QMiR Crab Cavity for ILC

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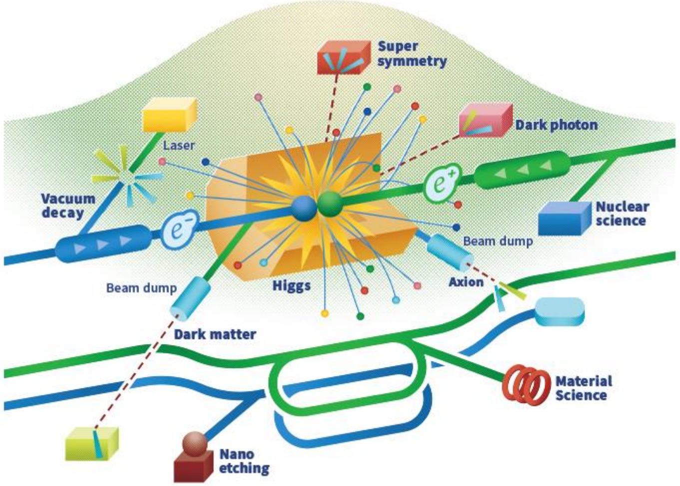
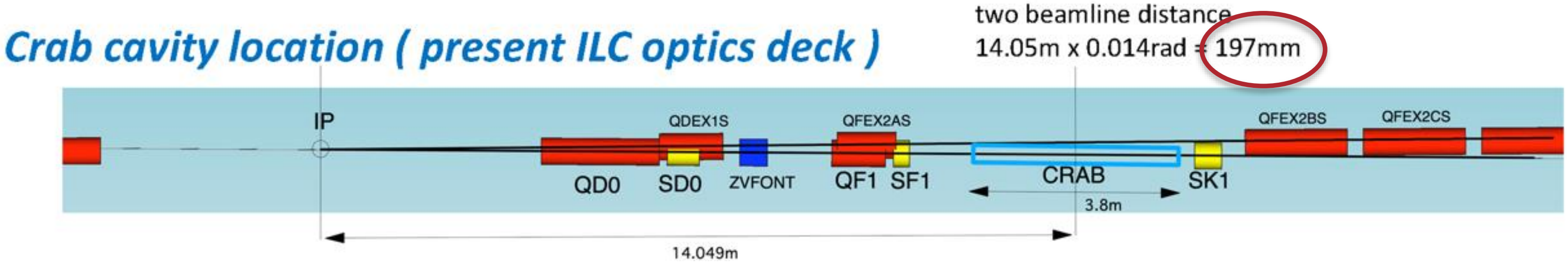
WP3 Crab Cavity Design Review Workshop #1



Outline

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

Requirements for the ILC Crab Cavities (CC)



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

a) Crabbing voltage distortion

- HOM kick voltage should be less than the crabbing voltage

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

b) Beam emittance dilution

- HOM kick should be less than the transverse momentum spread

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

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

- Horizontal Shunt Impedance Limit

$\boldsymbol{r_x f_{HOM} \ll}$ **61; 87; 122 MOhm·GHz**

- Vertical Shunt Impedance Limit

$\boldsymbol{r_y f_{HOM} \ll}$ **67; 95; 135 MOhm·GHz**

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

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

b) Beam emittance dilution

- Transverse kick should not increase the bunch emittance

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

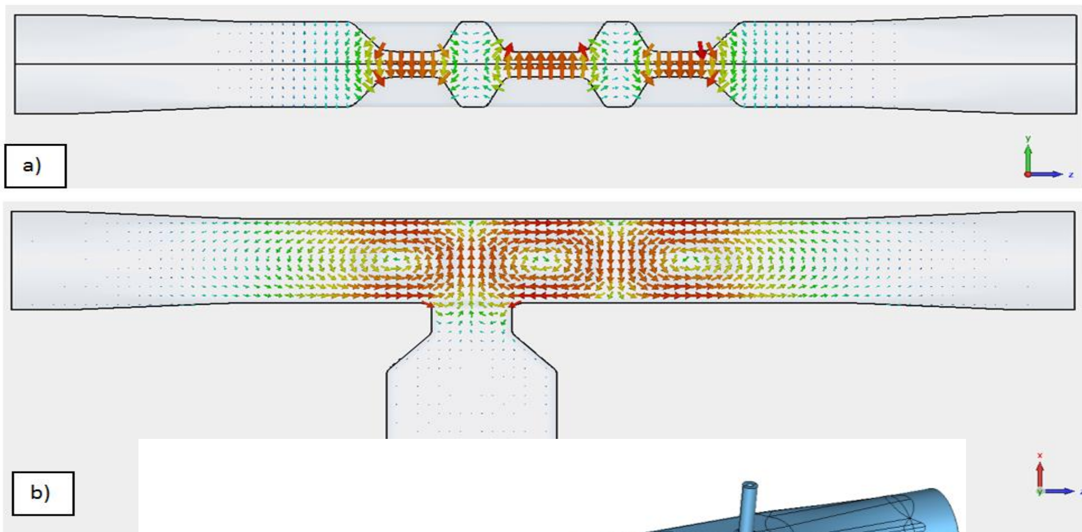
For max beam offset @CC: $\boldsymbol{x_0 < \sigma_x}$ and $\boldsymbol{y_0 < \sigma_y}$

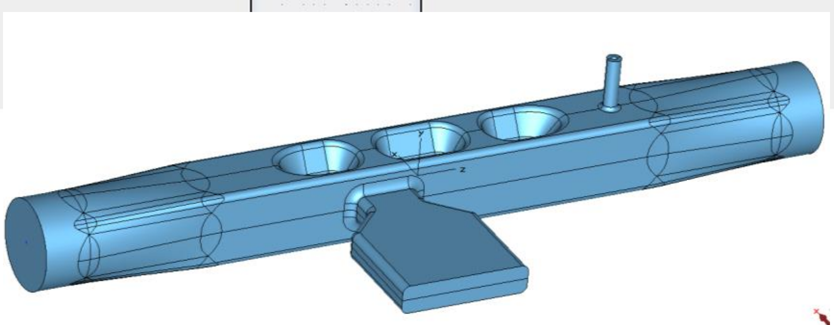
Horizontal Kick Factor Limit **k_x << 2.3; 3.3; 4.6 V/pC/m**

Vertical Kick Factor Limit **k_y << 2.5; 3.6; 5.1 V/pC/m**

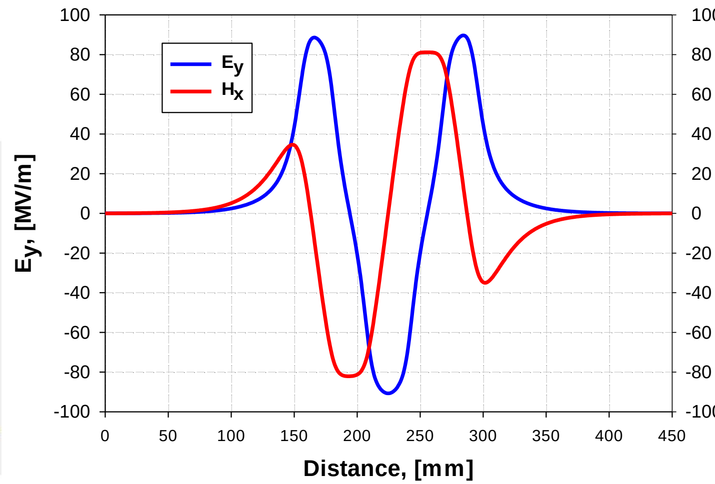
Compact HOM-free Deflecting Cavity QMIR

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

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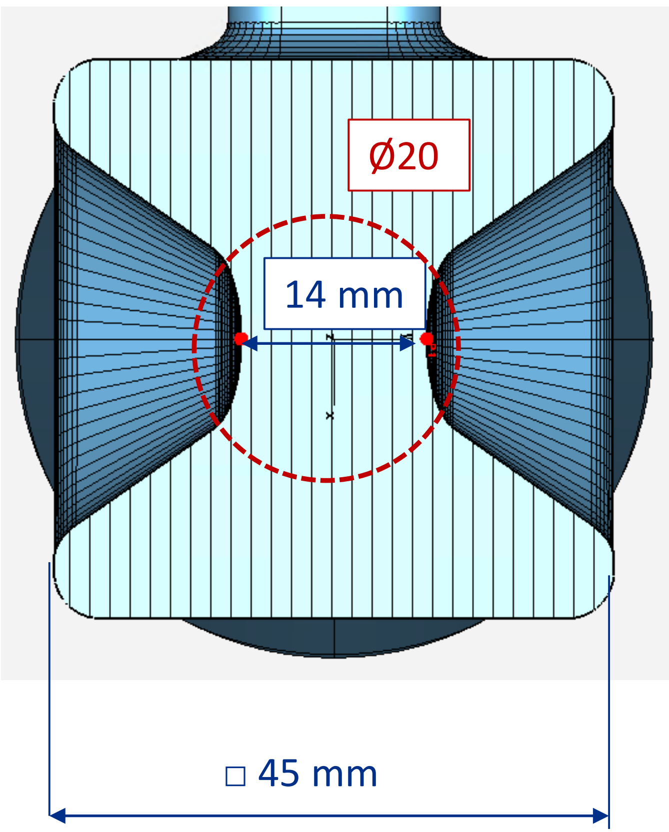
QMiR Cavity for ILC (scaled to 2.6 GHz)

ILC CC Aperture Limit is < Ø20 mm (?)

Variant A (2.6 GHz)



- **QMiR Deflecting Cavity has two opposite electrodes**
- **Smaller distance between electrodes provides a larger transverse kick**
- **The SR halo causes the heating of the electrodes**
- **The total area of SR interception is < 20% of the "effective" aperture**
- **Can we tolerate a smaller than 20mm distance?**
  - ILC BDS group input is needed
- **What is a safe maximal SR power dissipation?**
  - For a front pair of electrodes with dT<0.5K:

  $P_{max} \approx 2K_{NB}S_e dT/(DF*h_e) \approx 100W$

  K_{NB} = 10 W/m/K - thermal conductivity

  S_e, h_e - electrode cross-section and height

  DF = $3.6*10^{-3}$ – duty factor
- **We can easily redesign QMiR to a lager aperture**
  - in progress …

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QMiR Cavity for ILC (scaled to 2.6 GHz)

Operation mode	$\left(\frac{r_\perp}{Q}\right) = 1040$ Ohm (@2.6 GHz)
Maximal dipole *horizontal* HOM	$\left(\frac{r_\perp}{Q}\right)_x < 10$ Ohm (@2.5 GHz);
	$Q < 1\times10^5$ ($< Q_{max} \approx 2.4\times10^6$)
Maximal dipole *vertical* HOM	$\left(\frac{r_\perp}{Q}\right)_y < 10$ Ohm (@4 GHz);
	$Q < 1\times10^4$ ($< Q_{max} \approx 1.7\times10^6$)
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:

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

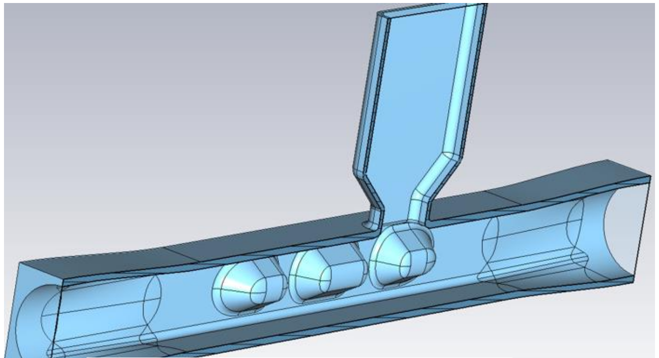
- For max beam offset $x_0 < 1$ mm and $\Delta f < 1$ kHz (LFD, microphonics)

Beam OFF:	$P_{min} \approx 200$ W
Optimal Coupling:	$Q_L \approx 1 \times 10^6$
Beam ON & Microphonics:	$P_{max} \approx 500$ W

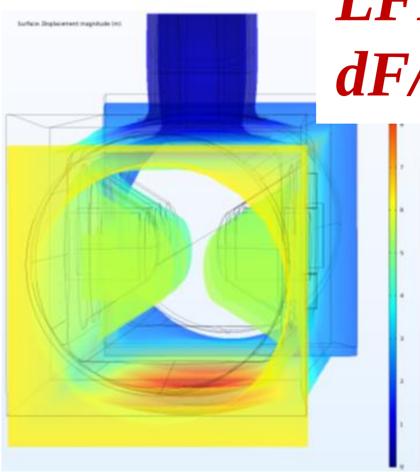
- Required RF power from the generator (overhead 100%):

$P_{gen} < 1$ kW

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

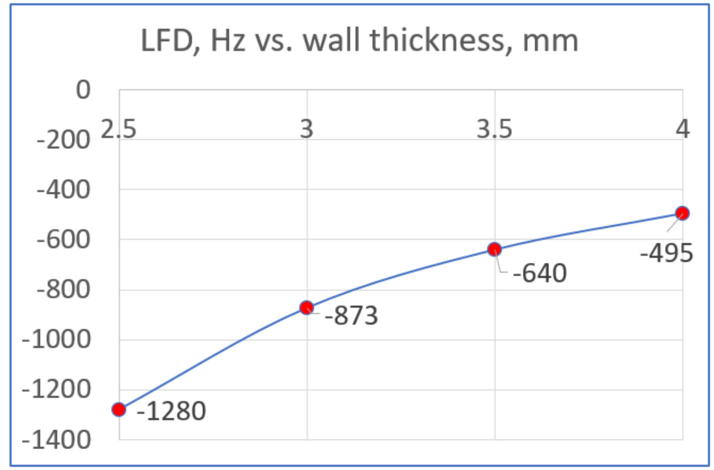


LFD at Kick = 0.9 MeV
Wall thickness 4 mm.
Δf ~ - 495 Hz

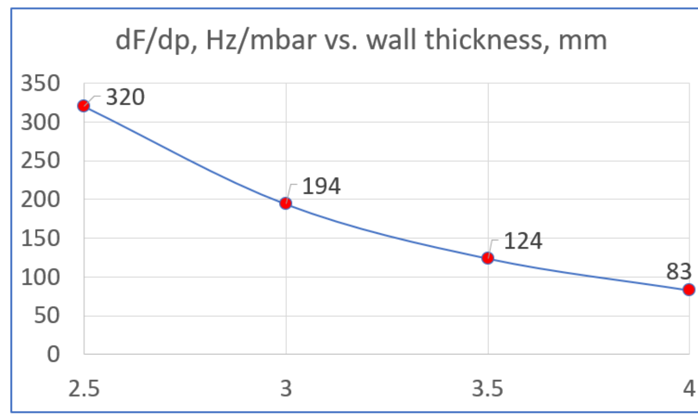


Deformation due to LFD

LFD < 500 Hz
dF/dP < 100 Hz



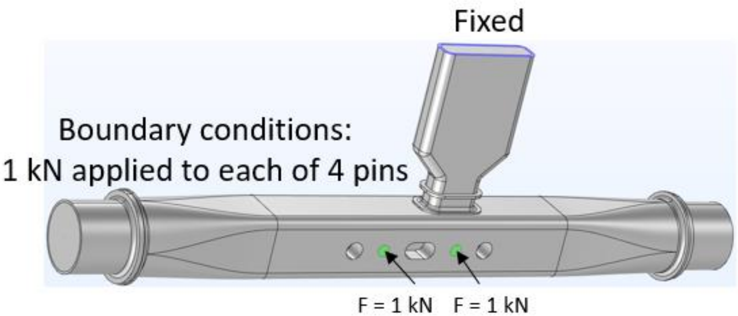
LFD in Hz at Kick = 0.9 MeV vs. cavity wall thickness

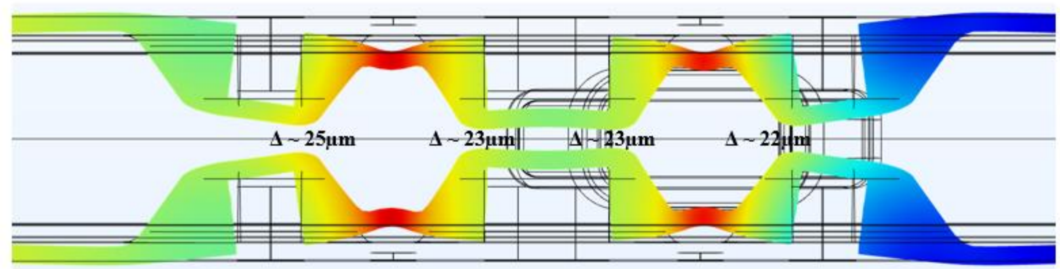


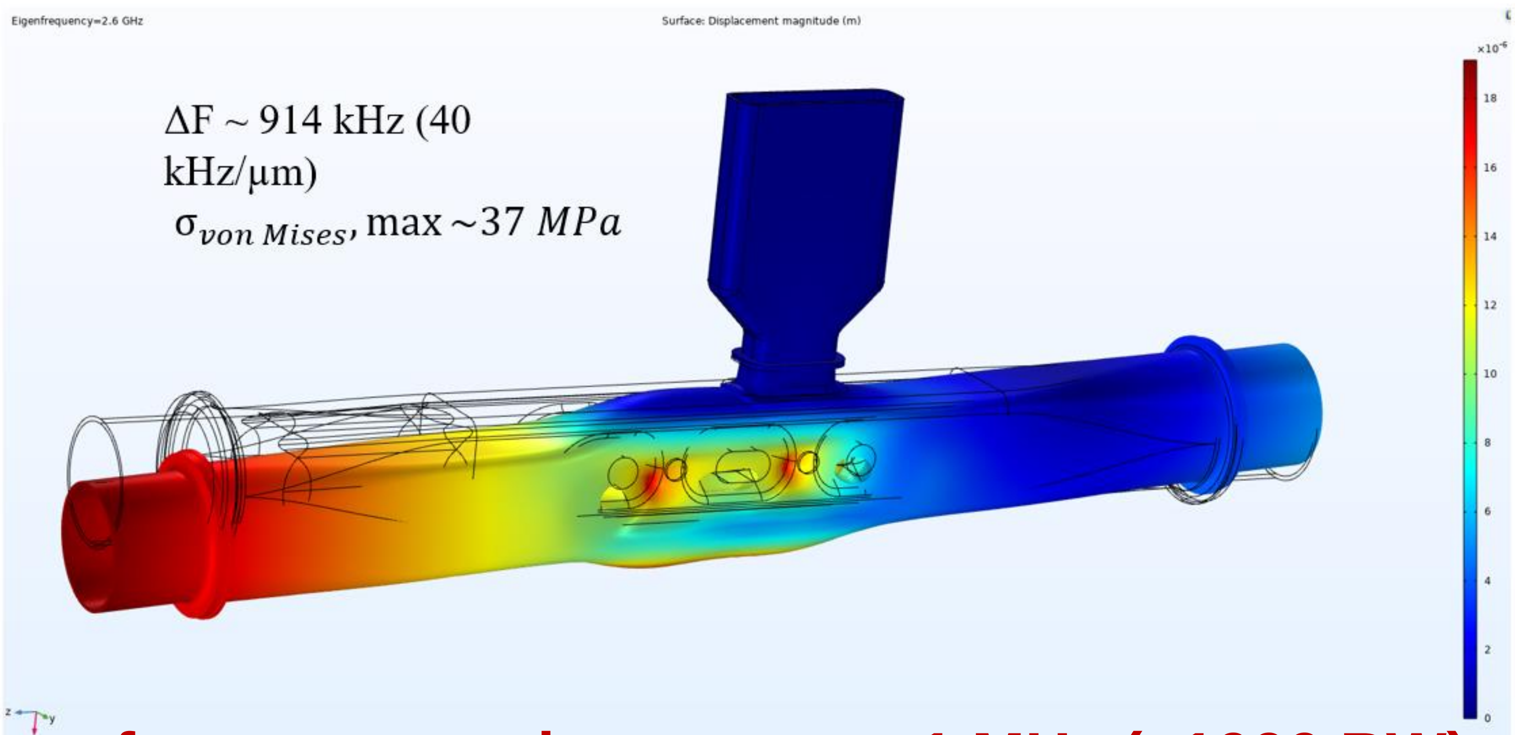
df/dP in Hz/mbar vs. cavity wall thickness

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

Mechanical Analysis of Frequency Tuning (by I. Gonin)



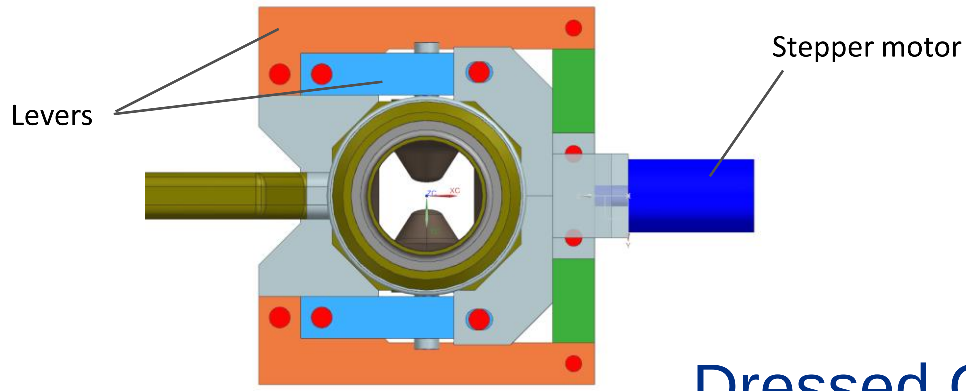




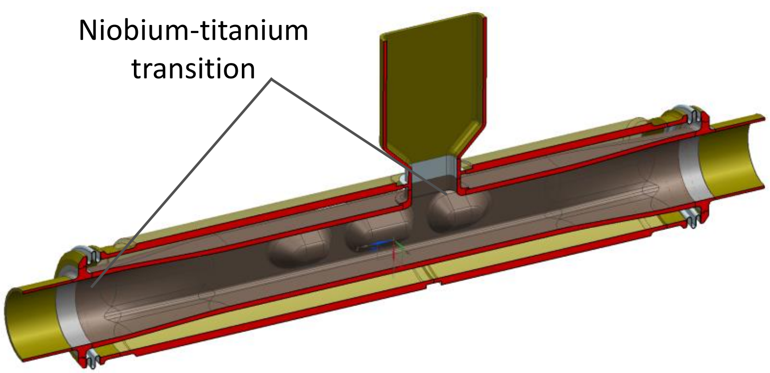
Maximum frequency tuning range: ~ 1 MHz (>1000 BW)

QMiR Cavity Slow Tuner Design (by V. Polubotko)

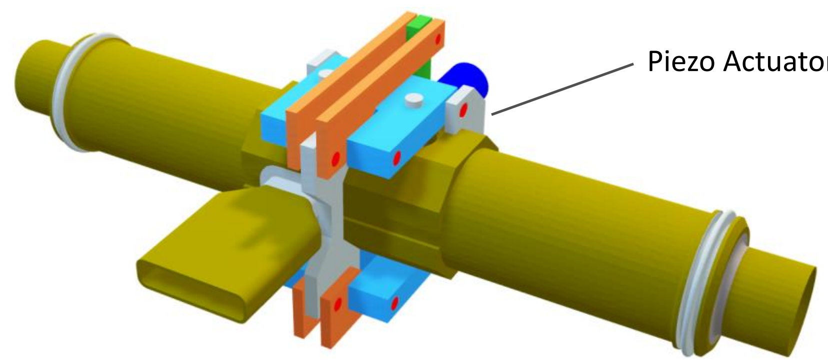
Compact double 2-lever frequency tuner



LHe Vessel

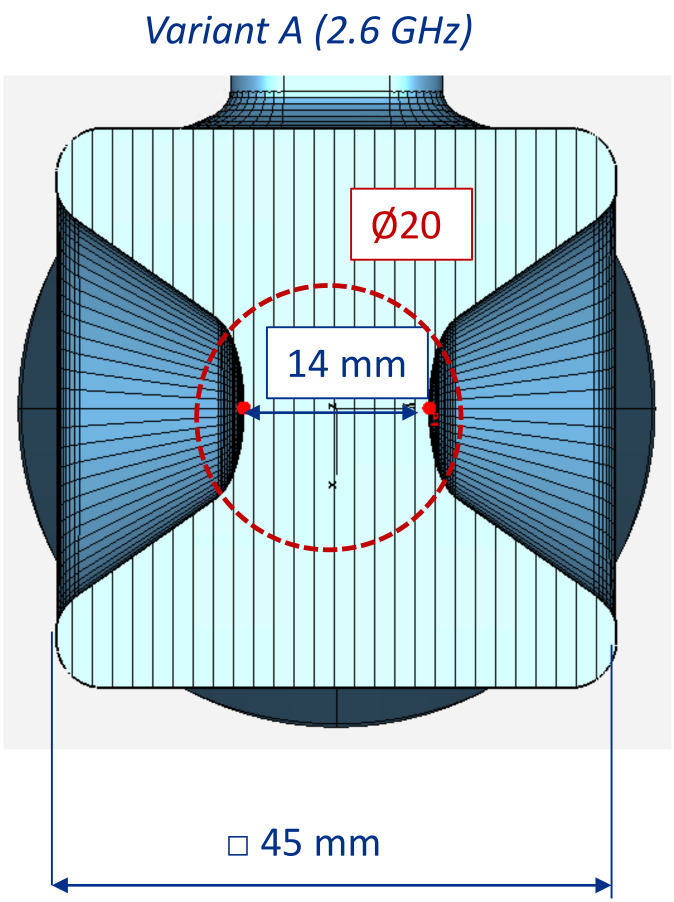


Dressed QMiR Cavity



- **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 for ILC (scaled to 2.6 GHz)



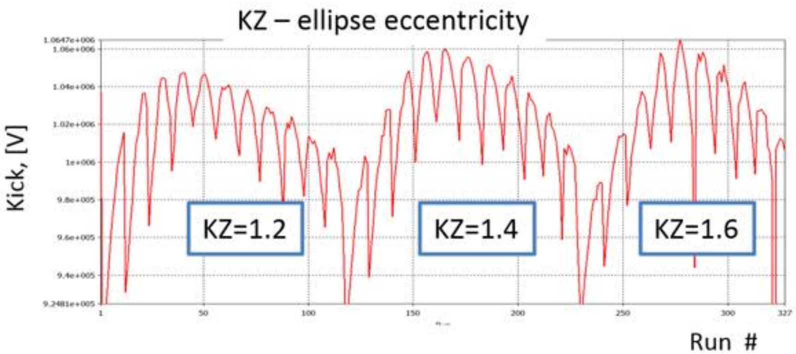
Open questions

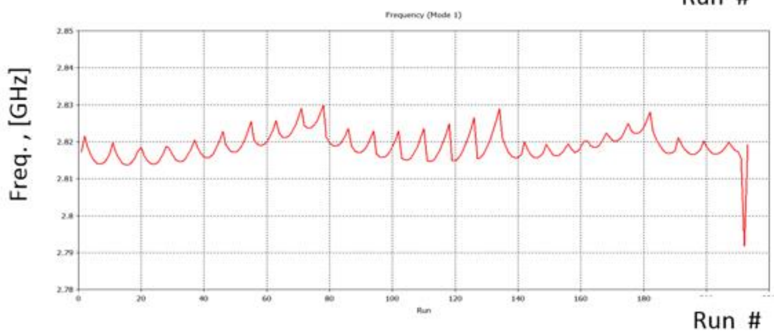
- **Minimal aperture/distance between electrodes**
  - ILC BDS group input is needed
- **Frequency tuner range**
  - How many BW (>1000) is required for detuning?
- **Beam size at CC location**
  - Is it the same for all ILC energies (250, 500, 1000 GeV)?
- **Multipole components**
  - Are there limits on operating mode uniformity?

Conclusions

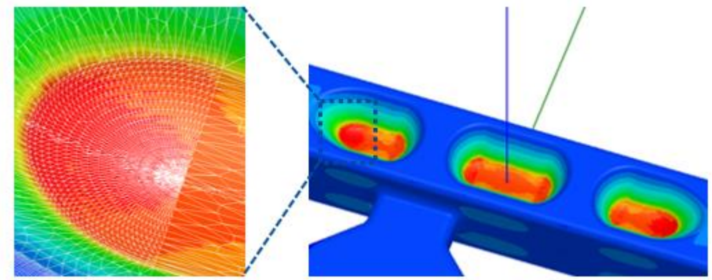
- ❑ Preliminary requirements for the ILC Crab Cavity developed
- ❑ A Quasi-Waveguide Multicell Deflecting Resonator (QMIR) is a good option for the ILC Crab Cavity
  - QMIR is very compact and simple;
  - It has sparse HOM spectrum;
  - It has acceptable loss/kick factors;
  - For the deflecting voltage of about 0.9 MV the cavity has considerably small surface fields, $E_p \approx 25$ MV/m, $B_p \approx 35$ mT.
  - No MP in operation voltage domain.
- ❑ QMIR cavity is considered now for Elletra-2, Trieste.
- ❑ The kick can be as large as 2MV – suitable for ILC upgrade
- ❑ Fermilab can design, build and test QMIR cavity for ILC application.

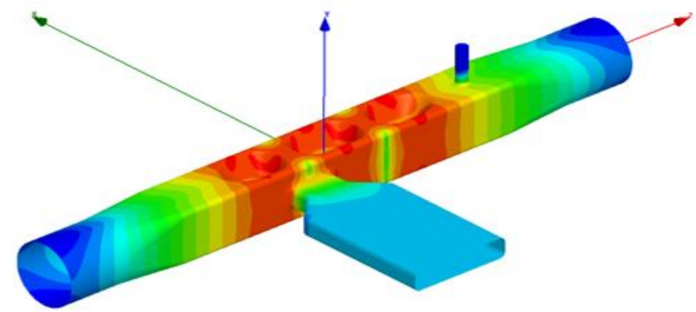
EM design of the QMiR deflecting cavity





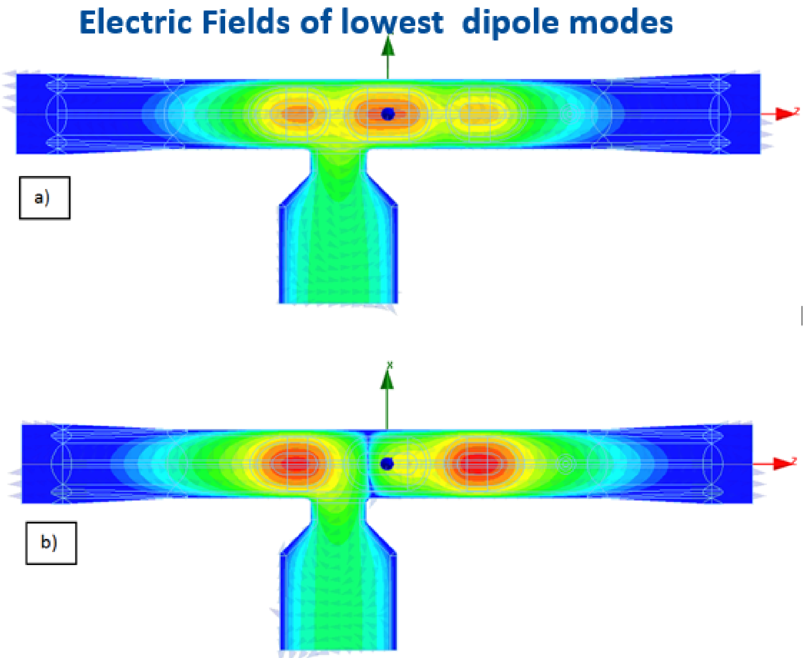
Operating trapped mode surface electric (up) and magnetic (down) fields

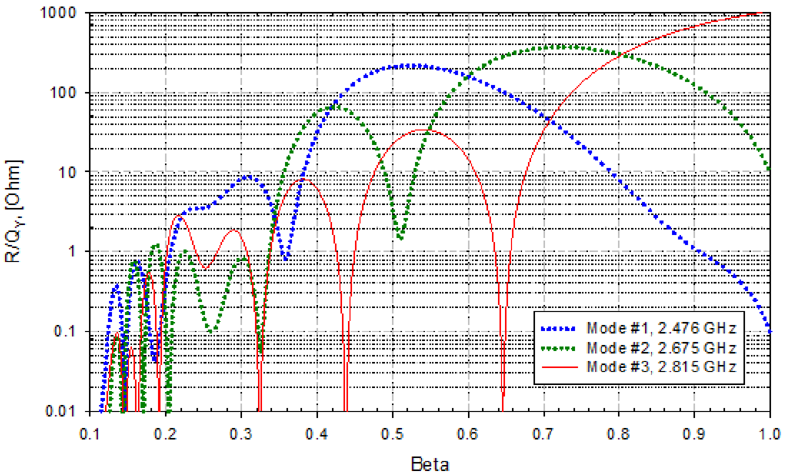




- Model is fully parameterized
- The frequency derivation was calculated for each parameter in order to preserve the operating mode frequency on the stage of geometry creation.
- General ellipsoid is used for hollow surface representation
- Global optimum search algorithm

Same Order Mode (SOM) Damping





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

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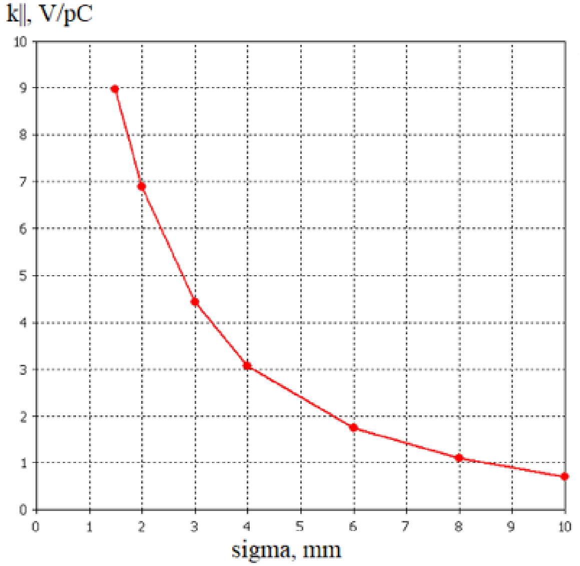
Backup Slides

❑ Loss factor:

- For step collimator $k_{||}$ ~$1/\sigma$;
- 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:

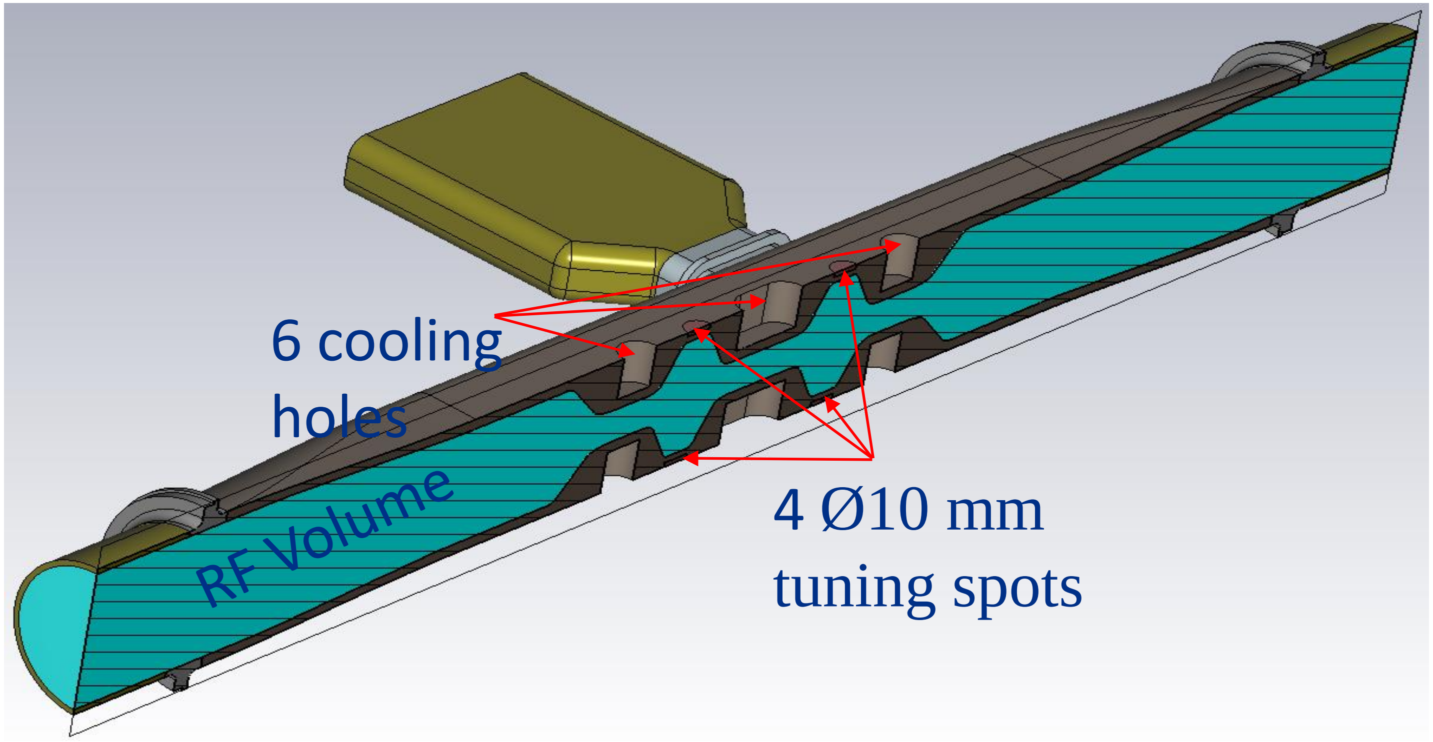
- At 2K one may expect the following surface resistance R_s for N-doped Nb:
  - 2.6 GHz: $R_s \approx 30$ *nOhm;*
  - *3.9 GHz:* $R_s \approx 68$ *nOhm.*



- 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)

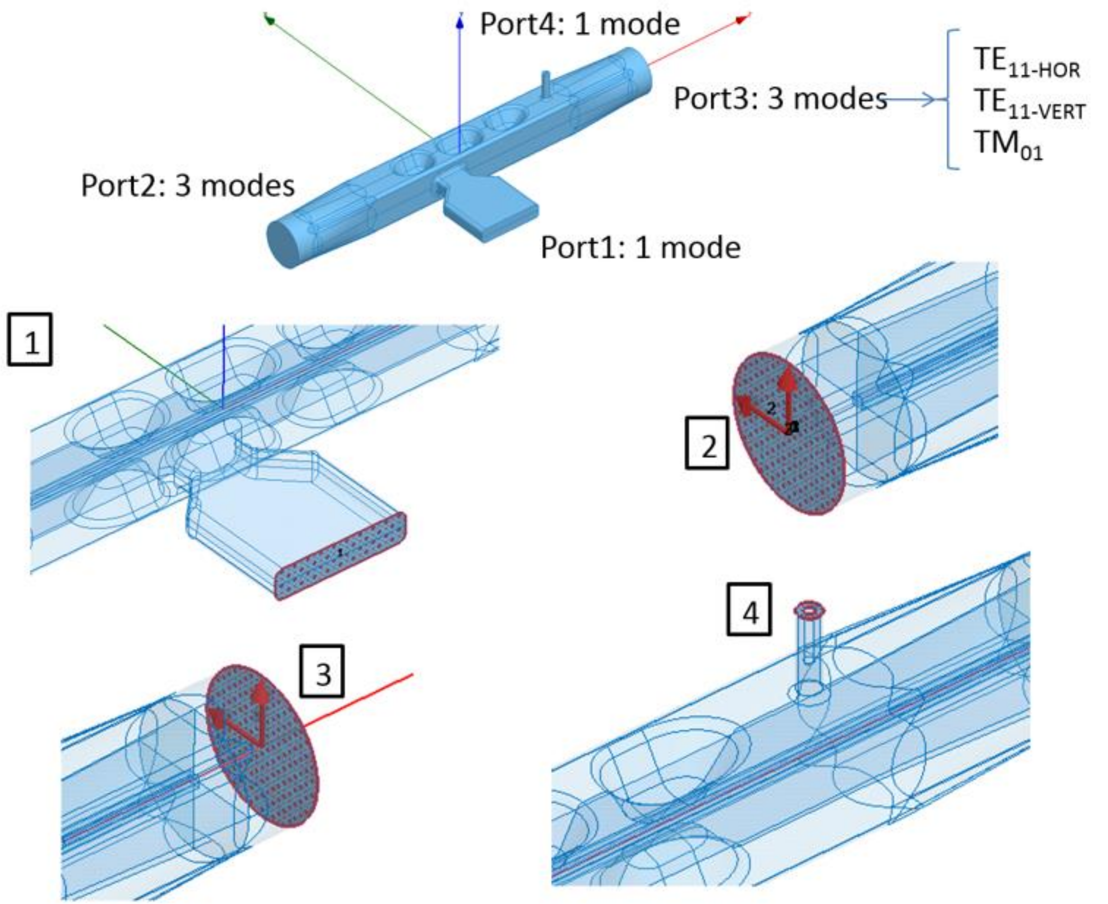


Maximum frequency tuning range: ~ 1..2 MHz

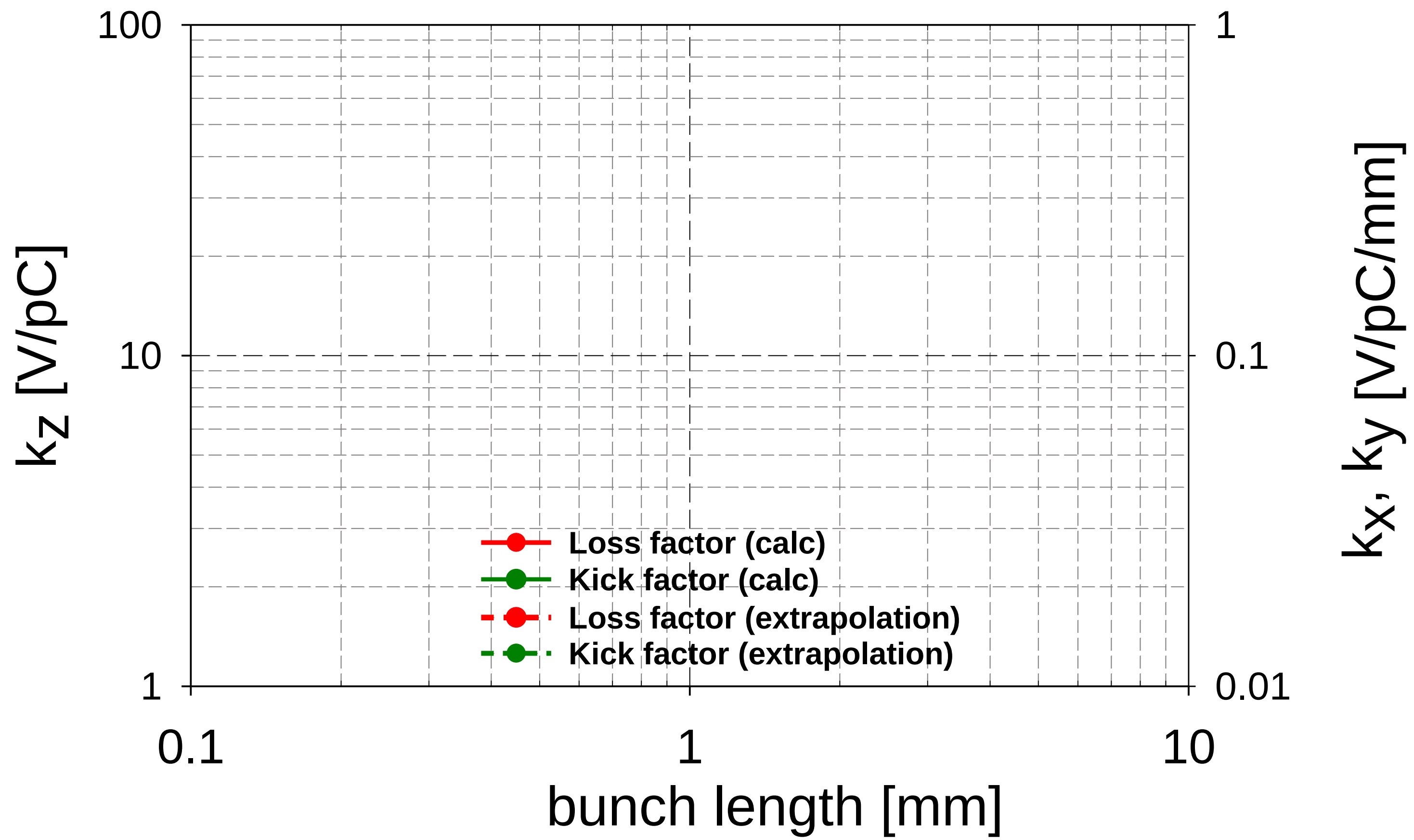
Backup Slides

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