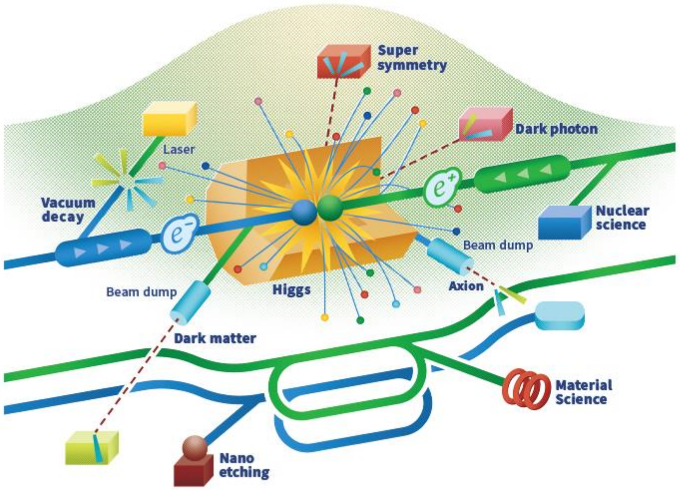
Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

QMiR Crab Cavity for ILC

Andrei Lunin, Vyacheslav Yakovlev

October 21, 2022

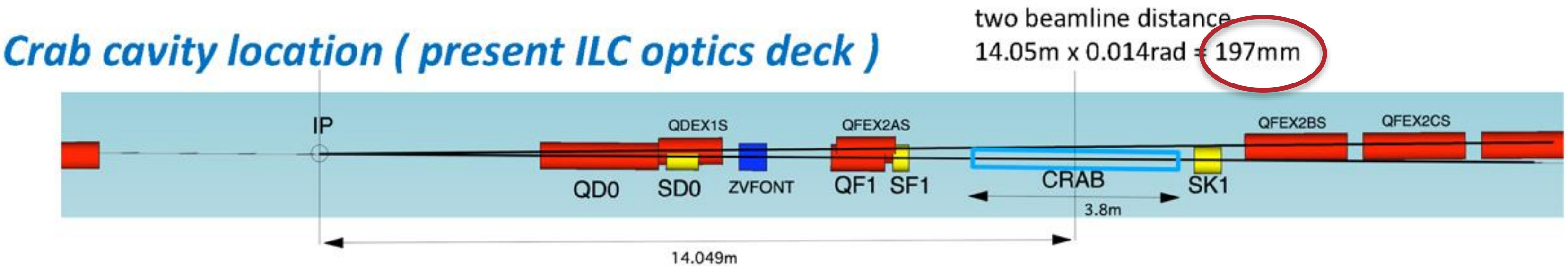
WP3 Crab Cavity Design Review Workshop #3



Outline

- General Requirements for the ILC deflecting cavities
  - HOM impedance limitation due to resonance excitation
  - Transverse wakefields effects
- QMiR (2.6 GHz) with increased aperture for ILC
  - New QMiR RF design
  - HOM and Wakefields Analysis
  - CC string layouts to meet the ILC requirements
  - 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)



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·GHz²**

- Vertical Shunt Impedance Limit

$r_y f_{HOM}^2 \ll$ **0.7 GΩ·GHz²**

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

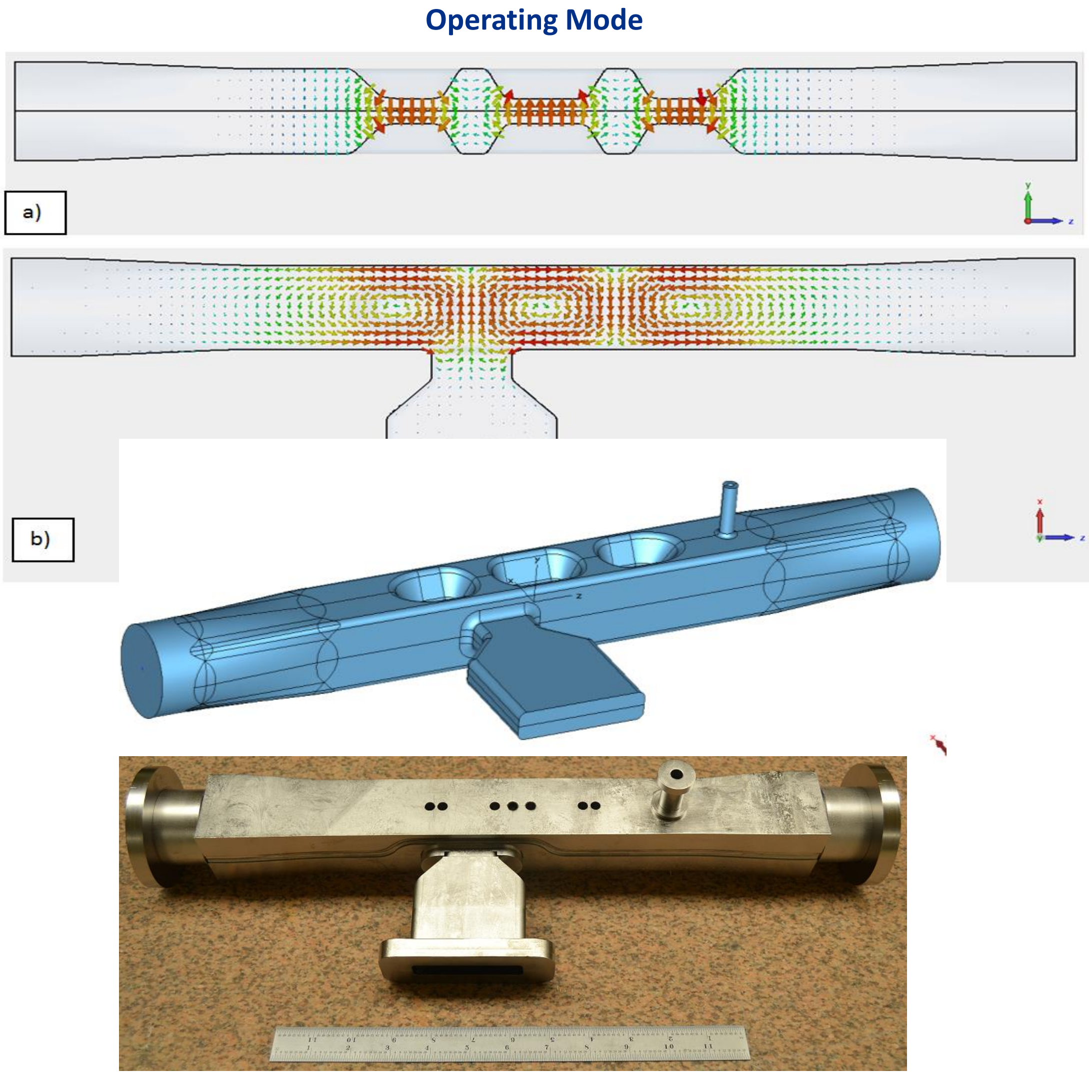
$$U_{kick} \ll \frac{\sigma_{p_\perp} c}{e} = \frac{p_\parallel c}{e}\sqrt{\frac{\varepsilon}{\gamma\beta}} \quad \text{or} \quad k_\perp \ll \frac{E}{q x_0}\sqrt{\frac{\varepsilon}{\gamma\beta}}$$

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

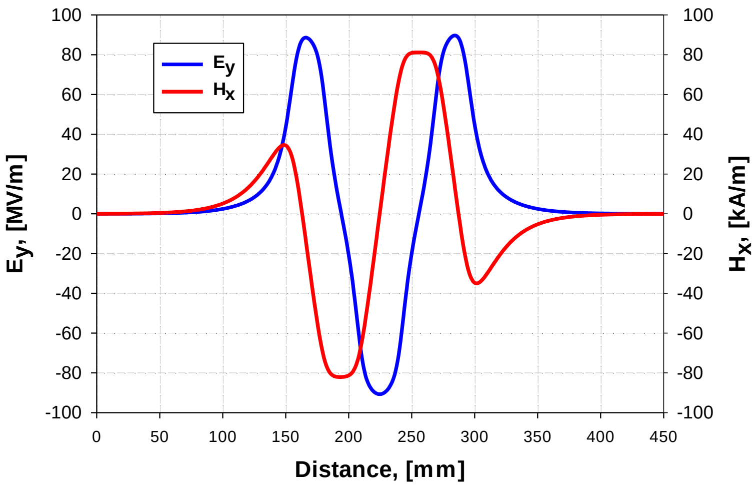
Horizontal Kick Factor Limit **k_x << 2.3 V/pC/mm**

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

Compact HOM-free Deflecting Cavity QMIR

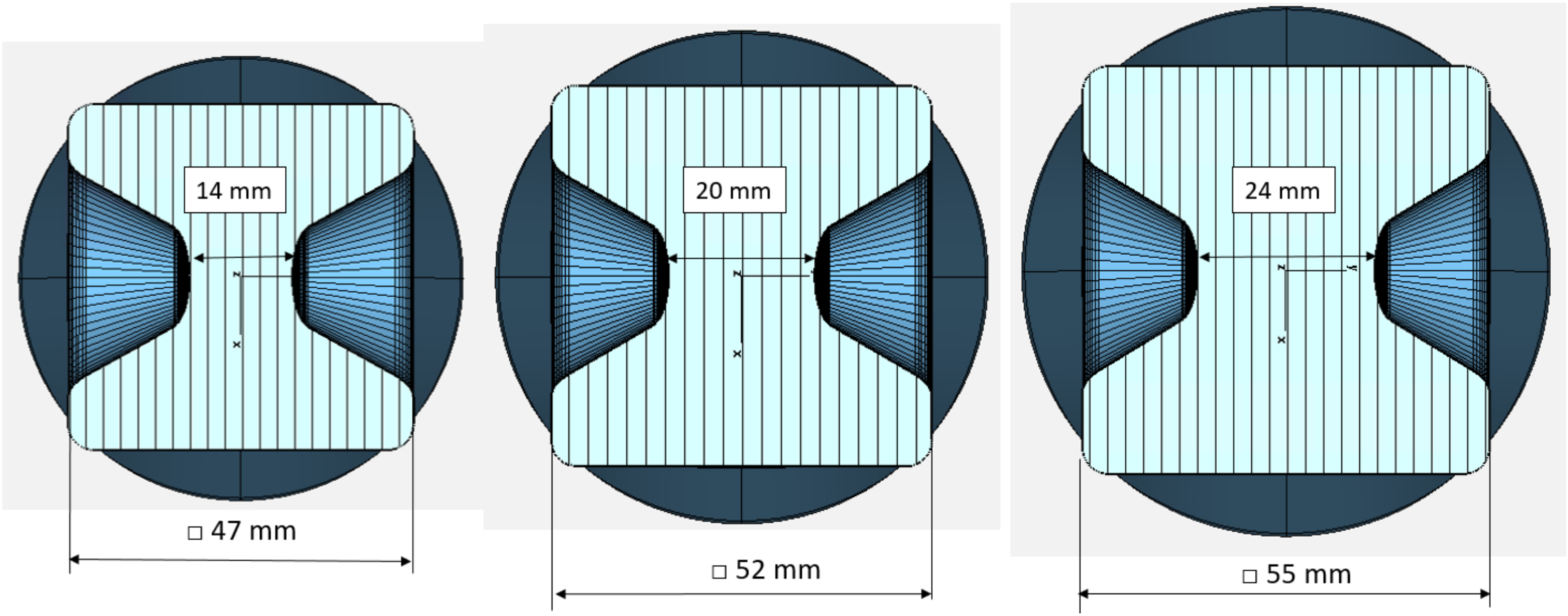


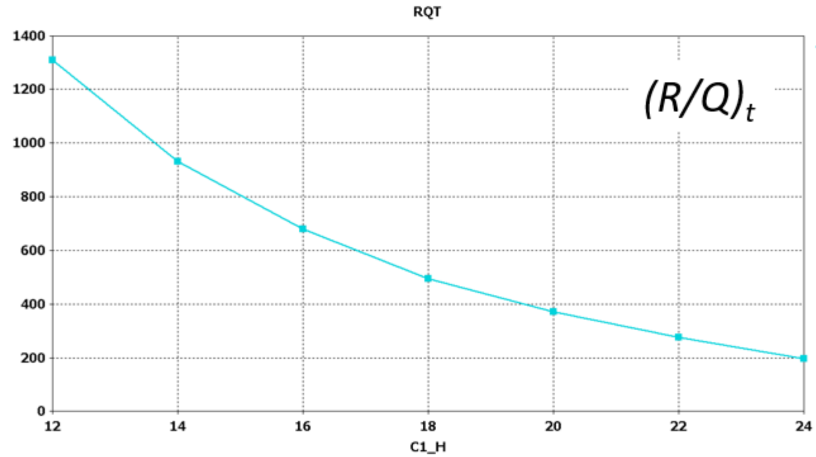
Transverse electric (blue) and magnetic (red) field components along the cavity axis.

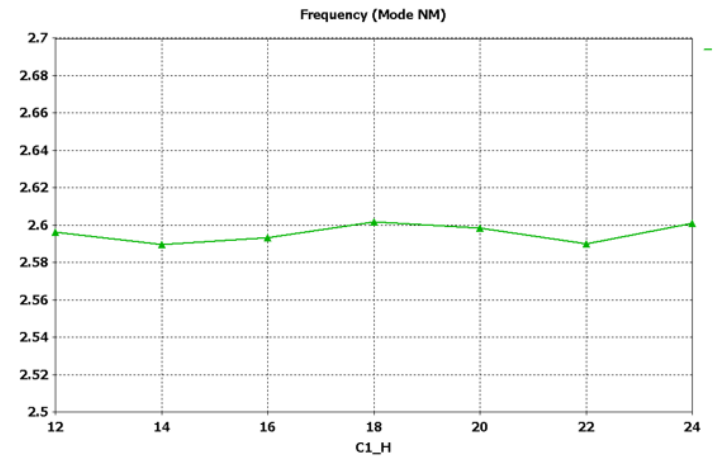


Freq	2815 MHz
V_{kick}	2 MV
E_{max}	55 MV/m
B_{max}	76 mT
$(R/Q)_Y$	1040 Ω (acc. def.)
G	130
W_{STOR}	0.23 J
Length	450 mm

Scaling of QMiR Crab Cavity for ILC

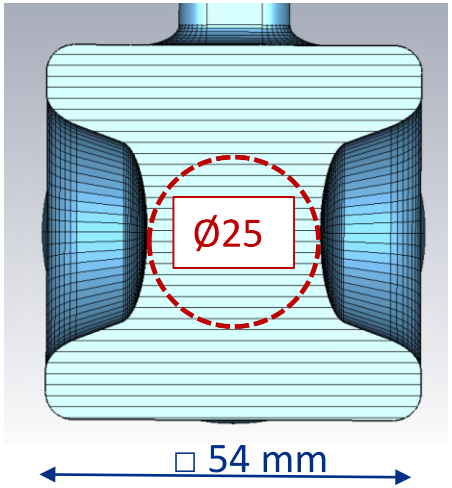




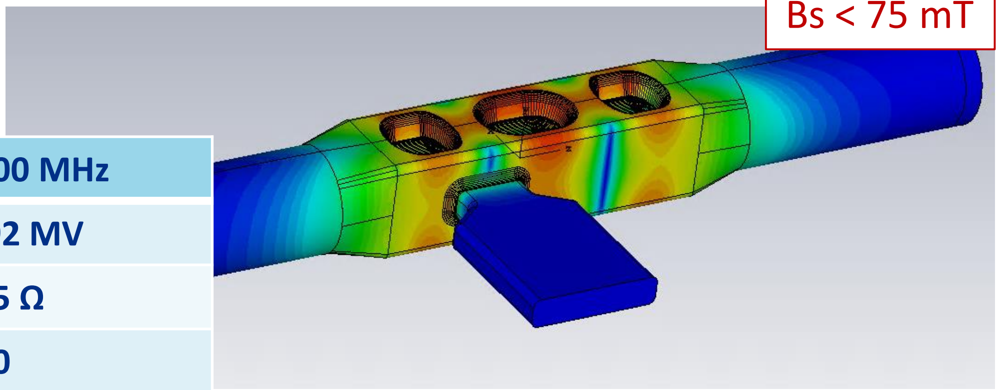


QMiR Cavity for ILC (2.6 GHz with increased aperture)

ILC Crab Cavity Aperture Limit: Ø25 mm

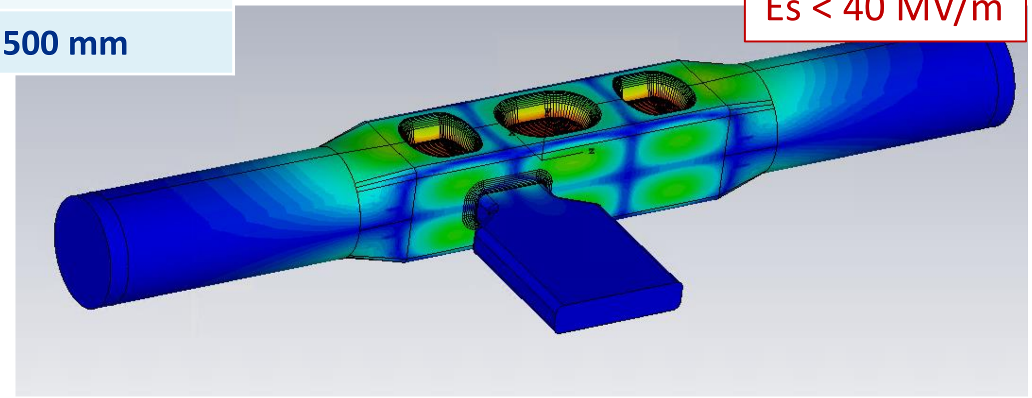


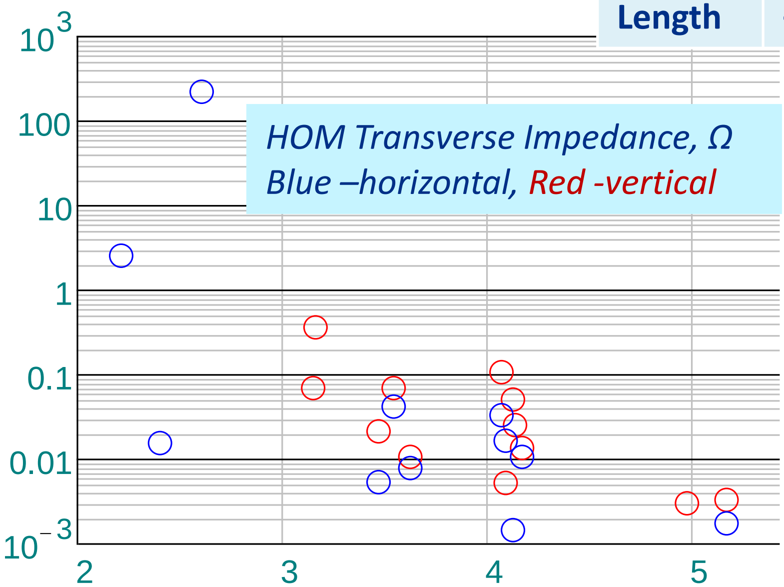
Magnetic Field



Freq	2600 MHz
V_{kick}	0.92 MV
$(R/Q)_t$	225 Ω
G-factor	130
W_{STORED}	0.24 J
Length	< 500 mm

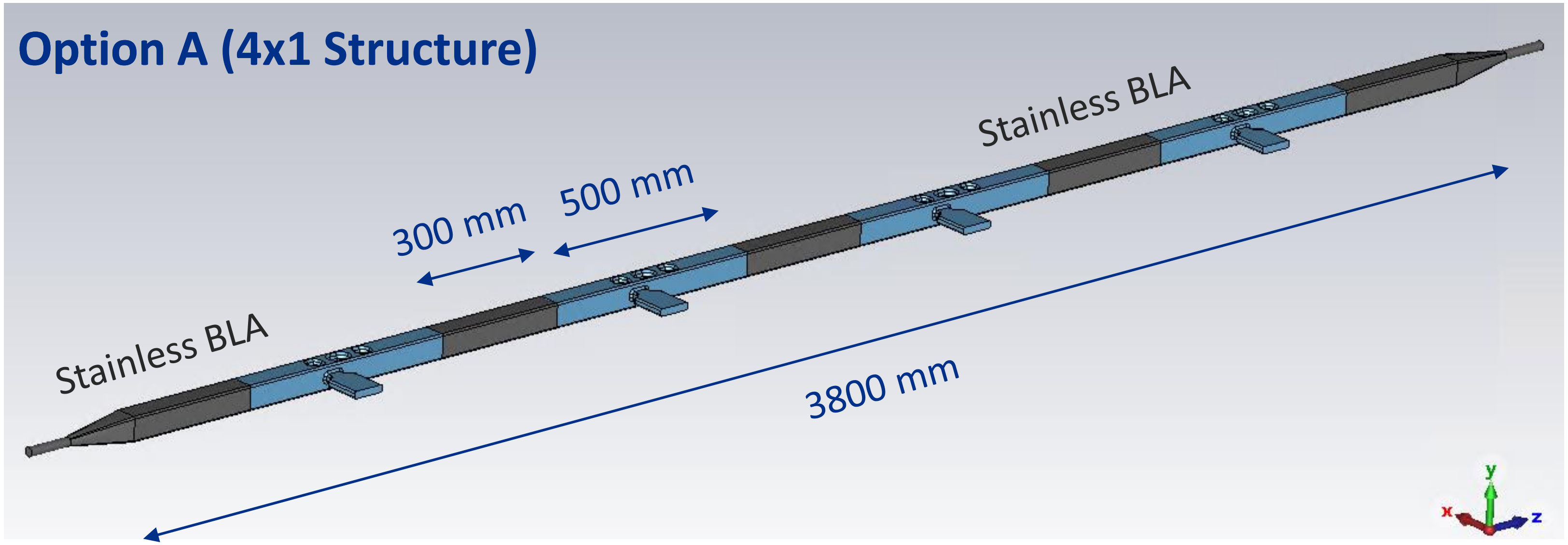
Electric Field

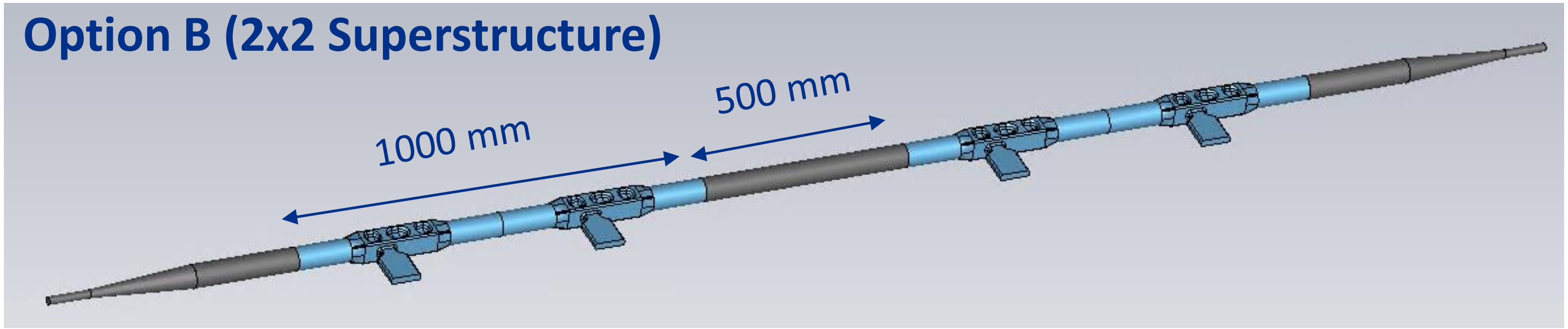




- **SOM strongly coupled with WG-port, Qext < 5x10³**
- **HOM spectrum is sparse and loaded to a beam pipe**
- **4 QMiR cavities can provide Vt ~ 4 MV for 1 TeV option**

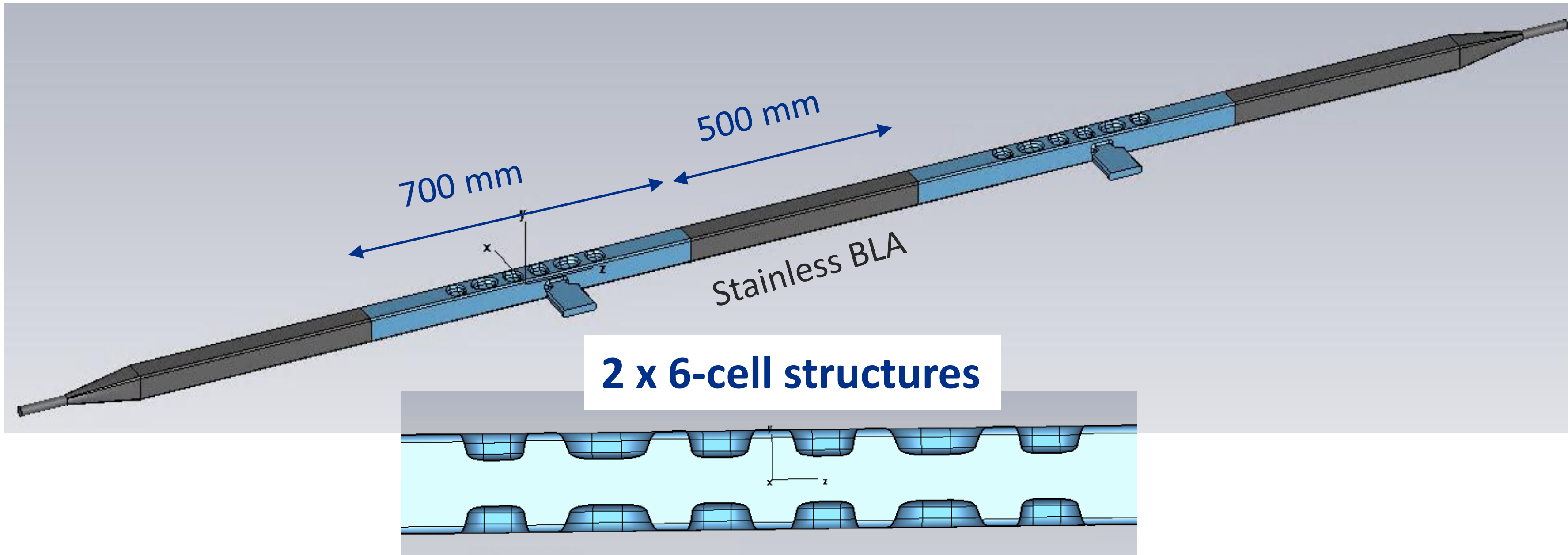
QMiR Cavity String for ILC





- **Two options are considered, a chain of 1x4 and 2x2 cavities**
- **Simple stainless-steel inserts to damp HOMs**
- **Ceramic BLA can be a backup if needed.**

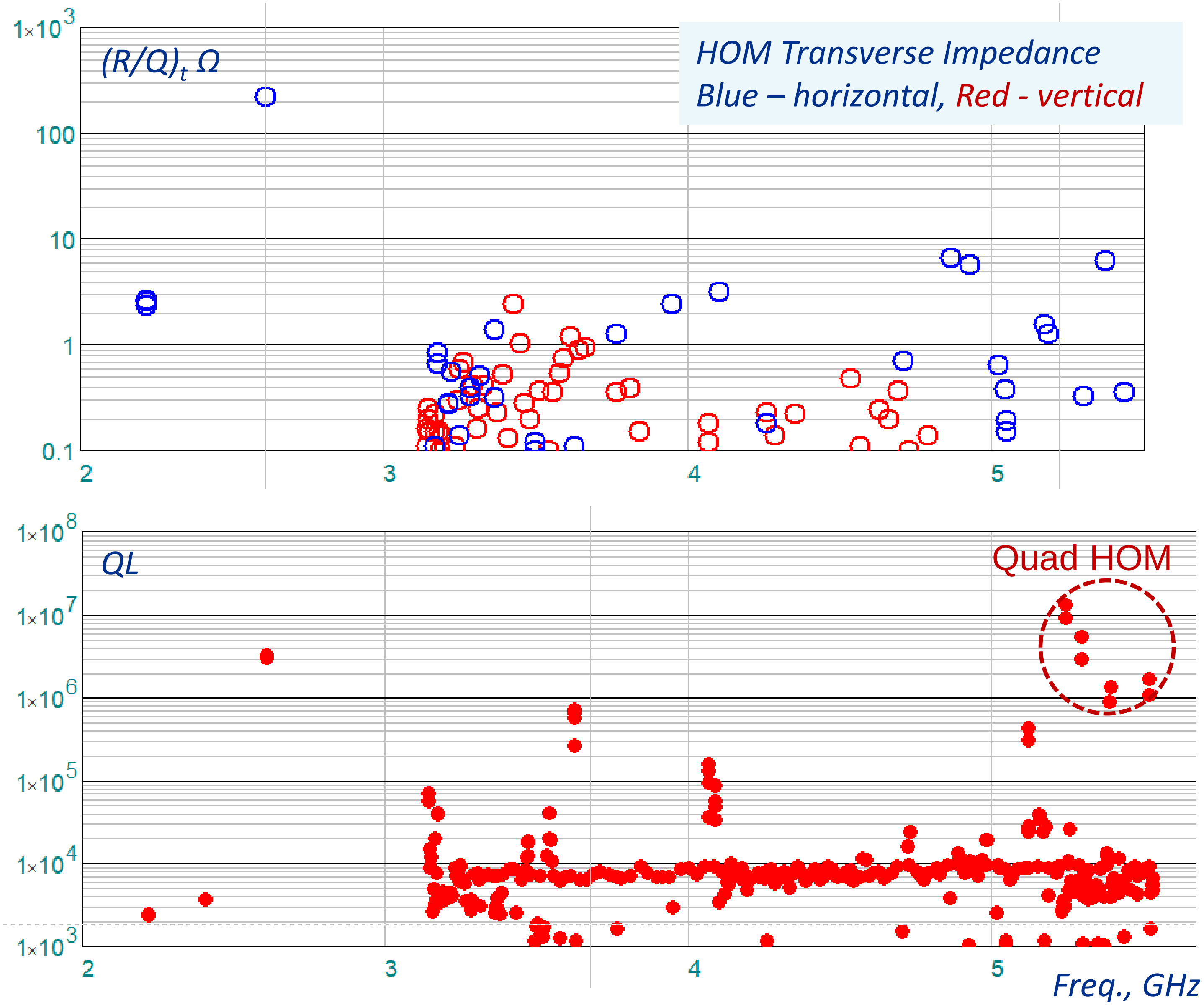
QMiR Multicell Cavity for ILC (R&D Option)



- **Multicell Structure can be more compact and efficient solution**
- **(R/Q) are typically very low for trapped HOM and SOM**
  - long distributed field structure without synchronism
- **R&D study is needed to verify the 6-cell QMiR performance**

Fermilab

QMiR Cavity String for ILC (Option A)



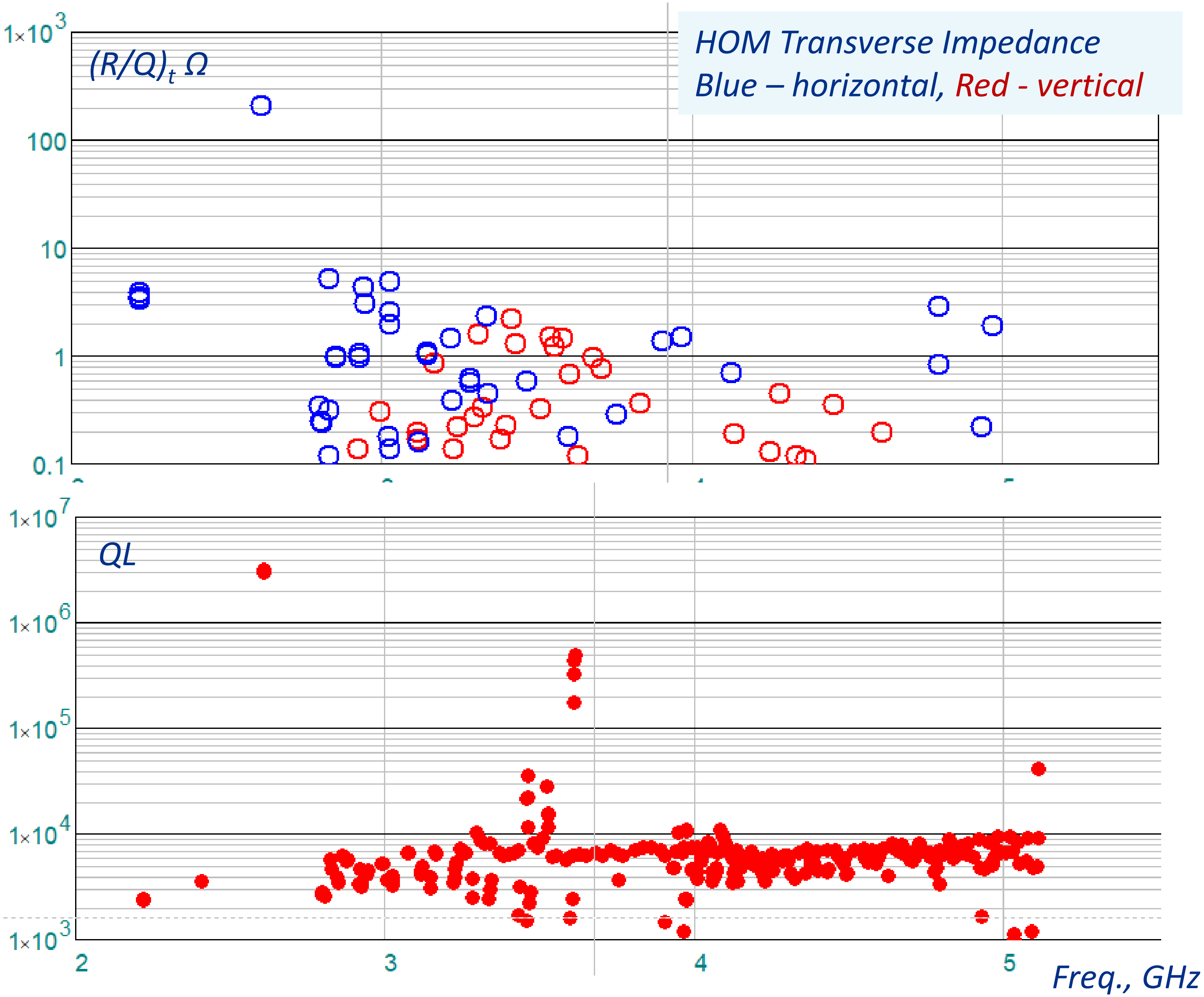
$(R/Q)_x$ < 10 Ω

$(R/Q)_y$ < 3 Ω

Dipole HOM

QL < 1E6

QMiR Cavity String for ILC (Option B)



$(R/Q)_x < 8\ \Omega$

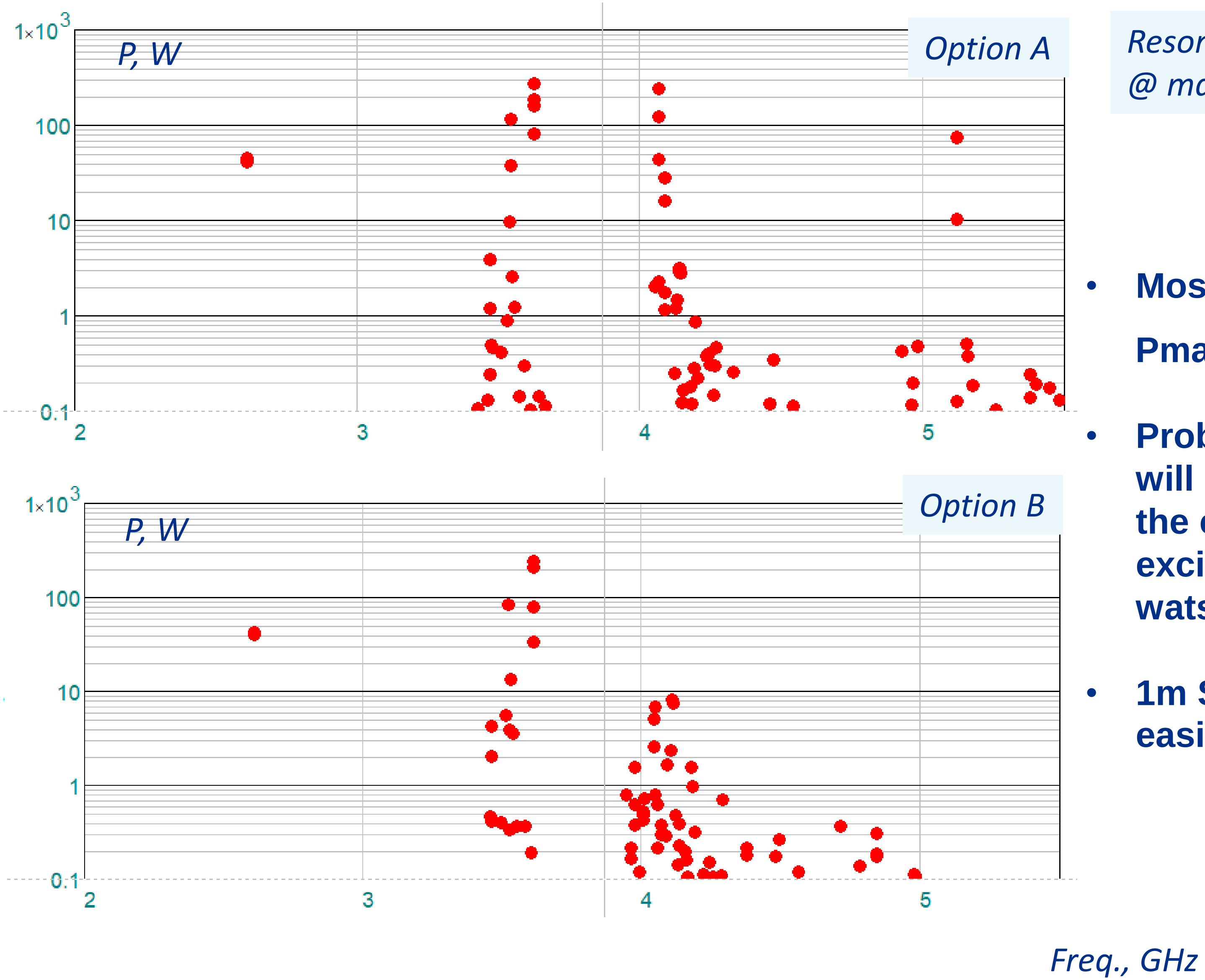
$(R/Q)_y < 3\ \Omega$

Dipole HOM

QL < 5E5

Fermilab

QMiR Cavity String for ILC



Resonant HOM Excitation @ max $x_0(y_0)$ = 1 mm

- **Most pessimistic case:**

  Pmax < 300W

- **Probabilistic analysis will most likely reduce the coherent HOM excitation to tens of wats**

- **1m SS section can easily dissipate ~100W**

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

Operation mode	$\left(\frac{r_\perp}{Q}\right) = 225$ Ohm (@2.6 GHz)
Maximal dipole *horizontal* HOM	$\left(\frac{r_\perp}{Q}\right)_x < 10$ Ohm , @4 GHz
	$Q < 2\times10^5 \ll Q_{max} \approx 1\times10^8$
Maximal dipole *vertical* HOM	$\left(\frac{r_\perp}{Q}\right)_y < 3$ Ohm, @3.5 GHz
	$Q < 1\times10^6 \ll Q_{max} \approx 2\times10^7$

Calculations are made for 14 mm aperture, for 25 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 Δf < 1 kHz (LFD, microphonics)

Beam OFF:	$P_{min} \approx 940$ W
Optimal Coupling:	$Q_L \approx 1\text{x}10^6$
Beam ON & Microphonics:	$P_{max} \approx 1500$ W

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

P_{gen} < 3 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:

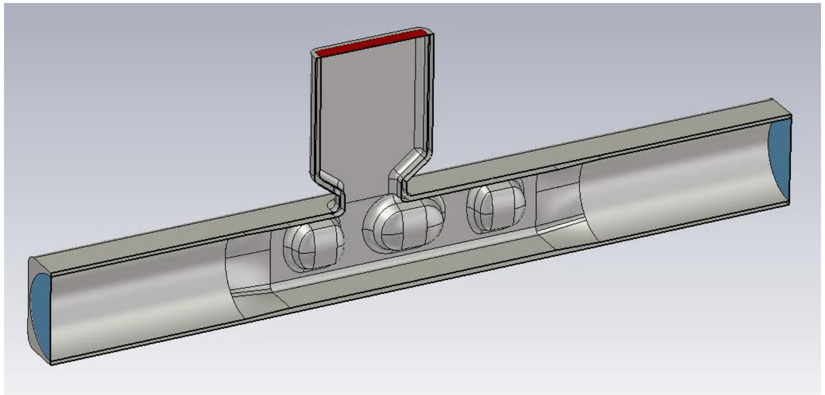
$$U_{kick} \approx \frac{1}{2m} k_0 x_0 I_p \left(\frac{r_\perp}{Q}\right) Q_L \,, \quad \text{where } m \equiv \frac{|\Delta\omega|}{\omega_0} Q_L$$

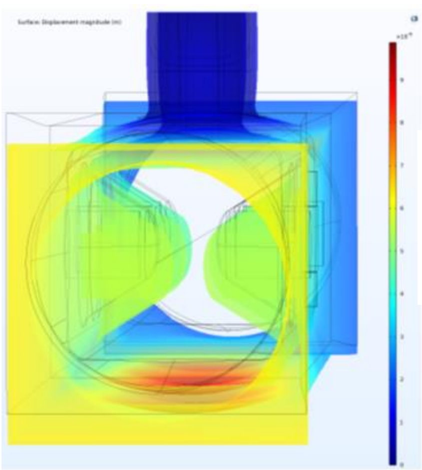
  - Required detuning:

$$m \gg \frac{\omega_0 x_0 I_p \left(\frac{r_\perp}{Q}\right) Q_L}{cE\sqrt{\frac{\varepsilon}{\gamma\beta}}} \approx 5 \,, \quad \text{or } \Delta f \gg 12 \text{ kHz}$$

- **Required frequency tuner range: F_{tuner} > 200 kHz**

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

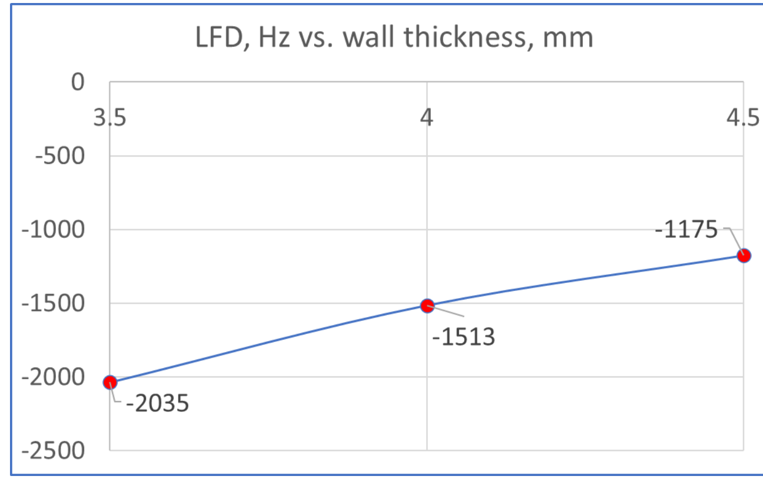


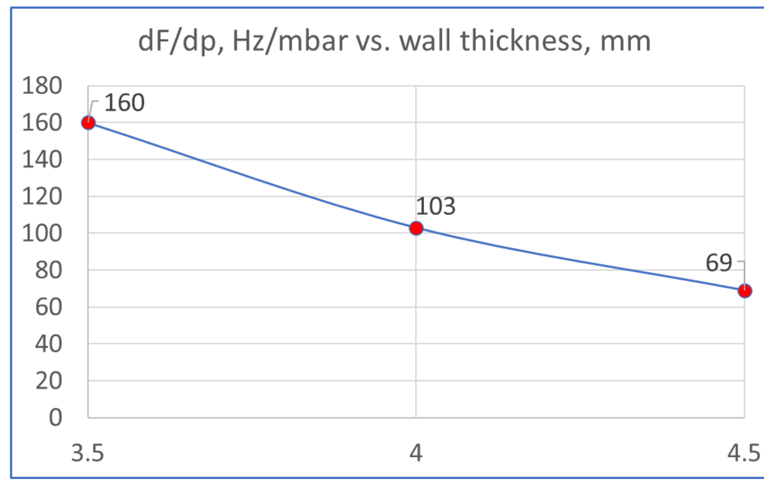


Deformation due to LFD

LFD < 1.5 kHz

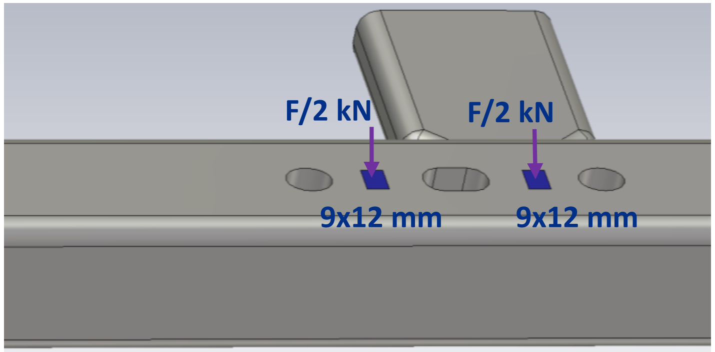
dF/dP < 150 Hz



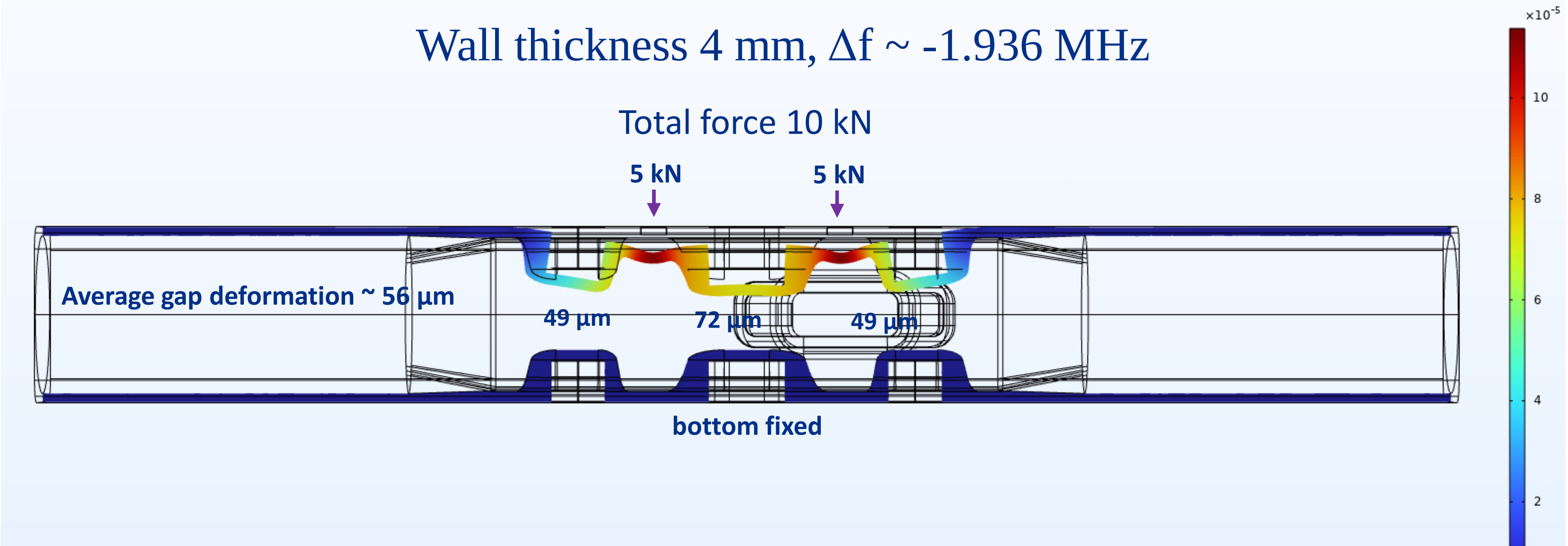


- **QMiR LFD and dF/dP are less than the cavity bandwidth (few kHz)**
- **LFD can be further reduced by adding rigid elements**

Mechanical Analysis of Frequency Tuning (by I. Gonin)



Thickness mm	Ave. gap change µm	Δf/ ΔForce kHz/kN	Δf/ ΔL kHz/µm	Δ σ/ΔForce Mpa/ kN
3.5	74	-250.7	-33.8	27.6
4.0	56	-193.6	-34.5	21.8
4.5	46	-155.1	-33.7	17.5

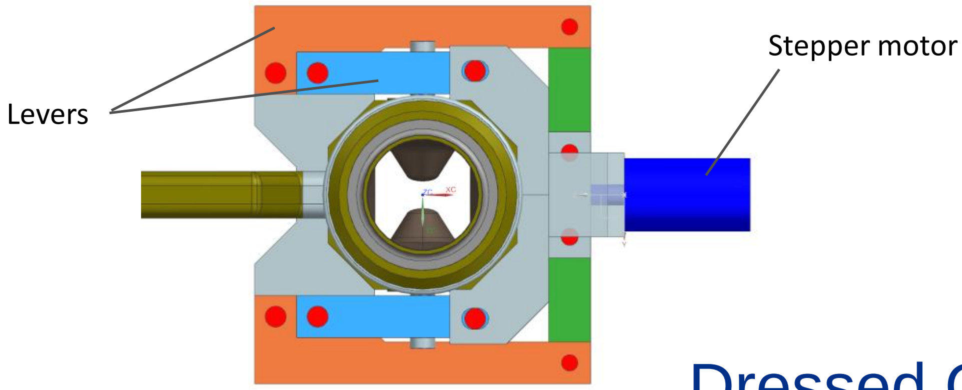


Expected frequency tuning range: ~ 2 MHz (1 MHz)

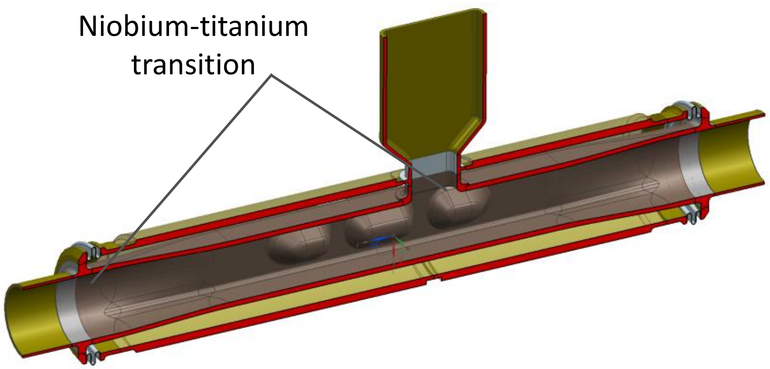
Fermilab

QMiR Cavity Slow Tuner Design (by V. Polubotko)

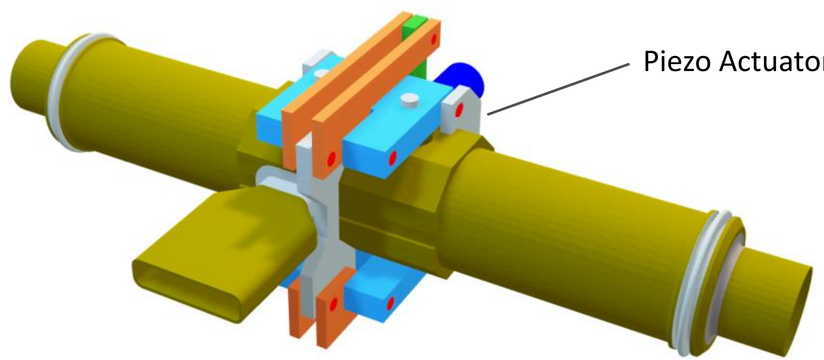
Compact double 2-lever frequency tuner



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

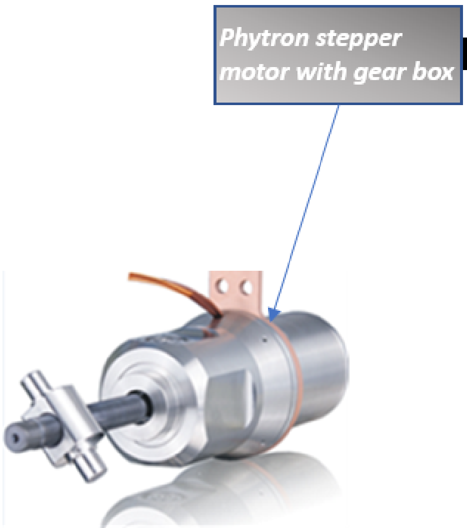
Proposed Tunings system for QMiR cavity
Slow/coarse tuner -Double lever tuner
Fast/fine tuner- piezo-actuators

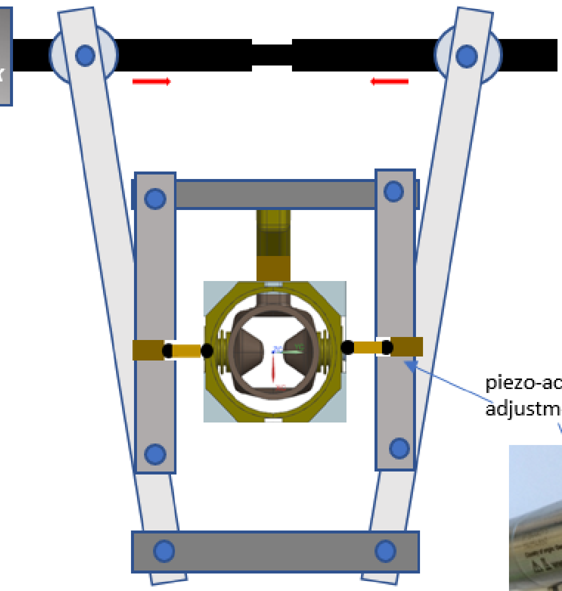
Cavity parameters:
df/dL ~45kHz/um

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*

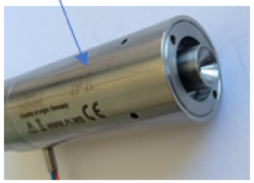
Slow tuner range > 1 MHz…

Titanium shaft with right and left threads





piezo-actuator with adjustment screw



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)

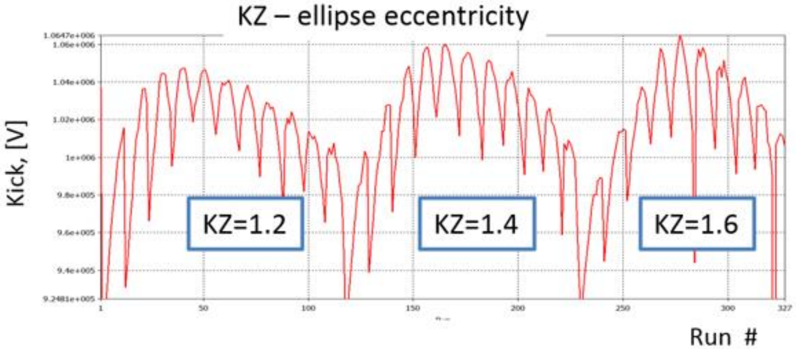
Yu. Pischalnikov 12/07/21

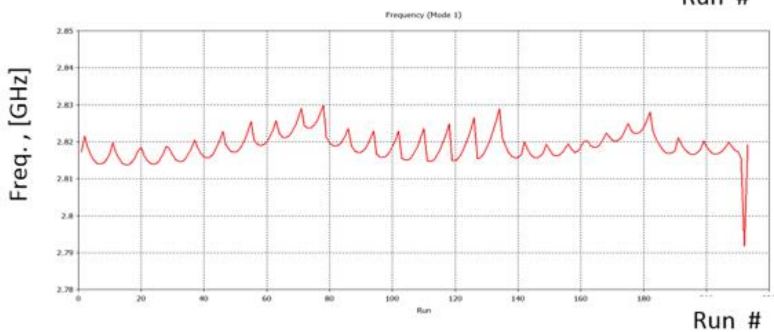
Conclusions

- **QMIR is a good option for the ILC Crab Cavity**
  - design is very compact (<0.5 m) and simple;
  - sparse HOM spectrum and small loss/kick factors;
- **QMiR re-optimized for a larger aperture of 25 mm**
  - At a nominal deflecting voltage of 0.9 MV the cavity surface fields, $E_p \approx 40$ MV/m, $B_p \approx 75$ mT, meet the ILC/CC specifications.
  - 4 QMiR can provide 4 MV kick total for 1 TeV ILC option
  - SOM/HOM damped to meet ILC requirements (with SS sections)
- **Preliminary mechanical design of QMiR is completed**
  - LFD and dF/dP meet the requirements
  - The concept of a double 2-lever frequency proposed
- **Fermilab can design, build and test the QMIR cavity and cryomodule**

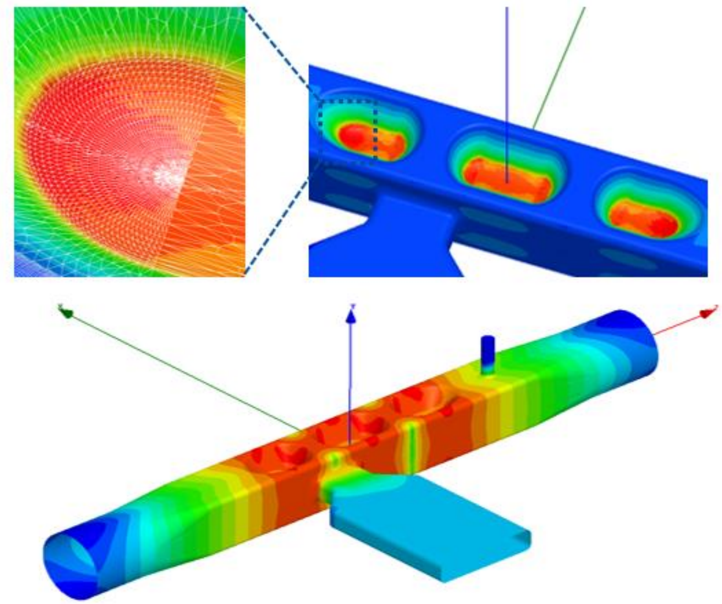
Backup Slides

EM design of the QMiR deflecting cavity





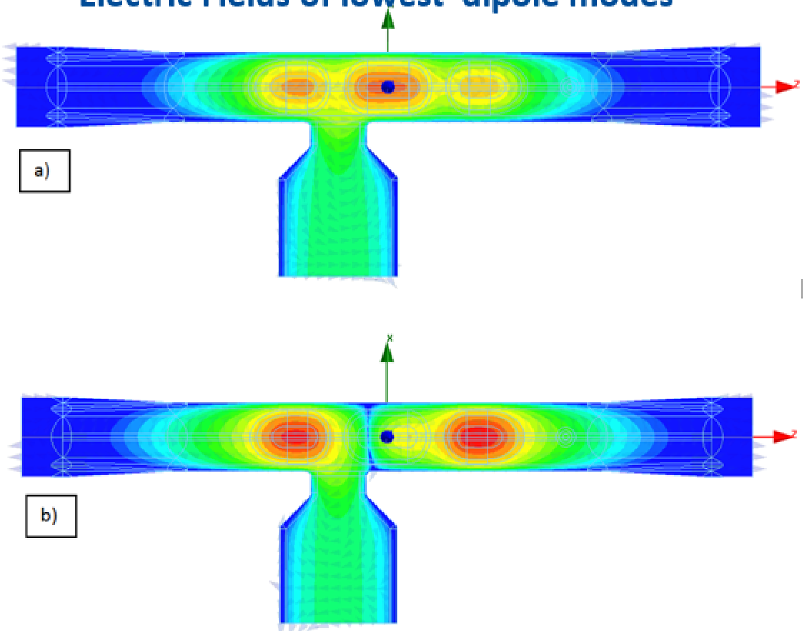
Operating trapped mode surface electric (up) and magnetic (down) fields

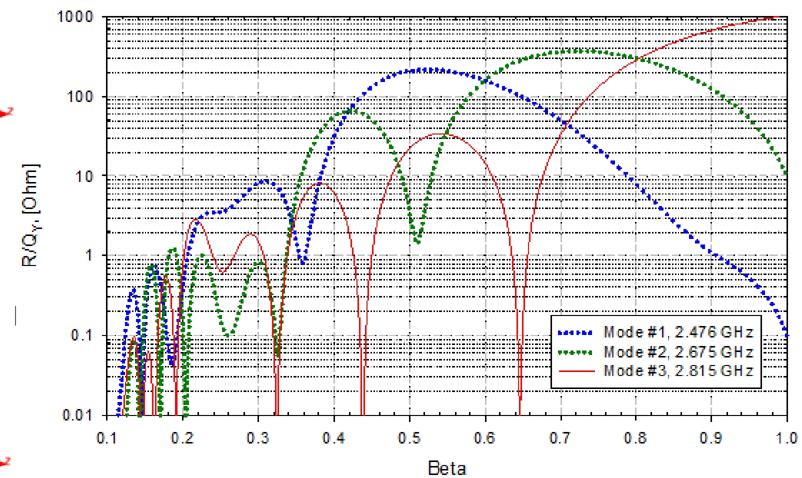


- Model is fully parameterized
- The frequency derivation was calculated for each parameter in order to preserve the operating mode frequency on the stage of geometry creation.
- General ellipsoid is used for hollow surface representation
- Global optimum search algorithm

Same Order Mode (SOM) Damping

Electric Fields of lowest dipole modes





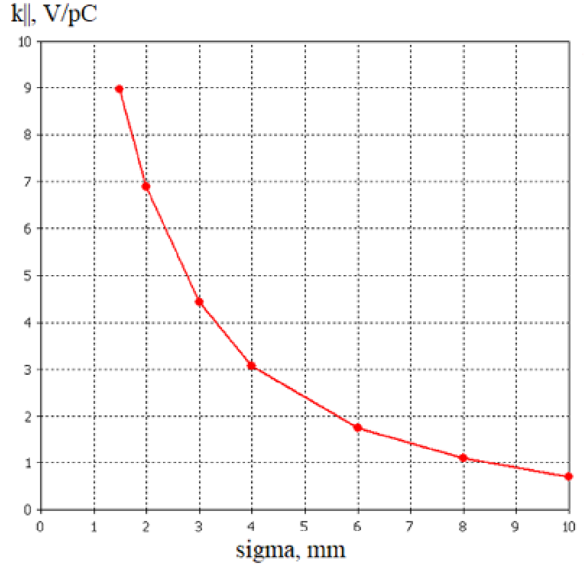
Freq., [GHz]	$(R/Q)_t$, [Ω]	Q_{ext}	R_t [MΩ/m]
2.476	0.03	2400	3e-3
2.675	5.0	6800	1.9

- 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

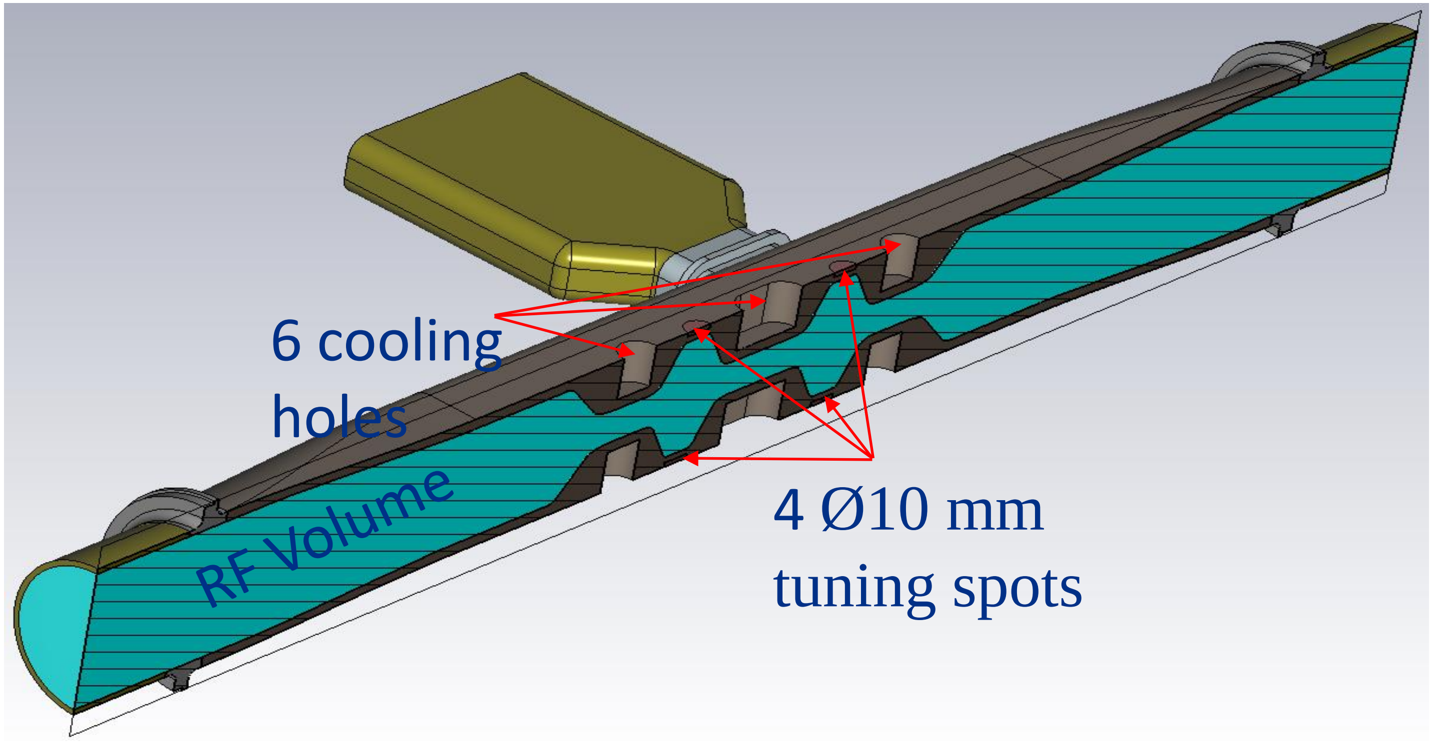
Backup Slides

- **Loss factor:**
  - For step collimator $k_{||}$ *~1/σ;*
  - Simulations for ANL/SPX agree well with estimations;
  - For *σ* =0.3 mm one may expect for ANL/SPX QMIR $k_{||}$*≈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 ≈ *30 nOhm;*
    - *3.9 GHz: R_s ≈ 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 ≈ 0.6 mW;
    - 3.9 GHz: V=0.9 MV and P_c ≈ 0.6 mW

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

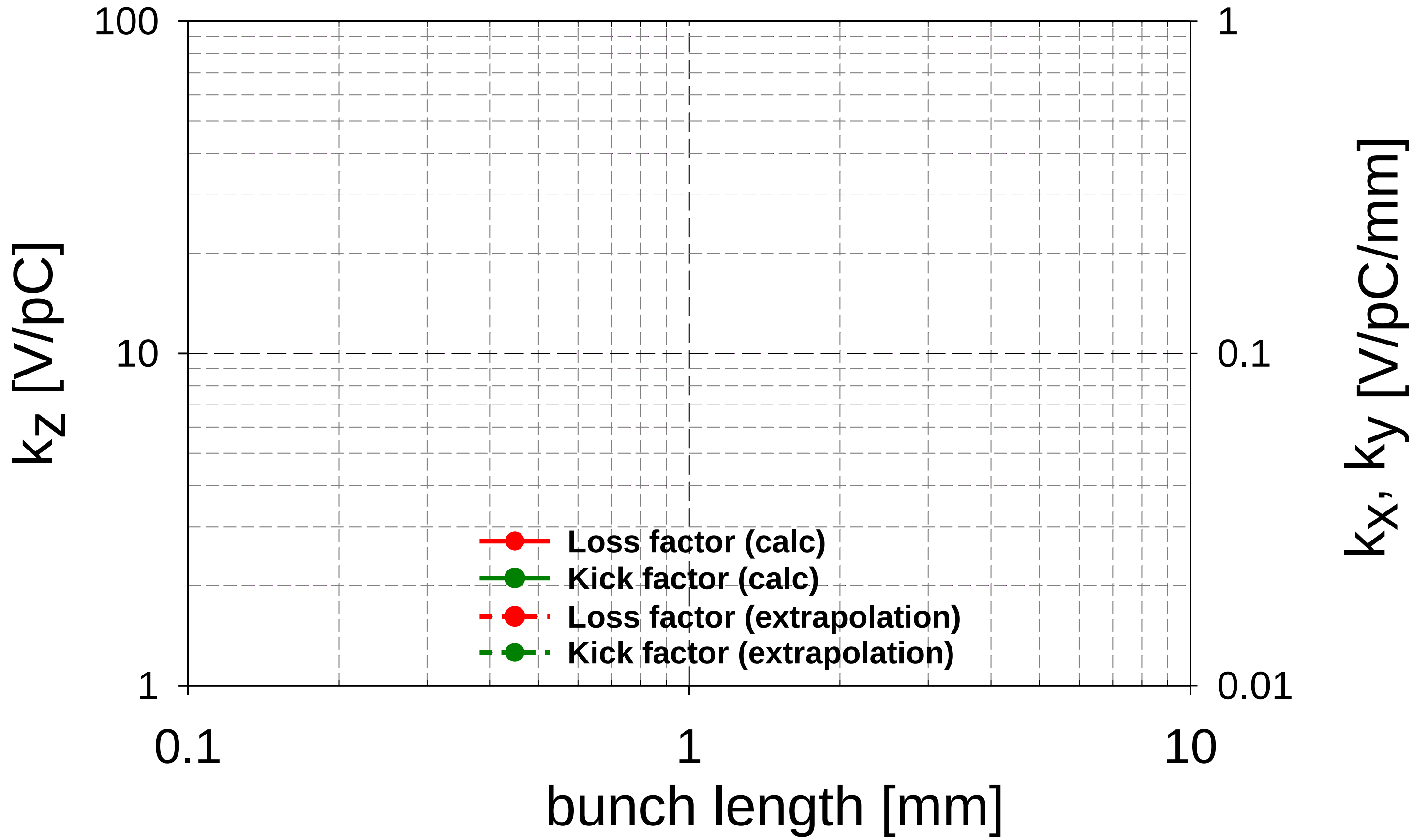


Mechanical Analysis of Frequency Tuning (by I. Gonin)



Maximum frequency tuning range: ~ 1..2 MHz

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