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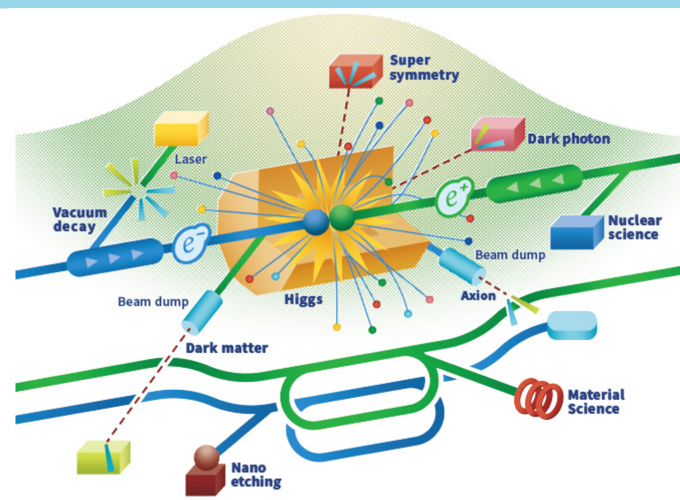
QMiR Crab Cavity for ILC

Andrei Lunin, Vyacheslav Yakovlev

October 27, 2021

ILC Workshop on Potential Experiments



ILCX2021

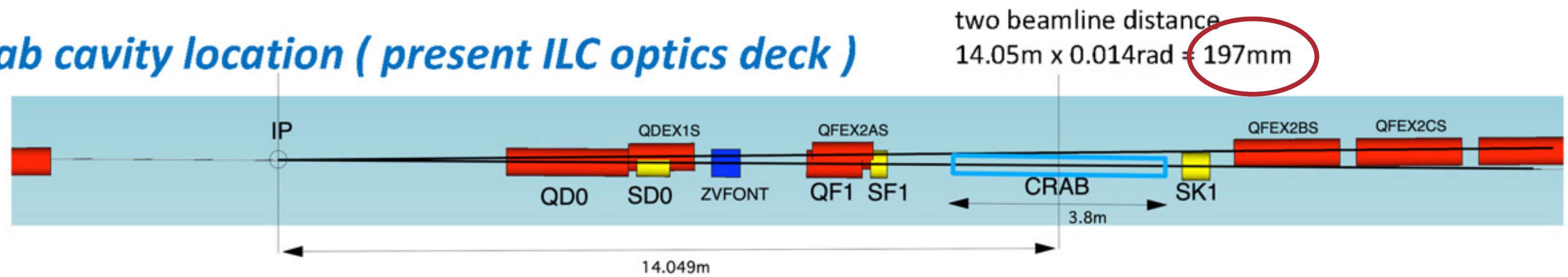
26–29 October 2021 Tsukuba, Japan

Outline

- General Requirements for the ILC deflecting cavities
  - HOM impedance limitation due to resonance excitation
  - Transverse effects
  - Single-bunch effects
- QMiR Deflecting Cavity for ANL/SPX
  - Conceptions
  - Production and Testing
- QMiR (2.6 GHz) scaled version for ILC
  - RF Power Requirements
  - HOM and Wakefields Analysis
  - 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)



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

Beam energy	E = 250 GeV and $\gamma = 5\times10^5$
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 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)**
- **Small CC aperture (< 10 mm) results in large transverse kick**
- **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

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

b) Beam emittance dilution

- HOM kick should be less than the transverse momentum spread

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

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 MOhm·GHz**

- Vertical Shunt Impedance Limit

$\boldsymbol{r_y f_{HOM} \ll}$ **0.67 MOhm·GHz**

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 be 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: $\boldsymbol{x_0} < \boldsymbol{\sigma_x}$ and $\boldsymbol{y_0} < \boldsymbol{\sigma_y}$

Horizontal Kick Factor Limit **k_x << 2.3×10^3 V/pC/m**

Vertical Kick Factor Limit **k_y << 2.5×10^3 V/pC/m**

HOM-free Deflecting Cavity

The key idea is based on the formation of TE "ghost" modes

GHOST MODES IN IMPERFECT WAVEGUIDES

BY

E. T. JAYNES

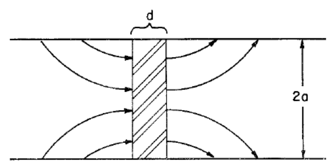
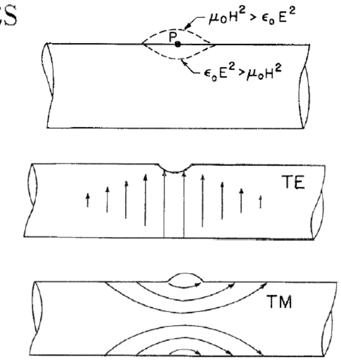


Fig. 1—TM_{01} ghost mode due to a dielectric disk.



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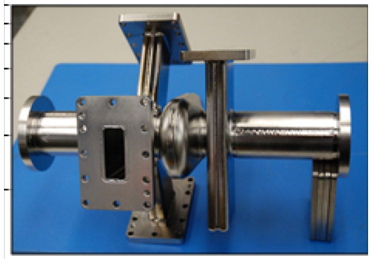
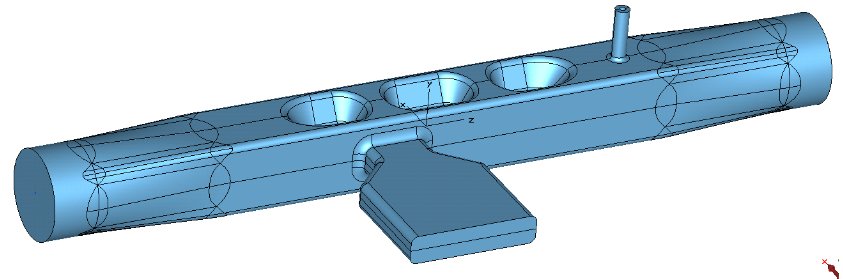
- Rediscovered in 1990s by G. Stupakov and S. Kurennoy [1]
- Further development of RFD at ODU (J. Delayen) [2]
- Transverse kick is produced by Quasi-TE modes which form transition zones with $grad_t(E_z)$
  - no contradiction with the Panofscy/Wenzel theorem!

[1] PHYS. REV. VOL. 49-1, 1994
[2] PHYS. REV. SPECIAL TOPICS - ACCELERATORS AND BEAMS 16, 012004 (2013)

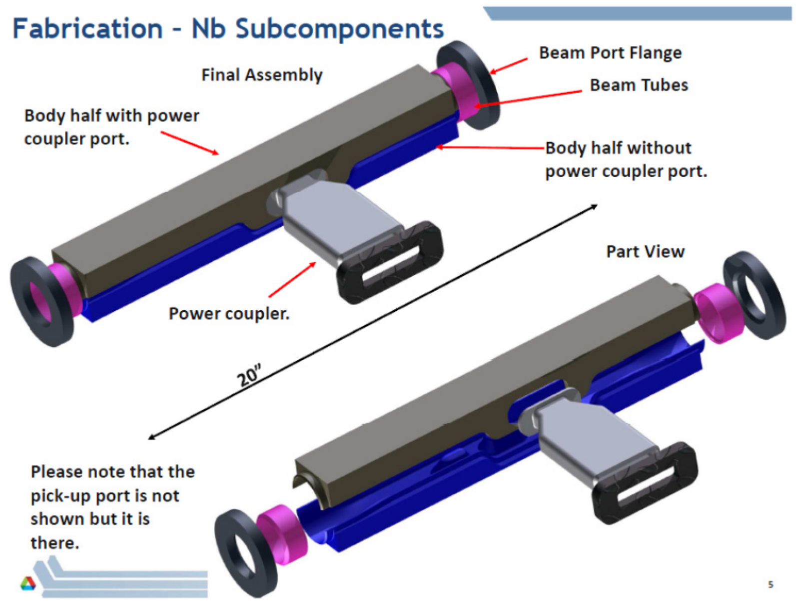
Compact HOM-free Deflecting Cavity QMIR

Quasi-Waveguide Multicell Deflecting Resonator [1]

- Proposed as replacement of Mark-II deflecting cavity for APS/SPX project

4 x  → 1 x 

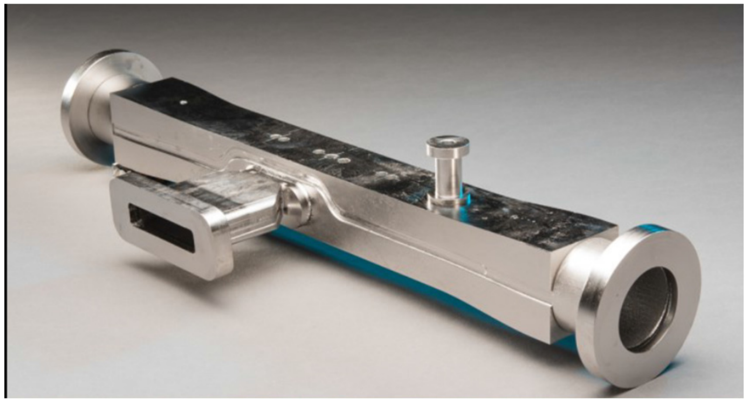
- Prototype built and tested at ANL in 2013 [2]

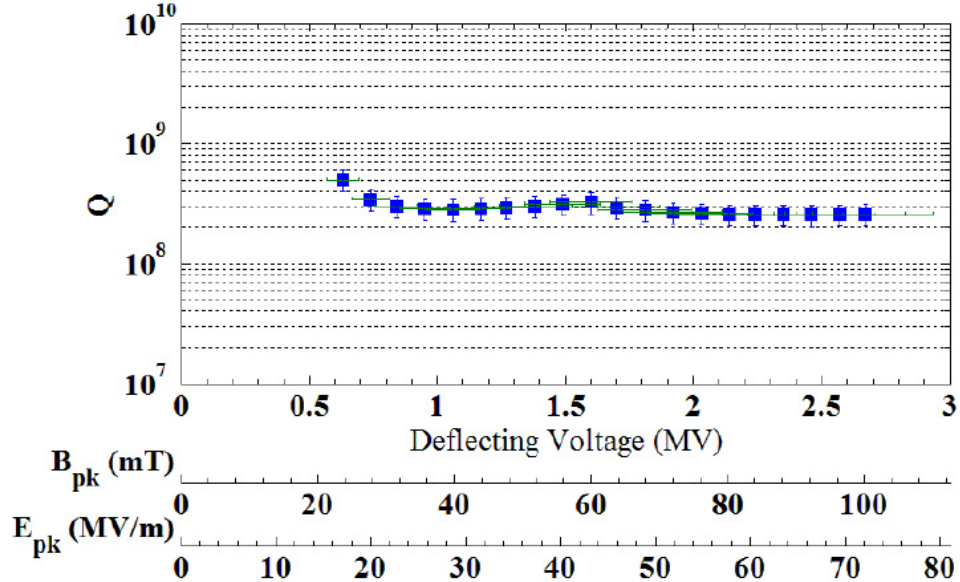


[1] A. Lunin, I. Gonin, M. Awida, T. Khabiboulline, V. Yakovlev, A. Zholents, Physics Procedia 79 (2015) 54 – 62
[2] Zachary Conway on behalf of ANL PHY LINAC Development Group, 04/23/2013

QMIR Prototype Production and Testing

Bare QMiR (21.75' Long) cavity

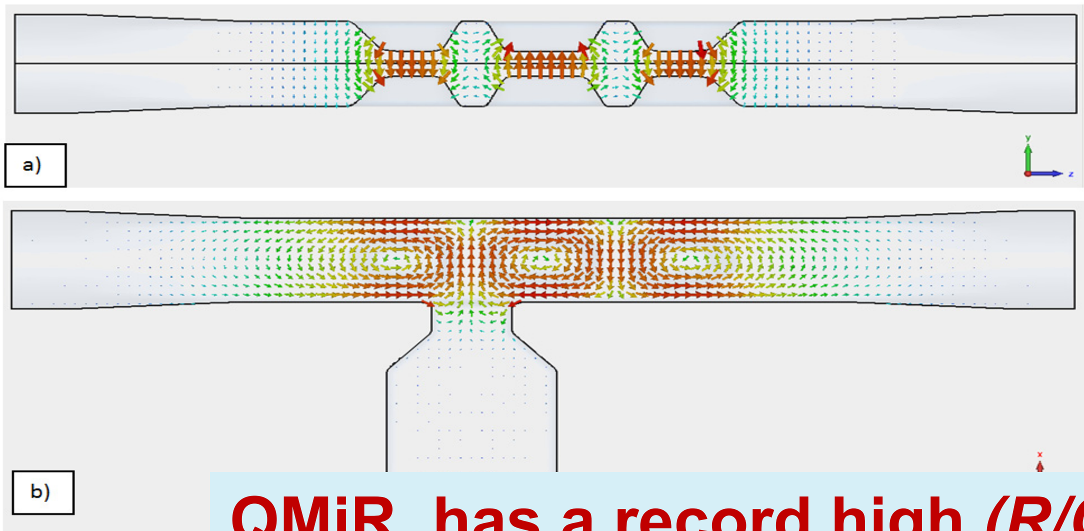




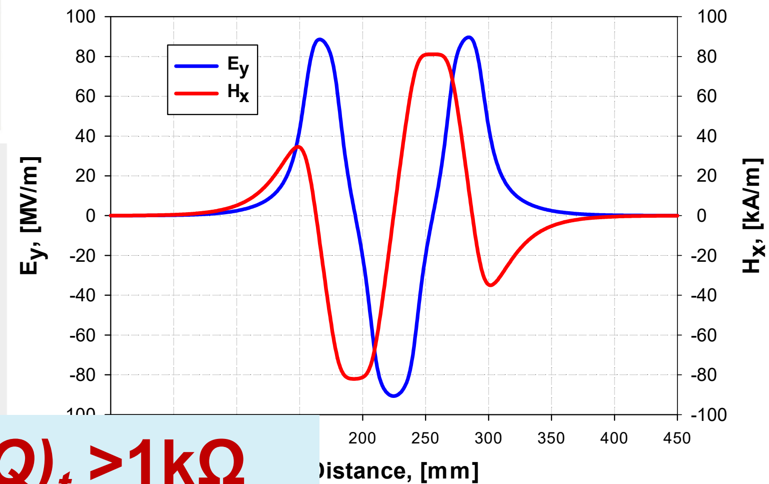
- Cavity received EP-treatment before the test
- Measured maximal deflecting voltage of 2.7 MV exceeded the design goal of 2.0 MV @2K vertical test of QMiR prototype [1]
- Relatively low Q_0 (3E8) is due to extra RF losses at covering flanges
- Further QMiR development was stopped due to the cancelation of ANL/SPX project

Z. Conway, et al., "Development and Test Results of a Quasi-waveguide Multicell Resonator", IPAC14, Dresden, Germany, 2014

Operating Dipole Mode

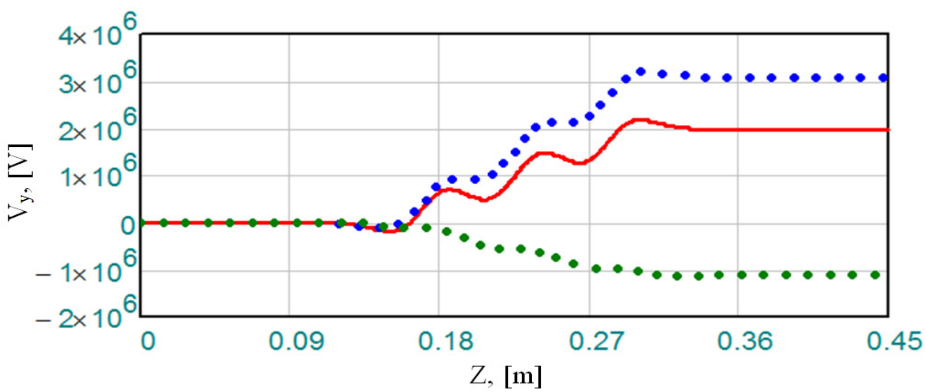


Transverse electric (blue) and magnetic (red) field components along the cavity axis.



QMiR has a record high *(R/Q)*$_t$ >1kΩ

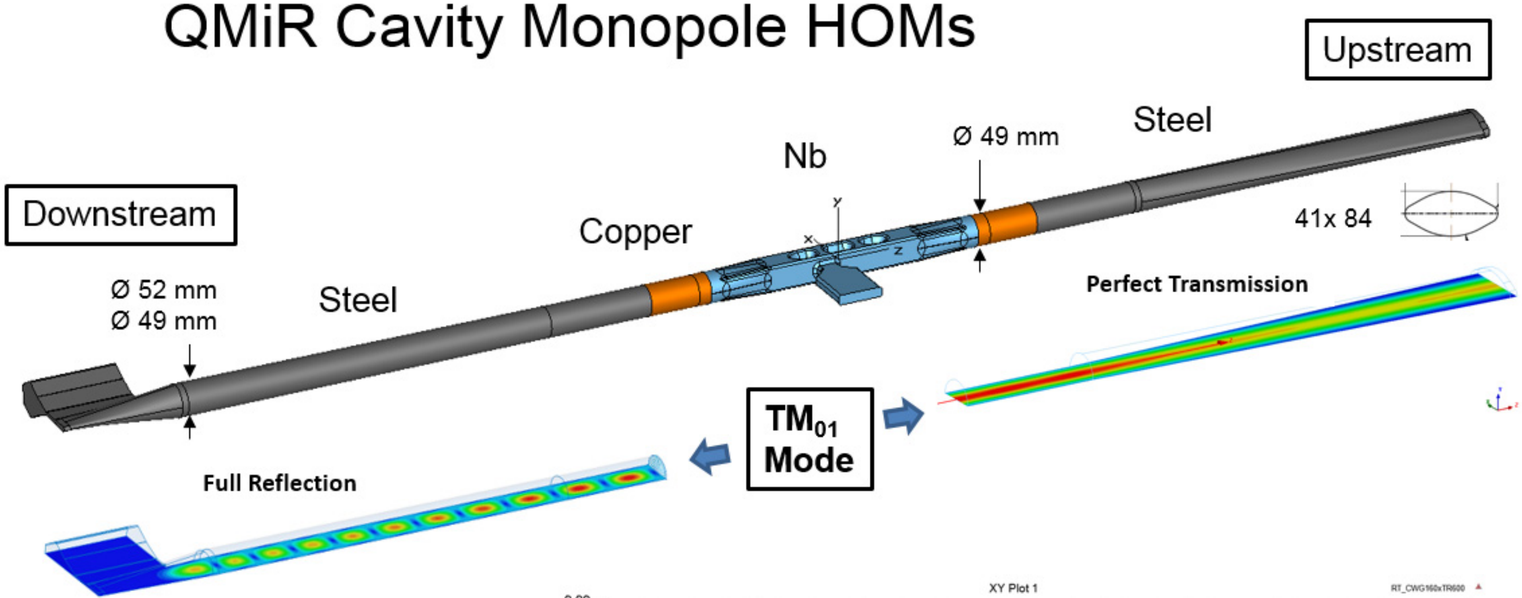
Integrated vertical kick along the cavity axis (solid red curve is the overall kick, dotted blue and green curves are electric and magnetic kicks).



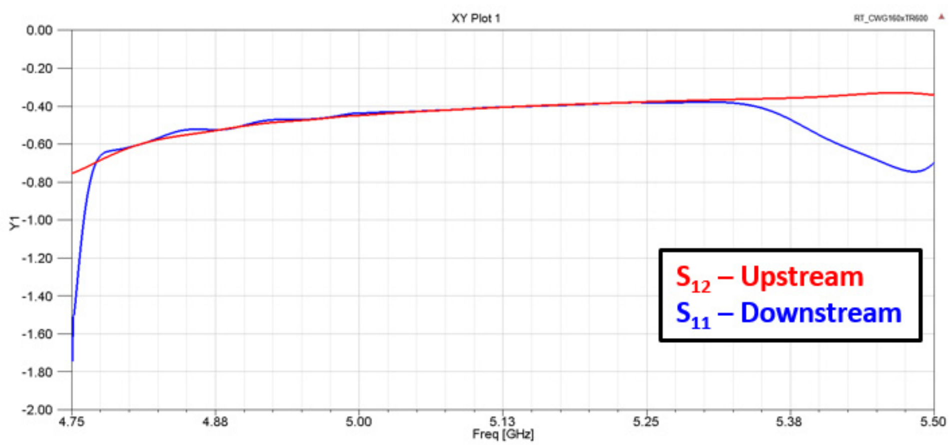
Freq	2815 MHz
V_{kick}	2 MV
E_{max}	55 MV/m
B_{max}	76 mT
$(R/Q)_Y$	1040 Ω
G	130
W_{STOR}	0.23 J

HOM Damping in the APS Ring

QMiR Cavity Monopole HOMs

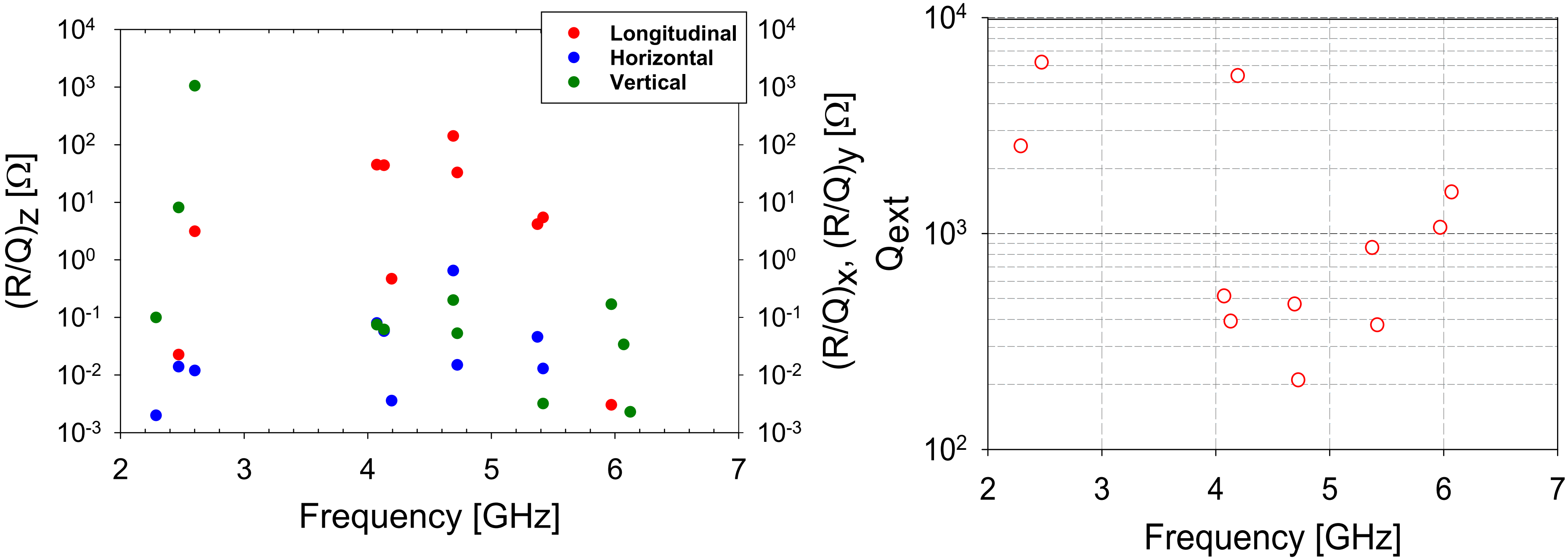


Cross Section	TM_{01} Cut Off
Ø 52 mm	4.4 GHz
Ø 49 mm	4.7 GHz
Upstream	4.5 GHz



Monopole HOMs RF power is radiated to the Upstream beam pipe !

QMiR Cavity for ILC (scaled to 2.6 GHz)



- There are two Same Order Modes (SOM) that have a low *(R/Q)*Q*
- SOM/HOM external couplings Qext < 10^4
- SOM/HOMs longitudinal and transverse impedances (@1mm): *(R/Q)z* <= 100 Ω, *(R/Q)x* <= 1 Ω and *(R/Q)y* <= 10 Ω
- **SOM/HOM spectrum is sparse and strongly damped**

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 = 100 (< 2300) V/pC/m
Vertical kick factor*	k_y = 400 (< 2500) V/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:

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

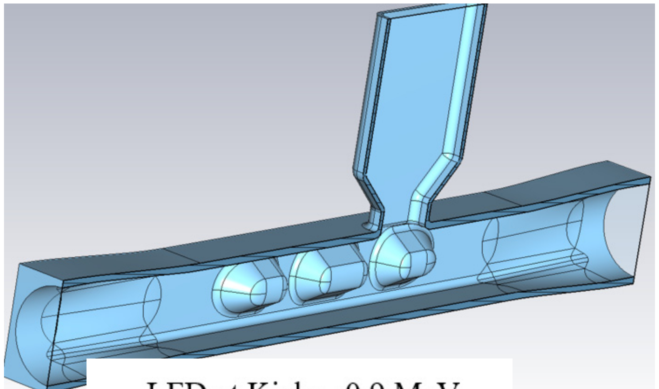
- For max beam offset $x_0 < 1$ mm and $\Delta f < 1$ kHz (LFD, microphonics)

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

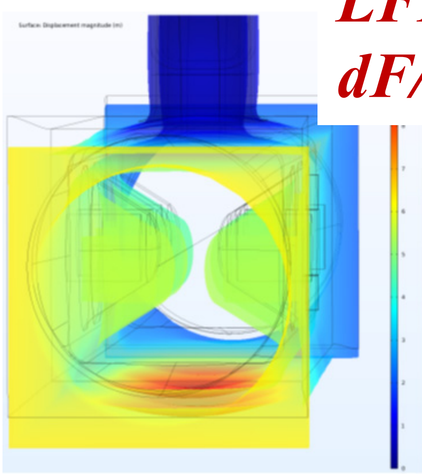
- Required RF power from the generator (overhead 100%):

$P_{gen} < 1$ kW

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

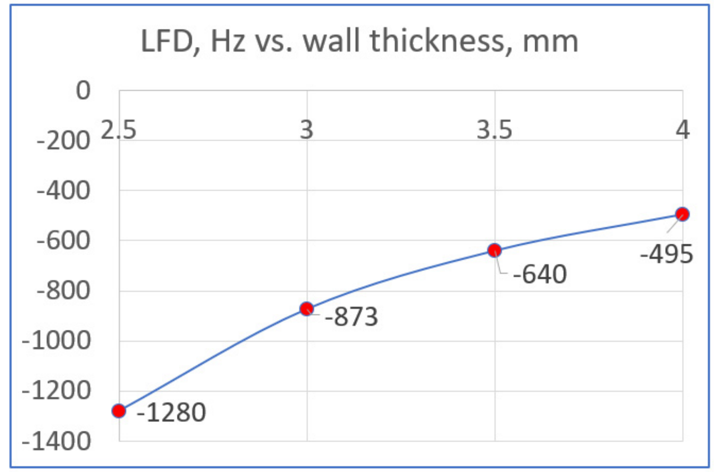


LFD at Kick = 0.9 MeV
Wall thickness 4 mm.
Δf ~ - 495 Hz

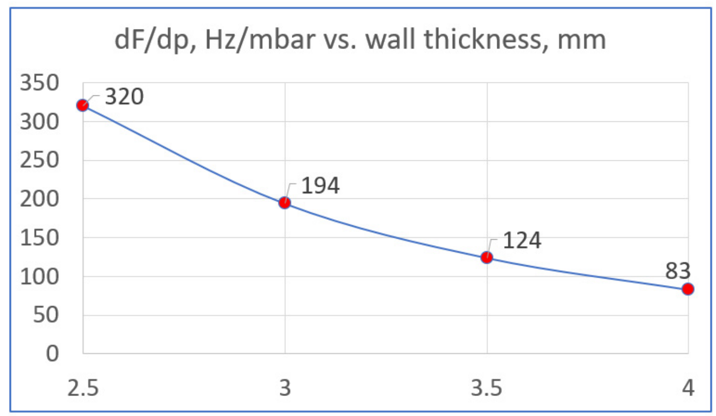


Deformation due to LFD

LFD < 500 Hz
dF/dP < 100 Hz



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



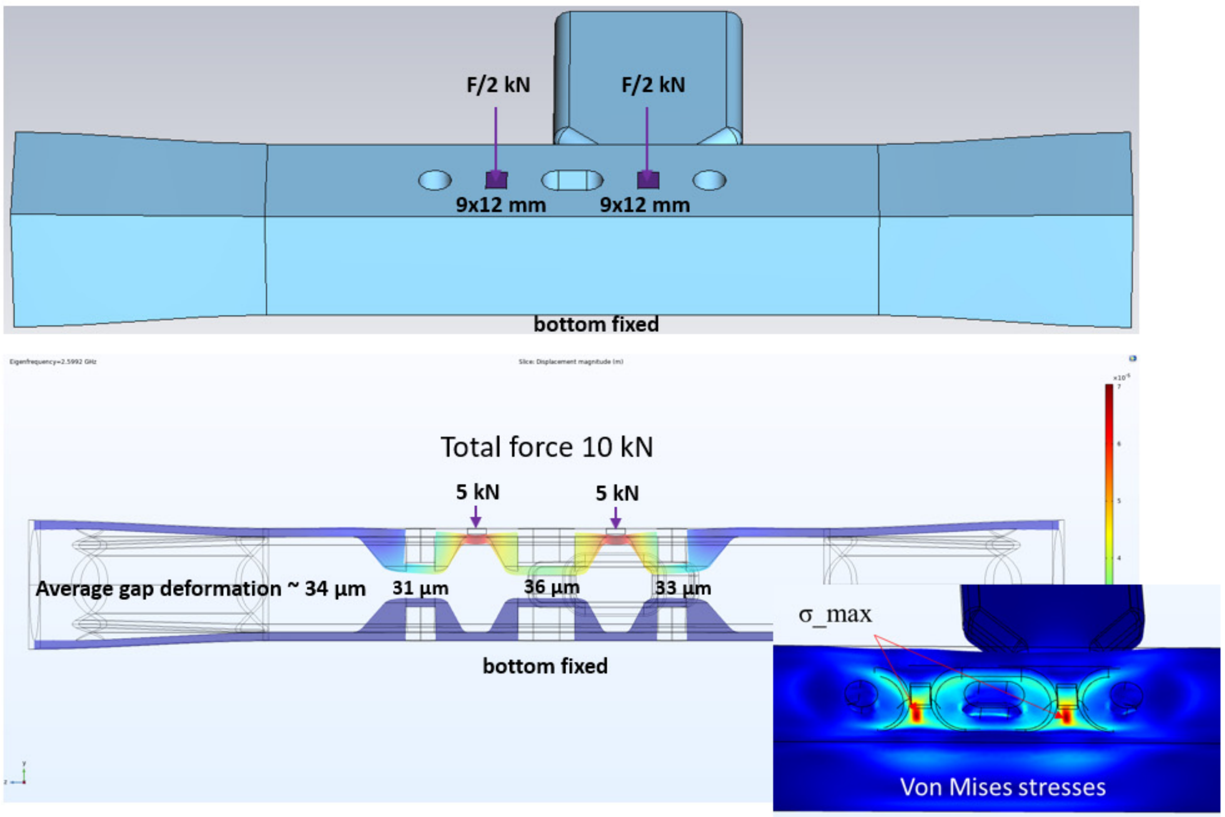
df/dP in Hz/mbar vs. cavity wall thickness

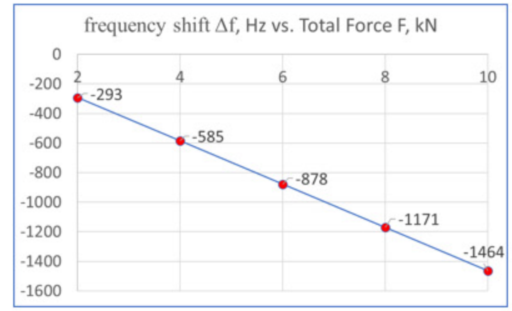
- **QMiR LFD and dF/dP are less than the cavity bandwidth (few kHz)**

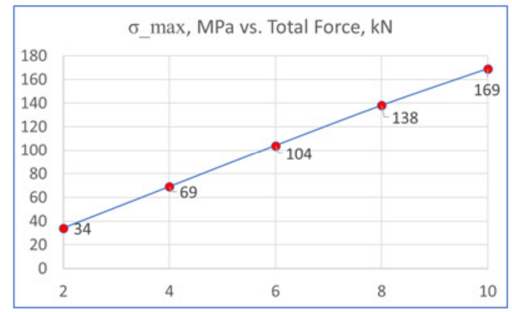
Mechanical Analysis of Frequency Tuning (by I. Gonin)

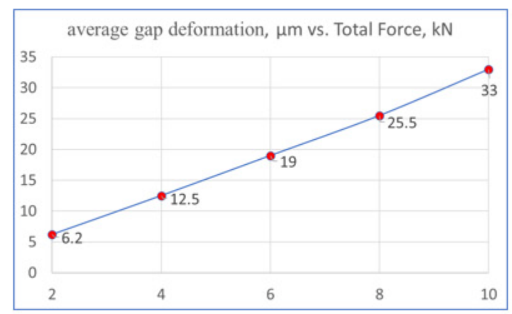
Cavity shell deformations under external force. Wall thickness 4 mm

$\Delta f/ \Delta L \sim -45$ kHz/µm
$\Delta \sigma / \Delta \text{Force} \sim 17.3$ MPa/kN





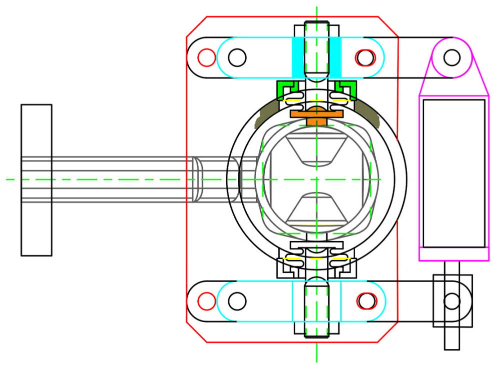


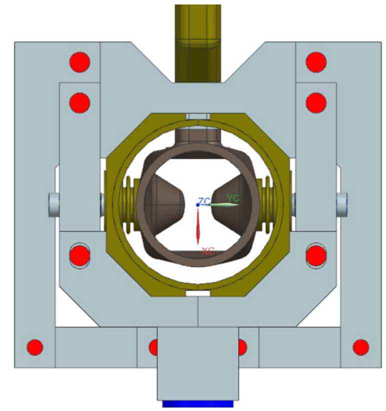


Maximum frequency tuning range: ~ 1..2 MHz

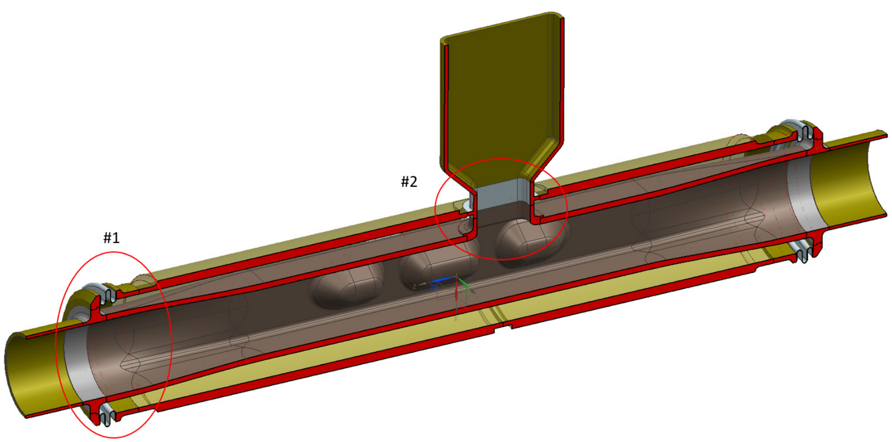
QMiR Cavity Slow Tuner Design (by V. Polubotko)

Compact lever-type frequency tuner

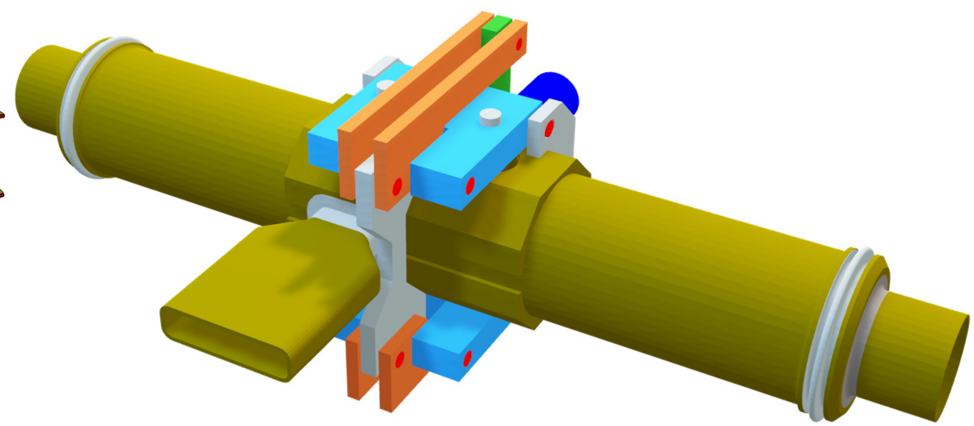




LHe Vessel



Dressed QMiR Cavity



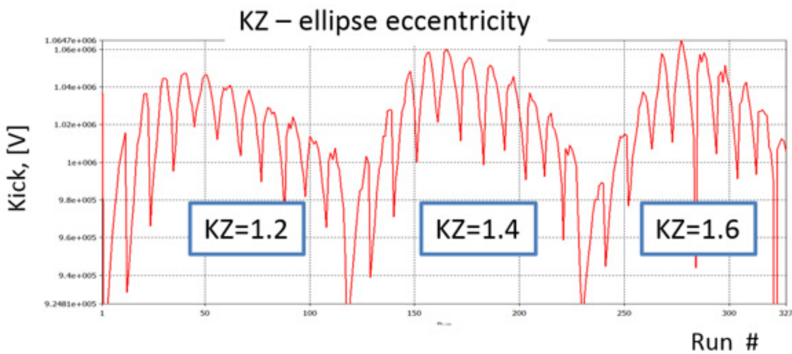
Design of frequency tuner integrated with dressed cavity is ongoing

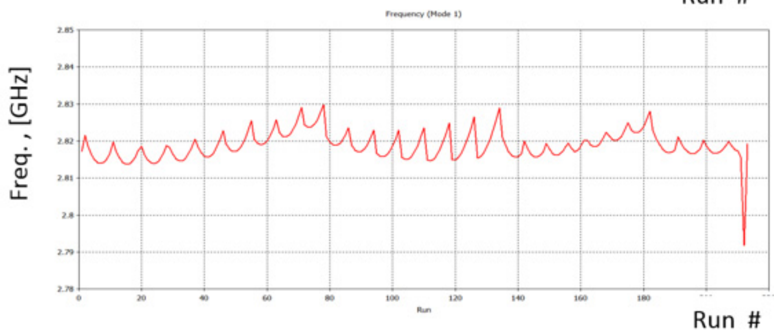
Conclusions

- ❑ 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.
- ❑ Fermilab can design, build and test QMIR cavity for ILC application.

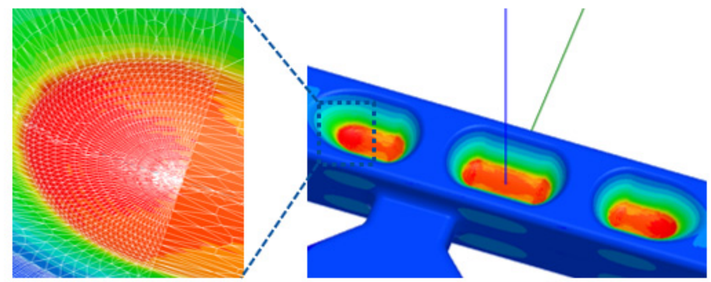
Backup Slides

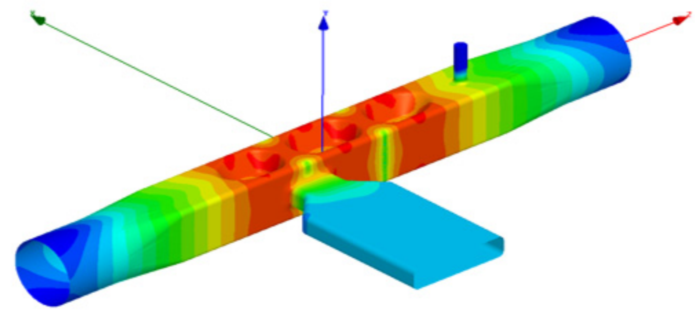
EM design of the QMiR deflecting cavity





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



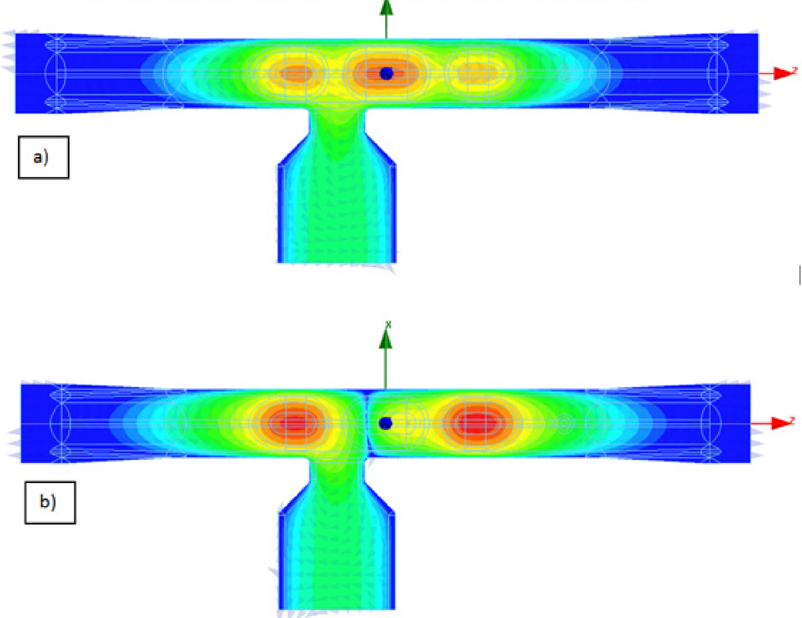


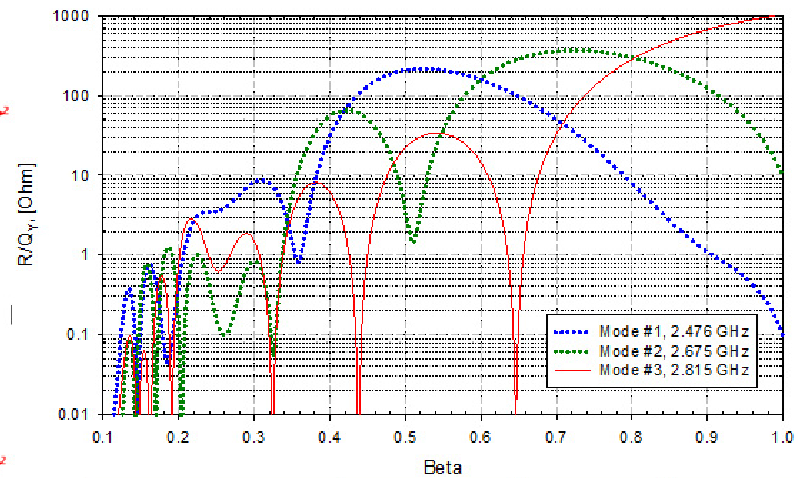
- Model is fully parameterized
- The frequency derivation was calculated for each parameter in order to preserve the operating mode frequency on the stage of geometry creation.
- General ellipsoid is used for hollow surface representation
- Global optimum search algorithm

Backup Slides

Same Order Mode (SOM) Damping

Electric Fields of lowest dipole modes





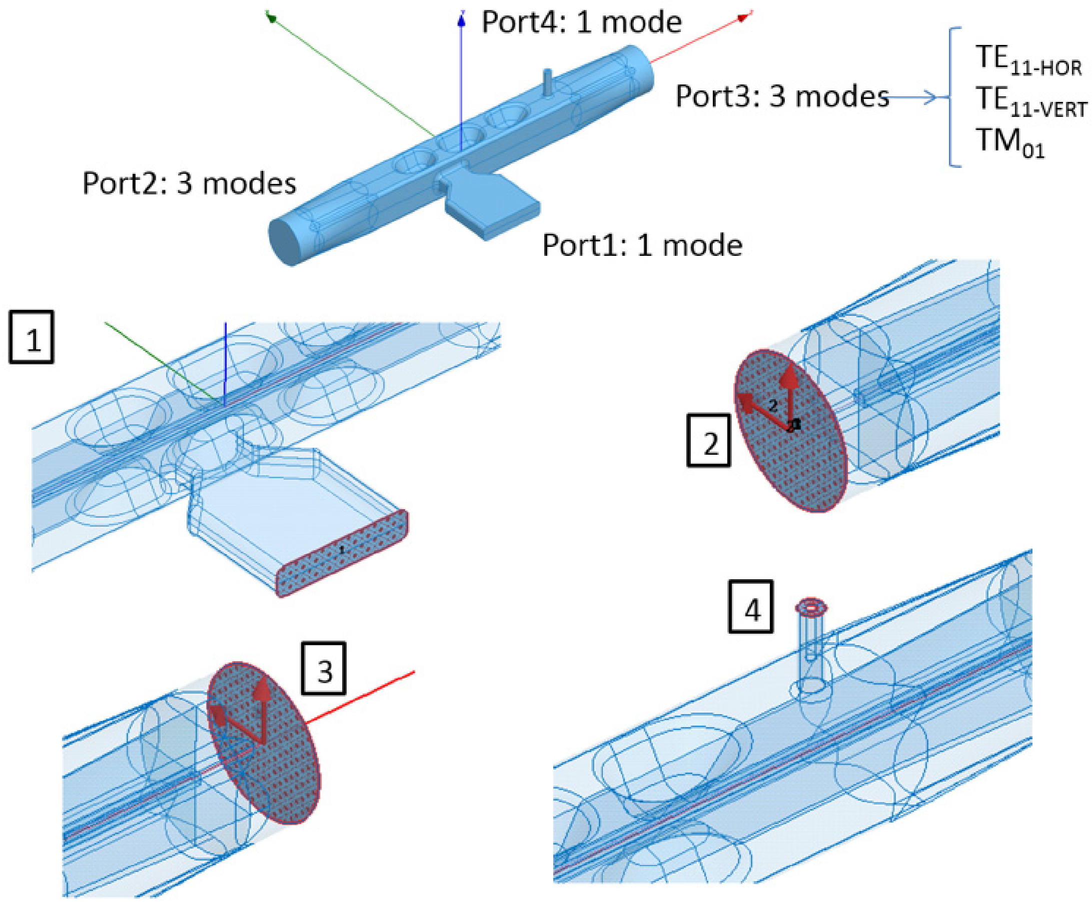
Freq., [GHz]	$(R/Q)_t$, [Ω]	Q_{ext}	R_t [MΩ/m]
2.476	0.03	2400	3e-3
2.675	5.0	6800	1.9

- 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

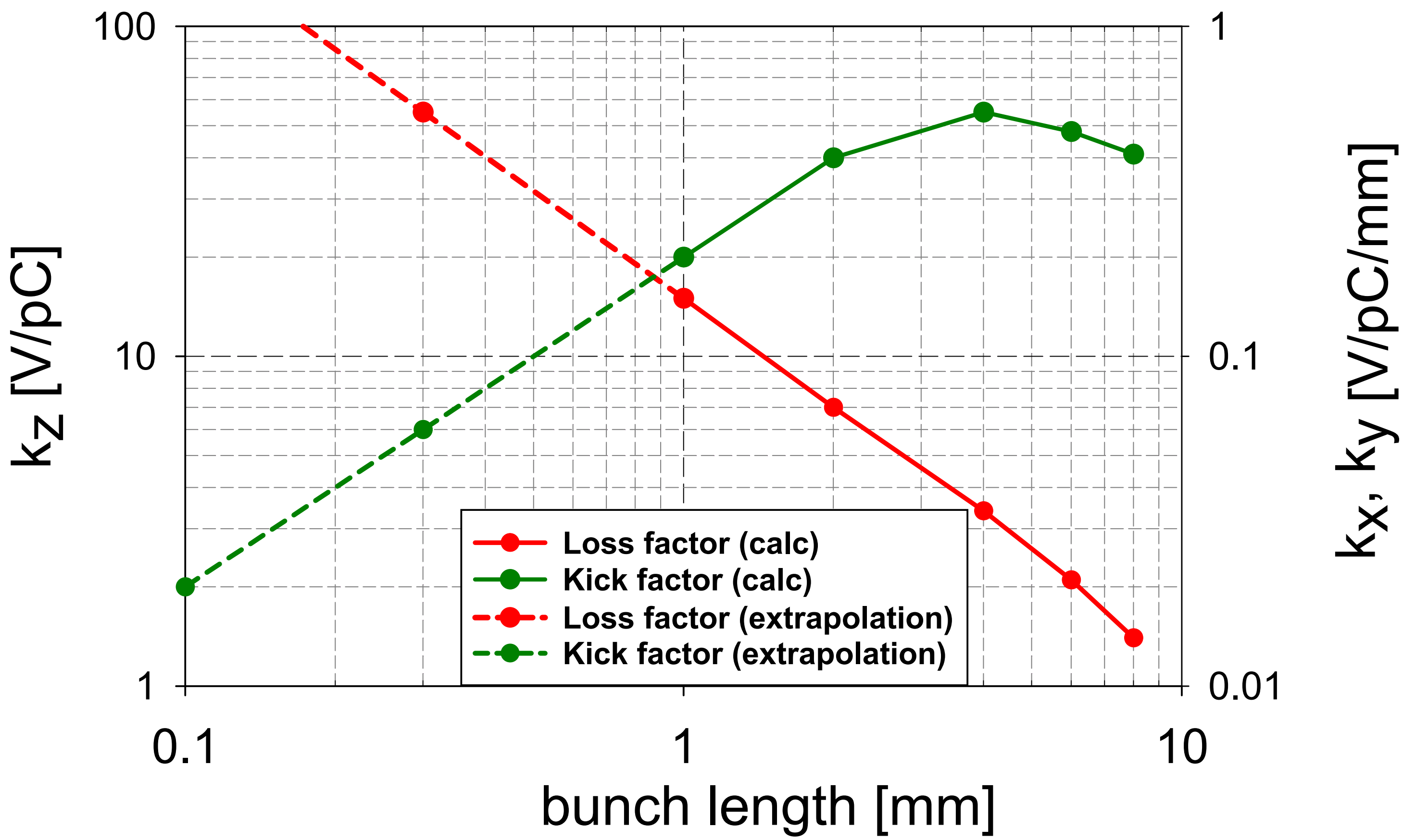
Backup Slides

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