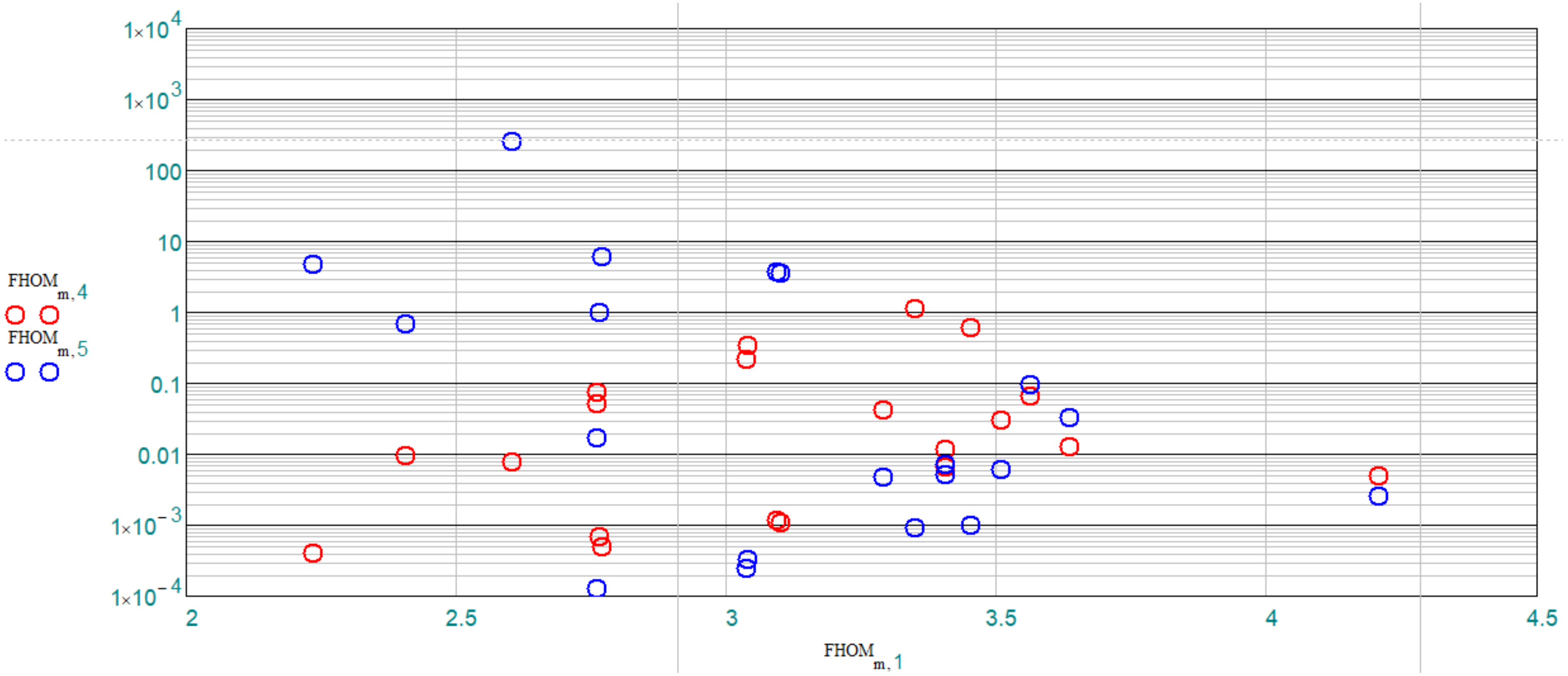


Es < 50 MV/m

- **Smaller distance between electrodes provides a larger transverse kick and lower surface fields**
- **There is a room for further reduction of Es and Bs**

QMiR Cavity for ILC (re-optimized to 2.6 GHz)

HOM Transverse Impedance, Ω
Blue – horizontal, Red - vertical



Cavity is HOM free above 4 GHz

QMiR Cavity for ILC (re-optimized to 2.6 GHz)

Operation mode	$\left(\frac{r_\perp}{Q}\right) = 250$ Ohm (@2.6 GHz)
Maximal dipole *horizontal* SOM	$\left(\frac{r_\perp}{Q}\right)_x < 5$ Ohm , @2.4 GHz
	$Q < 1\times10^4 \ll Q_{max} \approx 1\times10^8$
Maximal dipole *vertical* HOM	$\left(\frac{r_\perp}{Q}\right)_y < 10$ Ohm, @3.6 GHz
	$Q < 1\times10^4 \ll Q_{max} \approx 4\times10^6$

Calculations are made for 14 mm aperture, for 24 mm the figures will be much lower

Incoherent losses	$k_z \approx 45$ V/pC $P_{rad} \approx k_z q^2 n_b f_{rep} = 3\ W$
Horizontal kick factor*	$k_x = 0.1$ (< 2.3) kV/pC/m
Vertical kick factor*	$k_y = 0.4$ (< 2.5) kV/pC/m

* GdfidL calculation for 0.3 mm bunch length (cross check with ECHO-3D code is ingoing)

- **QMiR cavity meets the ILC/CC horizontal and vertical HOM impedance requirements**

QMiR Cavity for ILC RF Power

- RF power needed to maintain the crabbing voltage should compensate
  - the ohmic losses in the cavity (negligible for SRF cavities)
  - voltage induced by the beam if the is off the cavity axis
- The maximal required RF power for the detuned cavity:

$$P = \frac{U_0^2}{4Q\left(\frac{r_\perp}{Q}\right)}\left[\left(1+\frac{I_p Q\left(\frac{r_\perp}{Q}\right)k_0 x_0}{U_0}\right)^2+\left(\frac{2Q\Delta\omega}{\omega_0}\right)^2\right]$$

- For max beam offset $x_0 < 1$ mm and $\Delta f < 100$ Hz (LFD, microphonics)

Beam OFF: $P_{min} \approx 800$ W
Optimal Coupling: $Q_L \approx 1\text{x}10^6$
Beam ON & Microphonics: $P_{max} \approx 1000$ W

- Required RF power from the generator (overhead 100%):

$P_{gen} < 2$ kW (FPC design is ongoing)

Cavity Detuning (NO Crabbing)

- If Crab-cavity is not in operation, the beam induced voltage should not affect the beam emittance:
  - cavity needs to be detuned
- Cavity off-resonance excitation:

$$U_{kick} = \frac{\omega_0^2}{\omega^2-\omega_0^2-i\frac{\omega\omega_0}{Q}} k_0 x_0 I_p \left(\frac{r_\perp}{Q}\right)$$

  - If the cavity detune (Δf) is much larger than the bandwidth:

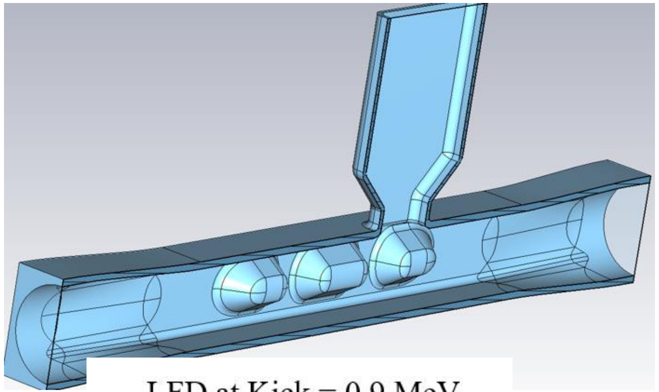
$$U_{kick} \approx \frac{1}{2m} k_0 x_0 I_p \left(\frac{r_\perp}{Q}\right) Q_L\,, \quad \text{where } m \equiv \frac{|\Delta\omega|}{\omega_0} Q_L$$

  - Required detuning:

$$m \gg \frac{\omega_0 x_0 I_p \left(\frac{r_\perp}{Q}\right) Q_L}{cE\sqrt{\frac{\varepsilon}{\gamma\beta}}} \approx 6\,, \quad \text{or } \Delta f \gg 15\text{ kHz}$$

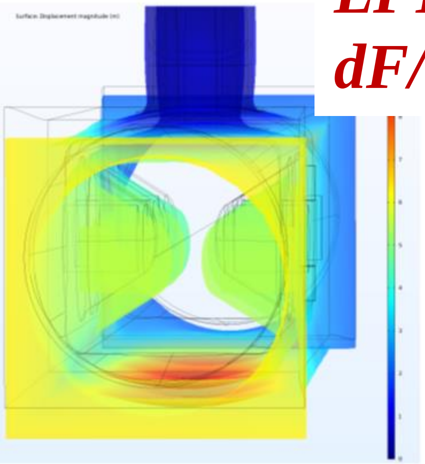
- **Frequency tuner range: F_{tuner} ~ 200 kHz**

Mechanical Analysis LFD and dF/dP (by I. Gonin)

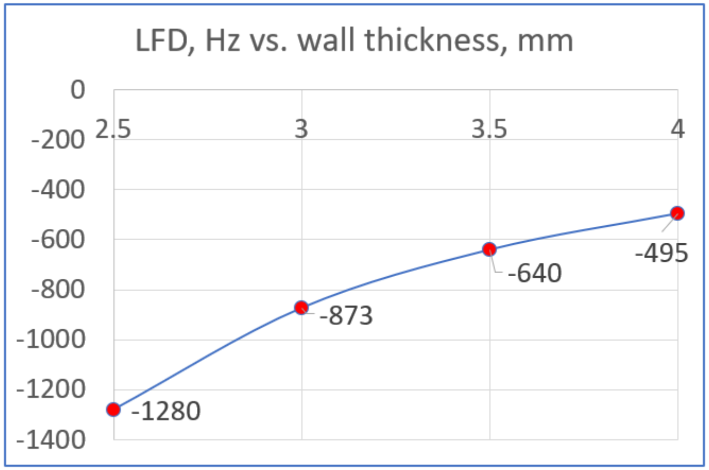


LFD at Kick = 0.9 MeV
Wall thickness 4 mm.
Δf ~ - 495 Hz

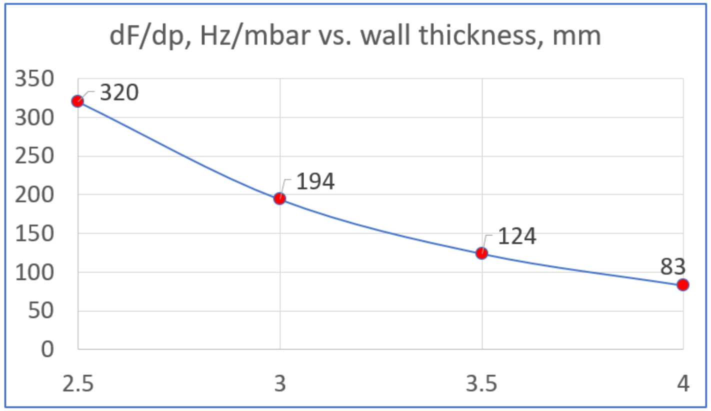
LFD < 500 Hz
dF/dP < 100 Hz



Deformation due to LFD



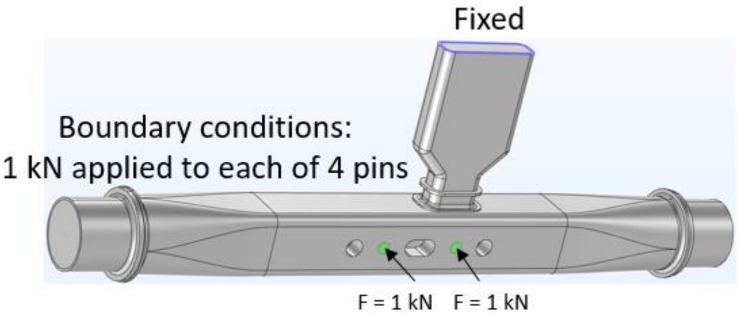
LFD in Hz at Kick = 0.9 MeV vs. cavity wall thickness



df/dP in Hz/mbar vs. cavity wall thickness

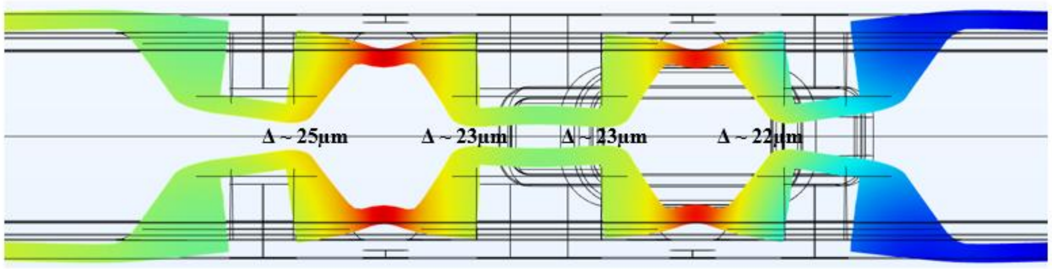
- **QMiR LFD and dF/dP are less than the cavity bandwidth (few kHz)**

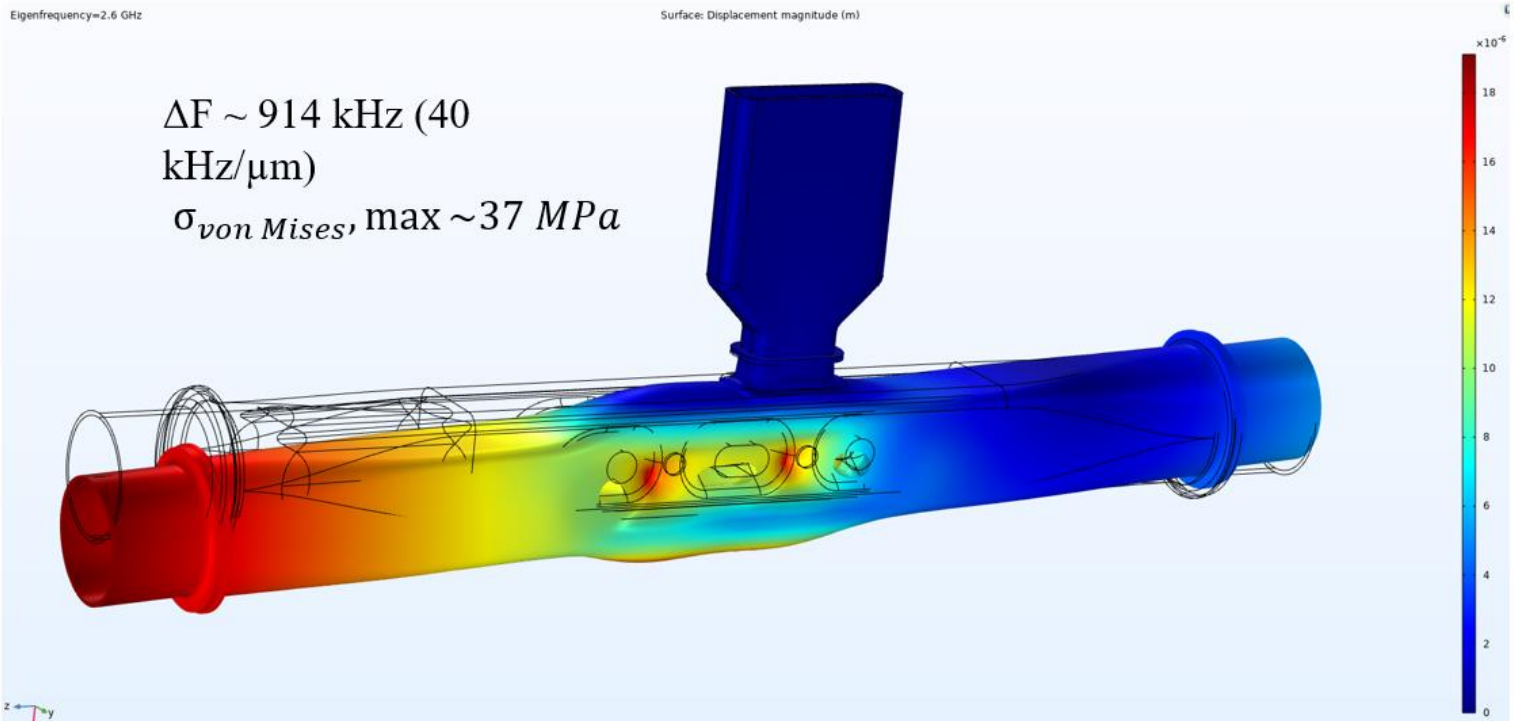
Mechanical Analysis of Frequency Tuning (by I. Gonin)



Fixed

Boundary conditions:
1 kN applied to each of 4 pins





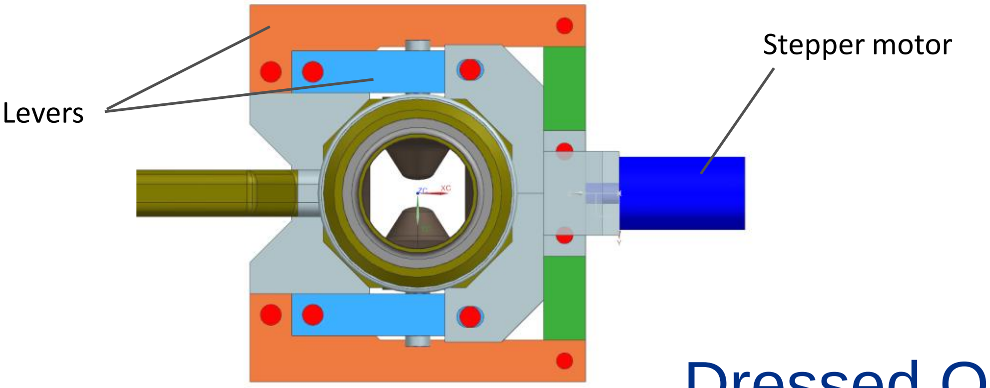
ΔF ~ 914 kHz (40 kHz/µm)

$\sigma_{von\ Mises}$, max ~$37\ MPa$

Expected frequency tuning range: ~ 1 MHz > 200 kHz

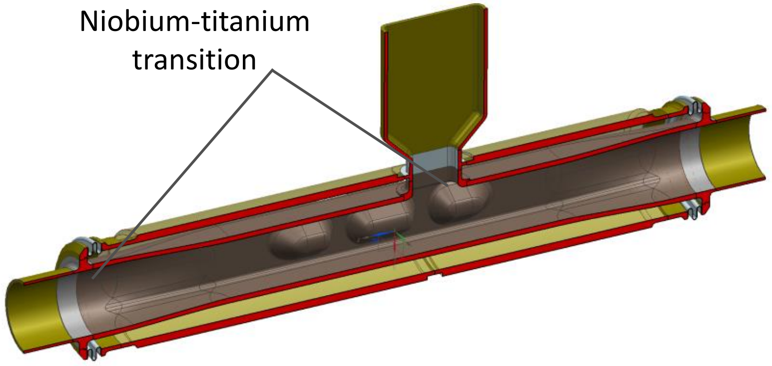
QMiR Cavity Slow Tuner Design (by V. Polubotko)

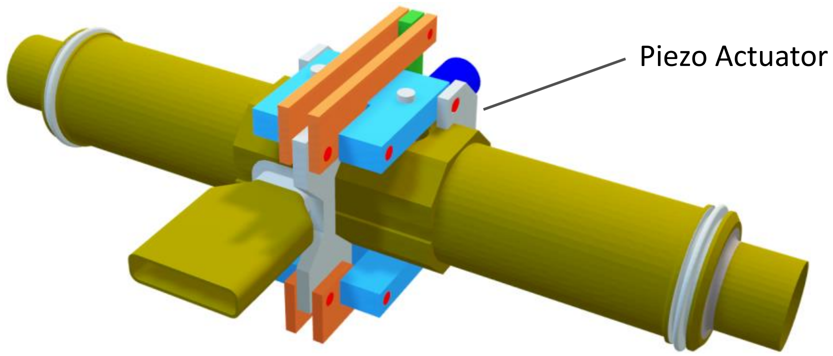
Compact double 2-lever frequency tuner



LHe Vessel

Dressed QMiR Cavity





- **Frequency tuner mechanical design concept is fixed**
- **Fine tuning will be done with piezo actuators (like in LCLS-II).**
- **Design of the tuner integration with dressed cavity is ongoing**

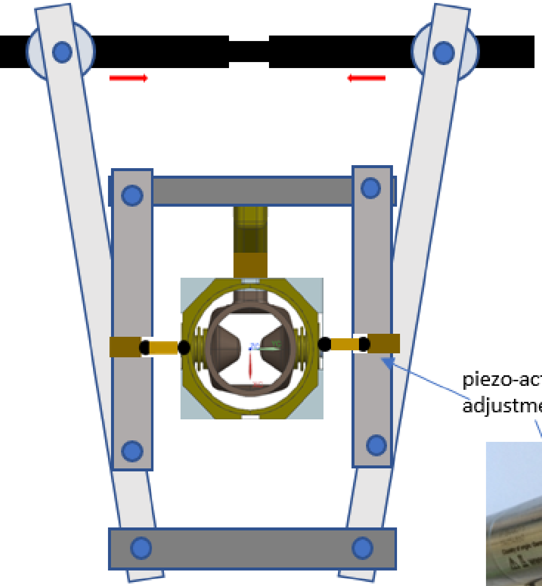
QMiR Cavity Fine Tuner Design

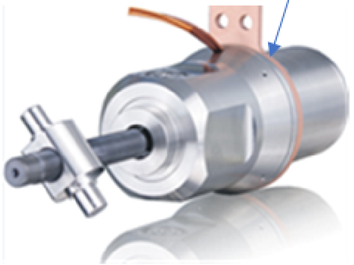
Proposed Tunings system for QMiR cavity
Slow/coarse tuner -Double lever tuner
Fast/fine tuner- piezo-actuators

Cavity parameters:
df/dL ~45kHz/um

Titanium shaft with right and left threads

Phytron stepper motor with gear box





piezo-actuator with adjustment screw

Parametrs fo the slow/coarse tuner		
Stepper	200	*step/360°*
Planetary Gear Box	100	*gear ratio*
Steps for 1mm stroke on shaft (M12X1)	20000	*steps*
Doubler lever ratio	10	
Cavity compression/stroke per 1 steps	5	*nm*
cavity tuning per one step	200	*Hz*

Slow tuner range > 1 MHz…

Parametrs fo the fast/fine tuner		
Piezo-stack	10*10*5	*mm*mm*mm*
Stroke at T=20K & V=100V	0.5	*um*
Cavity re-tuning at V=100V	20	*kHz*

Frame with two Double lever tuner running simultaneously with one stepper motor actuator… Shaft of the stepper actuator divided on the two half … ½ shaft has left thread and second ½ shaft right thread… traveling nut will move in opposite directions ..

Fine tuning will be done with encapsulated piezo actuators (similar used at LCLS II). Adjustment screw will help uniformly loading each of 4 piezo actuators (one actuator per each cavity knob)

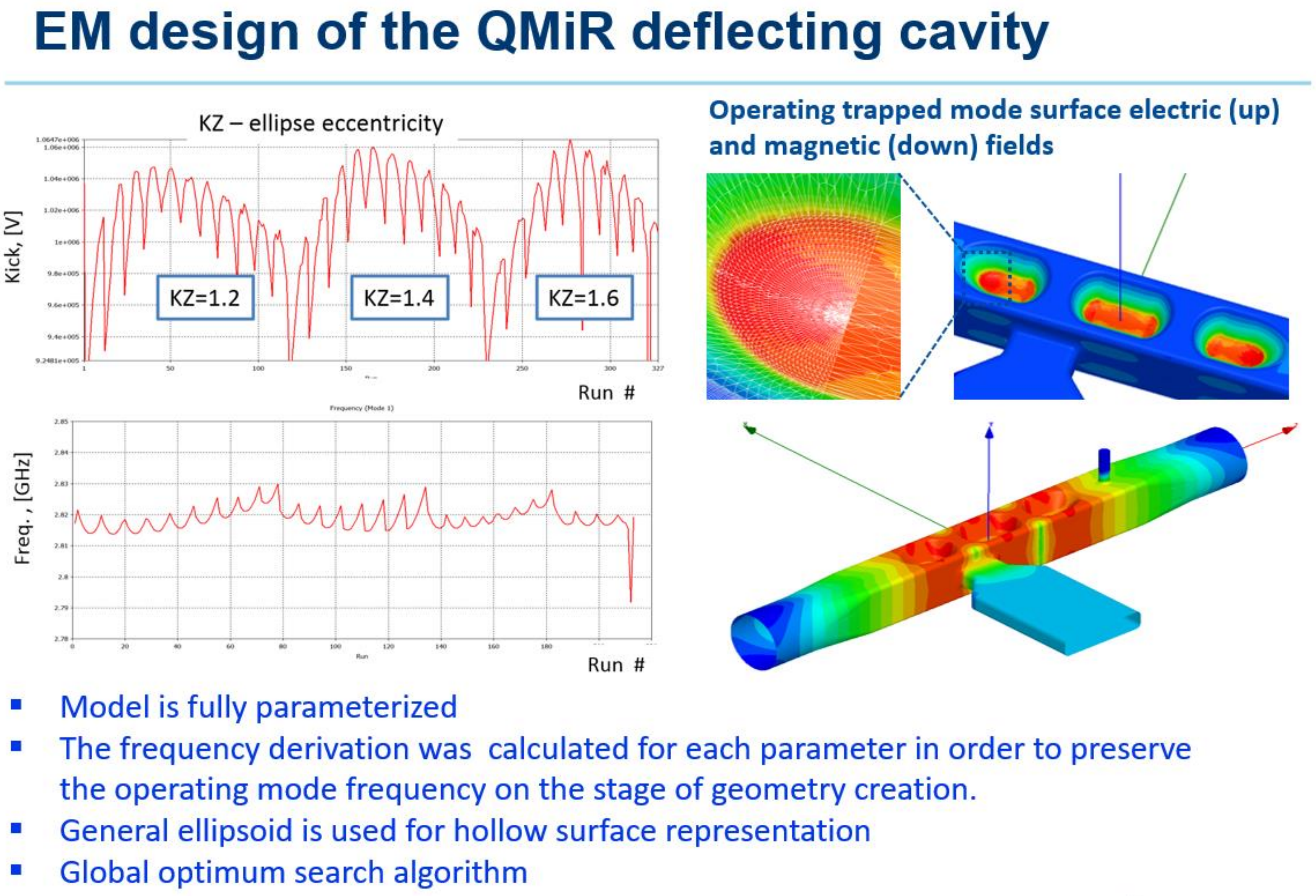
Yu. Pischalnikov 12/07/21

Conclusions

- ☐ Requirements for the ILC Crab Cavity developed
- ☐ A Quasi-Waveguide Multicell Deflecting Resonator (QMIR) is a good option for the ILC Crab Cavity
- QMIR is very compact (<0.5 m) and simple;
- It has sparse HOM spectrum;
- It has small loss/kick factors;
- No MP in operation voltage domain.

- ☐ QMiR re-optimized for a larger aperture of 24 mm
- For the deflecting voltage of about 0.9 MV the cavity has acceptable surface fields, $E_p \approx 50$ MV/m, $B_p \approx 80$ mT
- 4 QMiR can provide 4 MV kick total for 1 TeV ILC option
- ☐ QMIR cavity is considered now for Elletra-2, Trieste.
- ☐ Fermilab can design, build and test QMIR cavity for ILC application.

Backup Slides



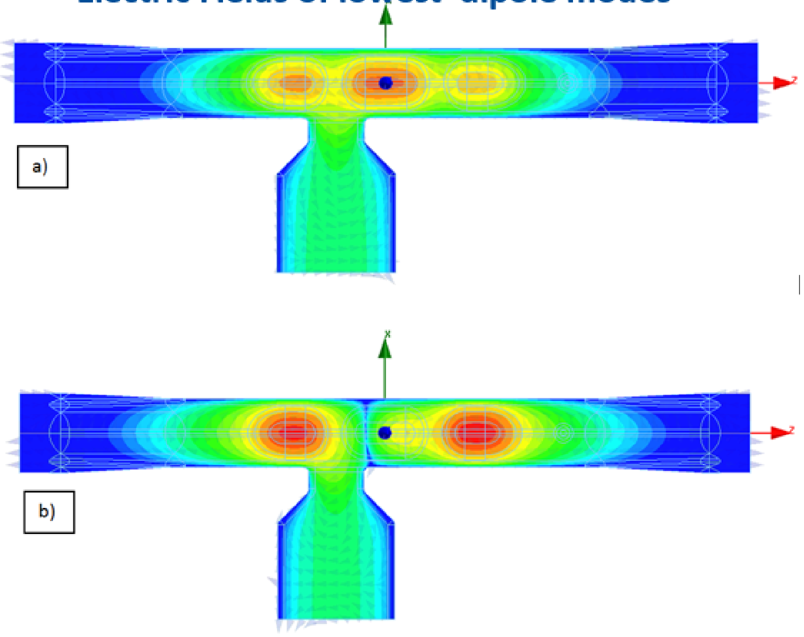
EM design of the QMiR deflecting cavity

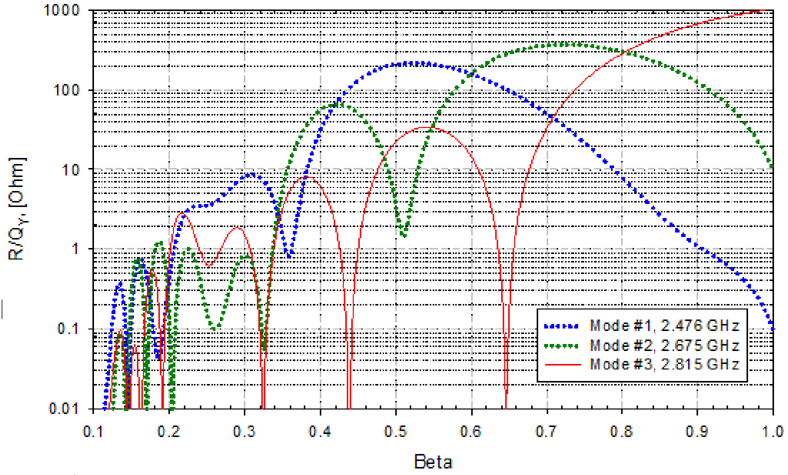
Operating trapped mode surface electric (up) and magnetic (down) fields

- Model is fully parameterized
- The frequency derivation was calculated for each parameter in order to preserve the operating mode frequency on the stage of geometry creation.
- General ellipsoid is used for hollow surface representation
- Global optimum search algorithm

Same Order Mode (SOM) Damping

Electric Fields of lowest dipole modes





Freq., [GHz]	$(R/Q)_t$, [Ω]	Q_{ext}	R_t [MΩ/m]
2.476	0.03	2400	3e-3
2.675	5.0	6800	1.9

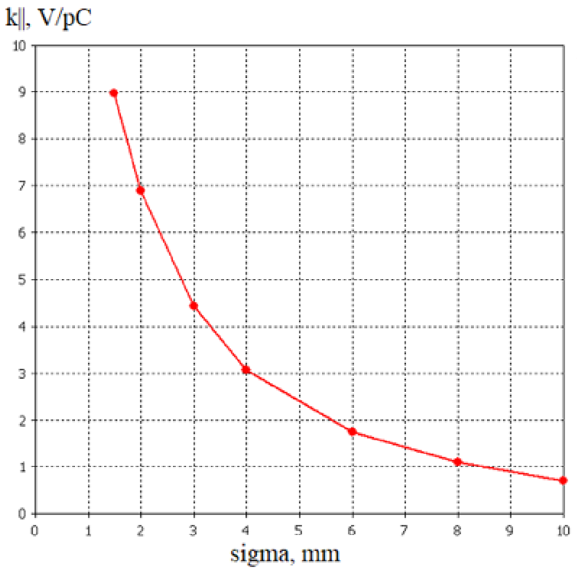
- The fundamental coupler waveguide is used to suppress SOM modes
- The FPC is purposely shifted from the cavity center in order to provide external coupling for the operating mode and damping lower frequency dipole modes simultaneously

Backup Slides

☐ **Loss factor:**

- For step collimator $k_{||} \sim 1/\sigma$;
- Simulations for ANL/SPX agree well with estimations;
- For σ =0.3 mm one may expect for ANL/SPX QMIR $k_{||} \approx 45$ *V/pC;*
- Expected radiation power: $P = k_{||}(eN)^2 n_b f_{rep} = 3$ *W.* This radiation will be dissipated in the beam channel, not in the cavity. Not an issue!

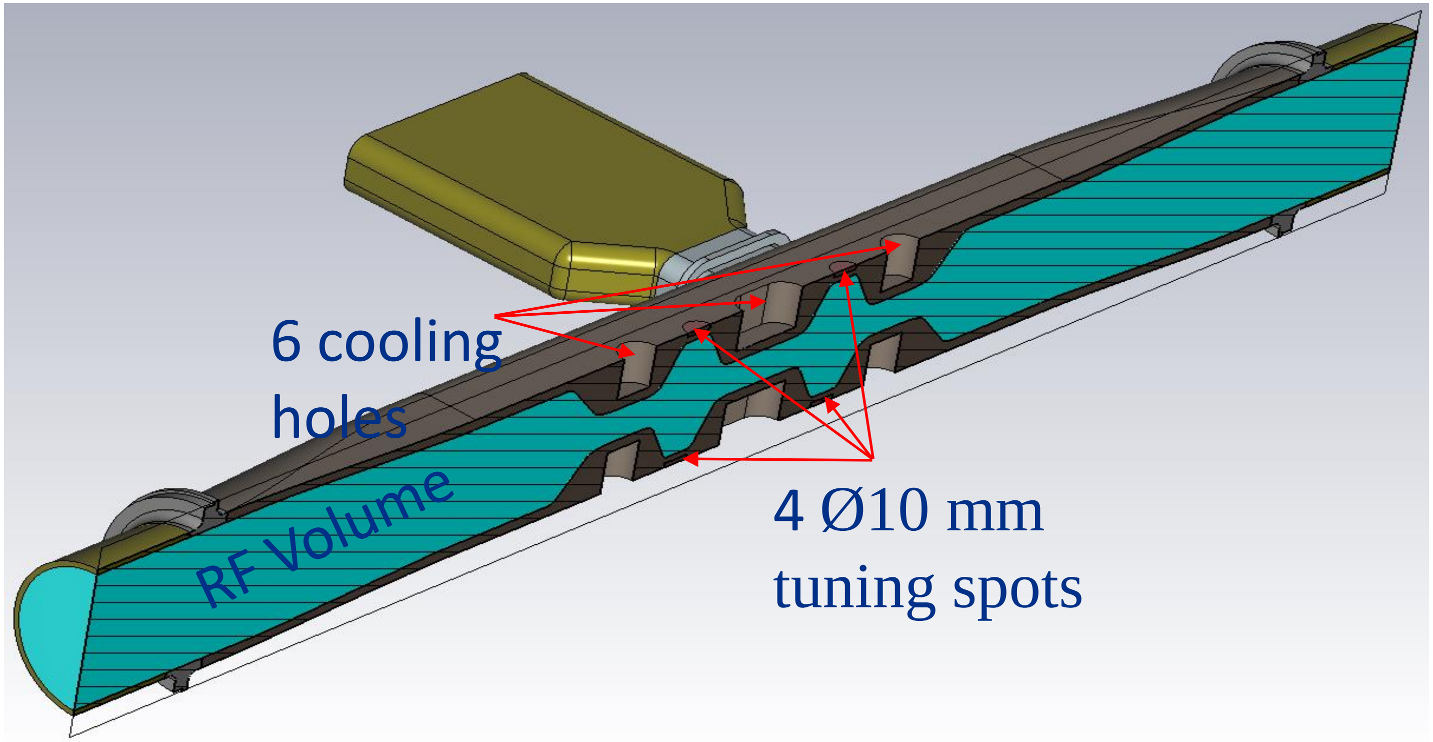
☐ **Cryo-losses:**



- At 2K one may expect the following surface resistance R_s for N-doped Nb:
  - 2.6 GHz: $R_s \approx 30$ *nOhm;*
  - *3.9 GHz:* $R_s \approx 68$ *nOhm.*
- Expected cryo-load (G=130 Ohm), therefore is $P_c = V^2/[2(R/Q)_t{*}G/R_s]{*}DF$. For
  - 2.6 GHz: V=1.35 MV and $P_c \approx 0.6$ mW;
  - 3.9 GHz: V=0.9 MV and $P_c \approx 0.6$ mW

  taking into account Duty Factor of DF=3.6e-3. Not an issue!

Mechanical Analysis of Frequency Tuning (by I. Gonin)

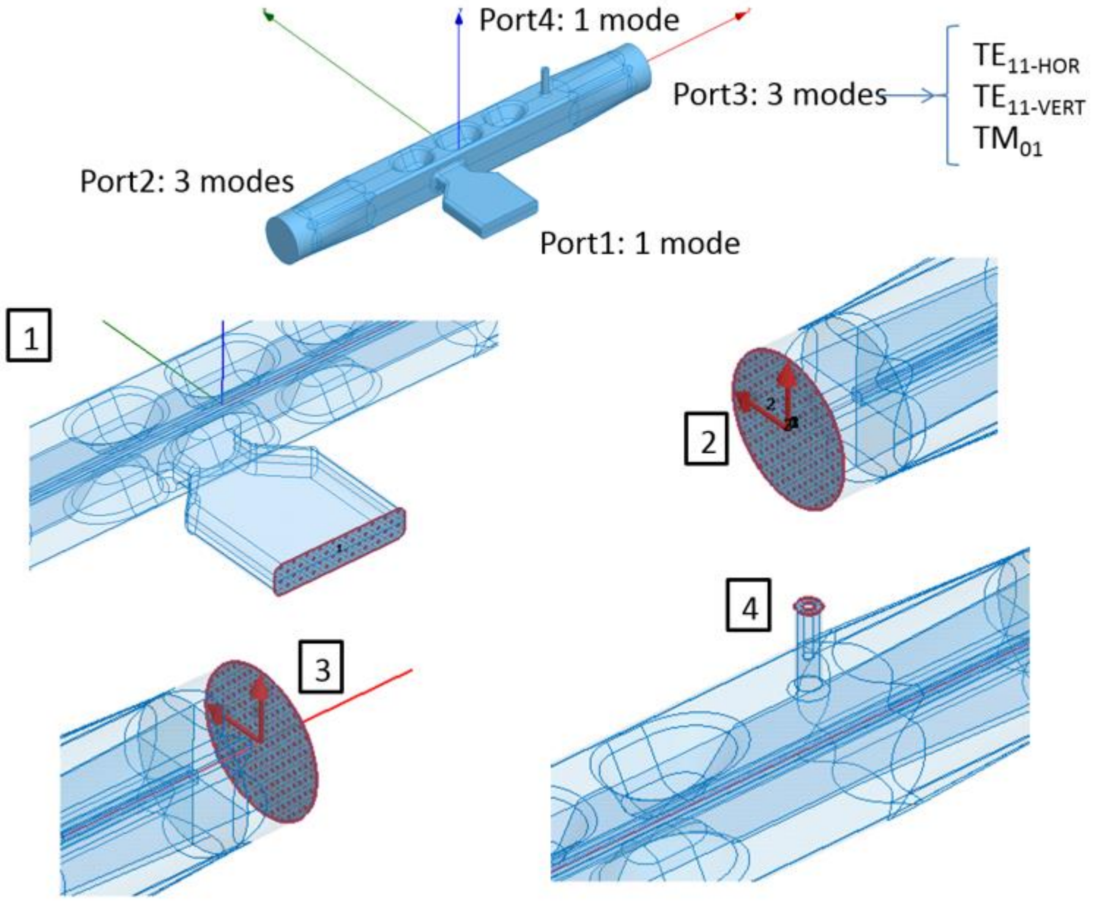


Maximum frequency tuning range: ~ 1..2 MHz

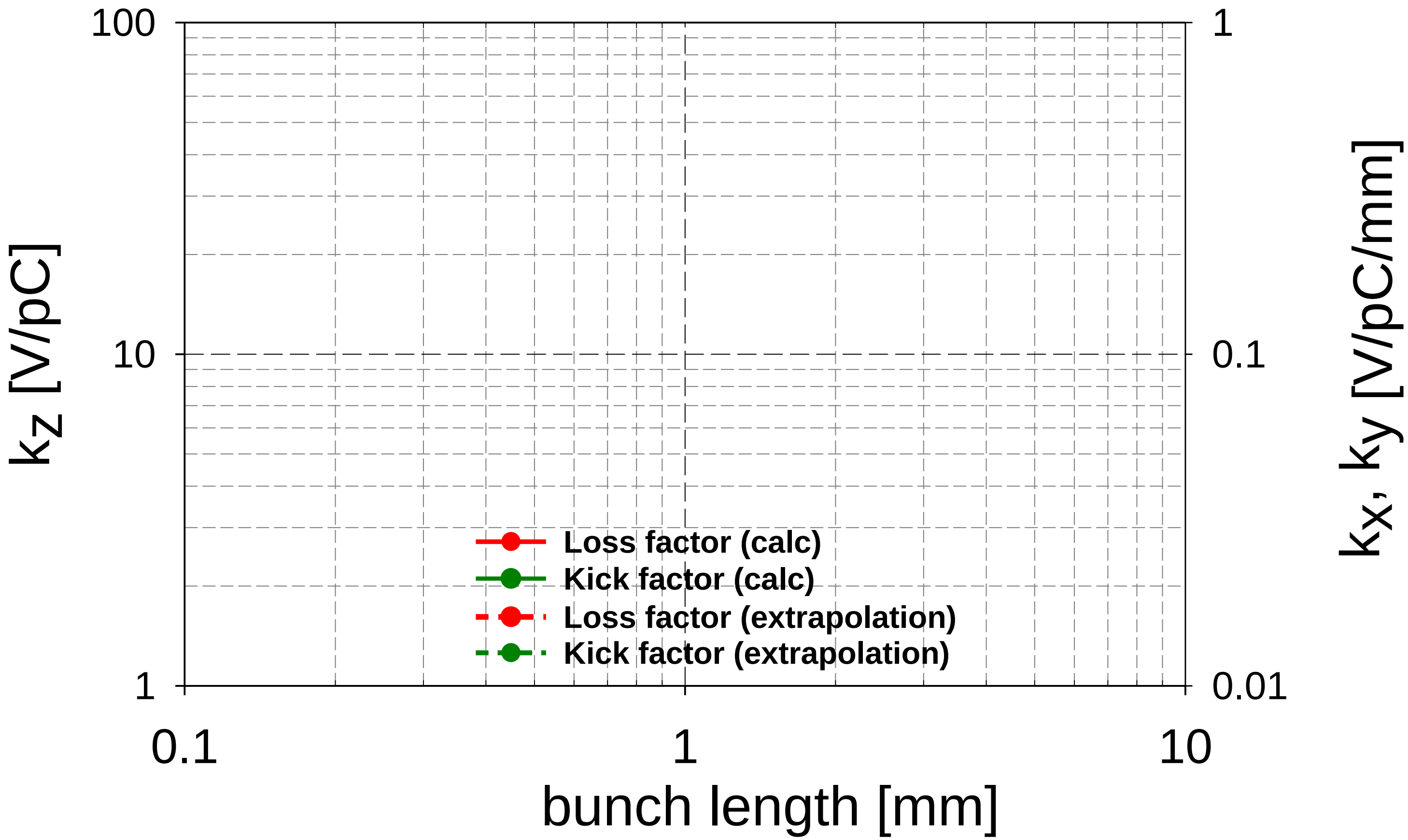
Backup Slides

High Order Modes (HOM) Damping

Driven Modal Simulations



2.6 GHz QMiR for ILC Crab Cavity



For the ILC bunch length (0.3 mm rms), the loss and kick factors:
k_loss <= 50 V/pC and k_kick <= 0.1 V/pC/mm