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QMiR Crab Cavity with Compact HOM Load for EIC Project

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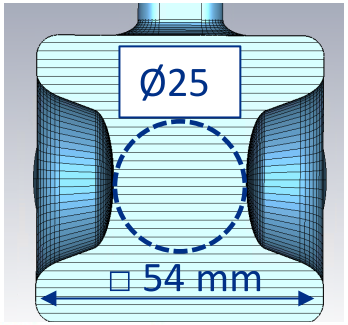
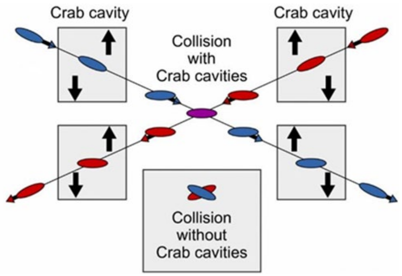
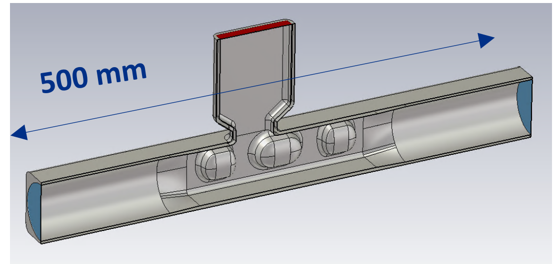
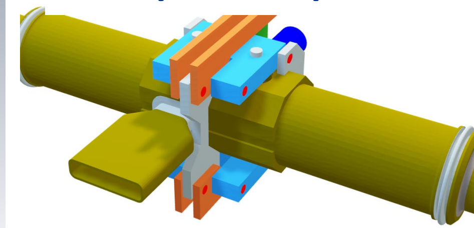
QMiR Crab Cavity for ILC (2.6 GHz)

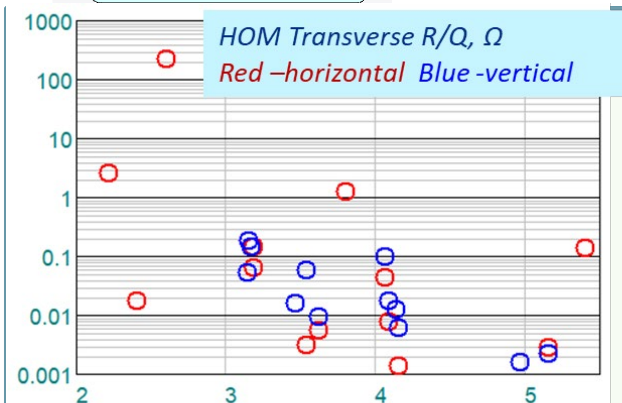






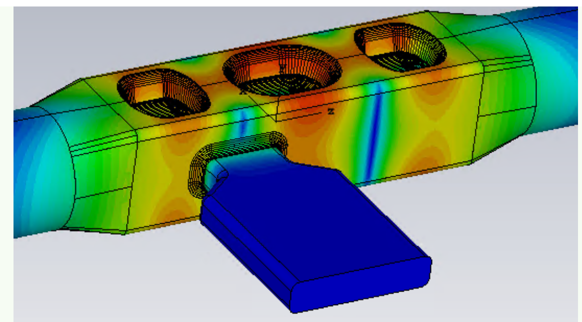
Compact Freq. Tuner





Freq	2600 MHz
V_{kick}	0.92 MV
E_{max}	35 MV/m
B_{max}	70 mT
$(R/Q)_t$	225 Ω
G	160

Highly optimized surface EM-fields



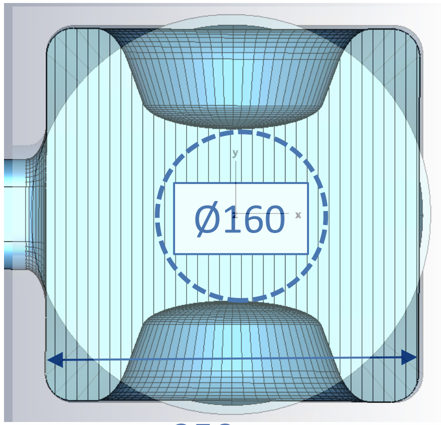
Compact and efficient single crab cavity for the ILC

- ✓ NO HOM-couplers
- ✓ HOMs are loaded to the beam pipe
- ✓ Sparse, low-Q HOM spectrum
- ✓ QMiR selected for ILC prototyping (doi: 10.18429 / JACoW - SRF2023 - TUPTB044)

Desing can be scaled to lower frequencies!

Scaled QMiR (x 6.5 = 400 MHz)

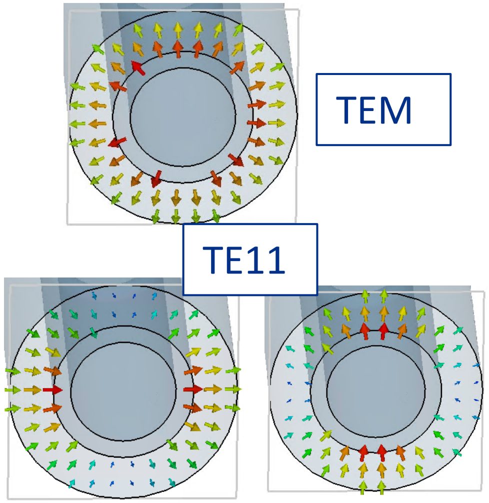
ILC QMiR (x 6.5)



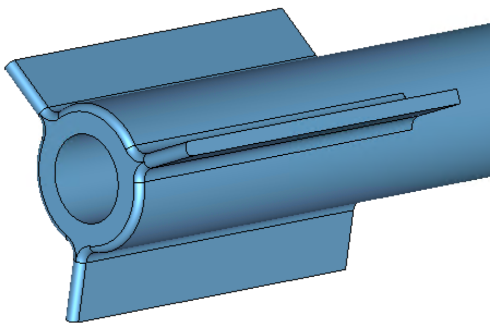
□ 350 mm

- ✓ **The cavity output aperture is very large**
- ✓ **Straight connection to the beam pipe creates a resonant volume with trapped HOMs inside**
- ✓ **The aperture can be divided into a beam pipe and an external coaxial**
- ✓ **Oversized coaxial can propagate both TEM mode and dipole modes**
- ✓ **Radially sectioned coaxial works as a filter for the operating mode, while being transparent for the HOMs**

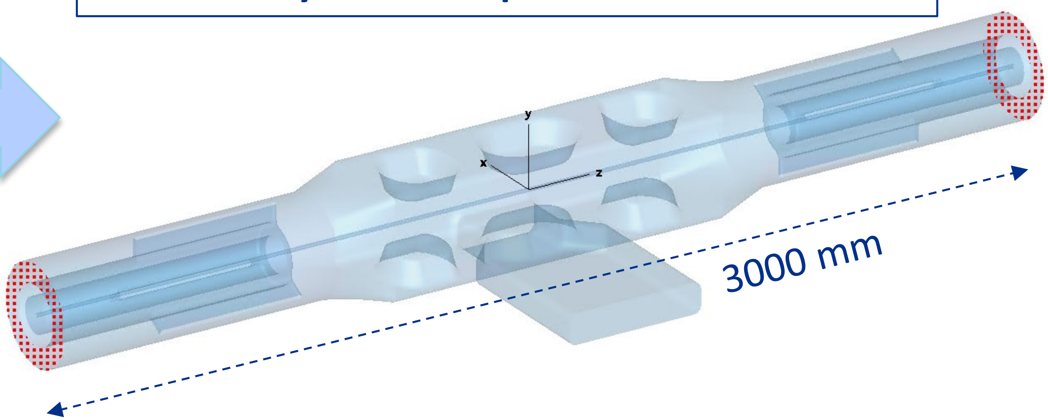
Multimoded Coaxial



SOM Filter

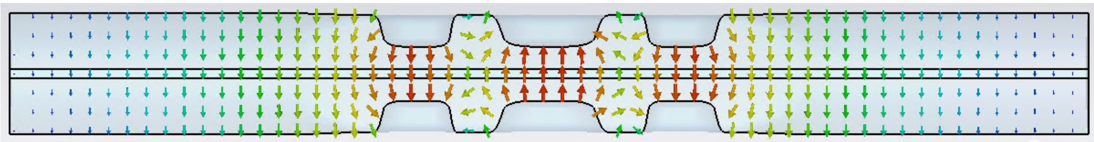


QMIR Cavity with compact coaxial HOM loads

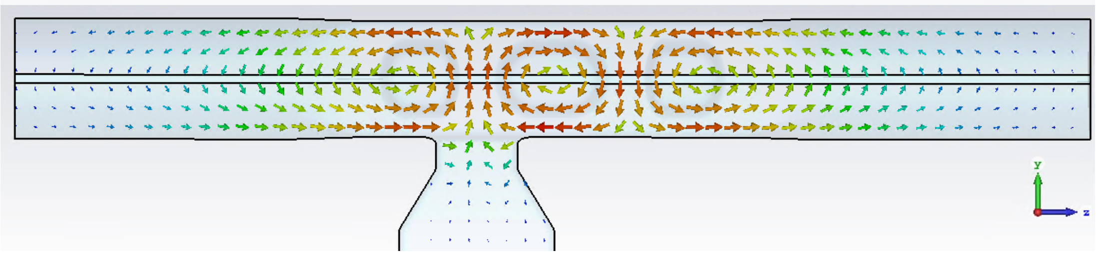


Dipole Mode Impedance Calculation

Electric Field



Magnetic Field



ANSYS HFSS Simulations	
$(R/Q)_Z$ @r_0= 1 mm	0.02 Ω
$(R/Q)_Y$, LF	225 Ω
$(R/Q)_Y$, PW	225 Ω

Normalized Shunt Impedance (R/Q) Definition

$$\left(\frac{R_{\parallel}}{Q}\right) = \frac{\left|\int_{-\infty}^{\infty}\left(E_z(r,z)\right)_{r=r_0} e^{ikz}dz\right|^2}{\omega_0 W} \equiv \frac{|V_z|^2}{\omega_0 W} \qquad [\Omega]$$

$$\left(\frac{R_{\perp}}{Q}\right) = \frac{\left|\int_{-\infty}^{\infty}\left(\vec{E}_t(r,z)+c\vec{z}\times\vec{B}_t(r,z)\right)_{r=r_0} e^{ikz}dz\right|^2}{\omega_0 W} \equiv \frac{|V_t|^2}{\omega_0 W} \qquad [\Omega]$$

Panofsky – Wenzel Theorem (PW)

$$\left(\frac{R_{\perp}}{Q}\right) = \frac{\left|\int_{-\infty}^{\infty}\left(\nabla_{\perp}\left(E_z(r,z)\right)\right)_{r=r_0,} e^{ikz}dz\right|^2}{\omega_0 W} \times \frac{1}{k^2}$$

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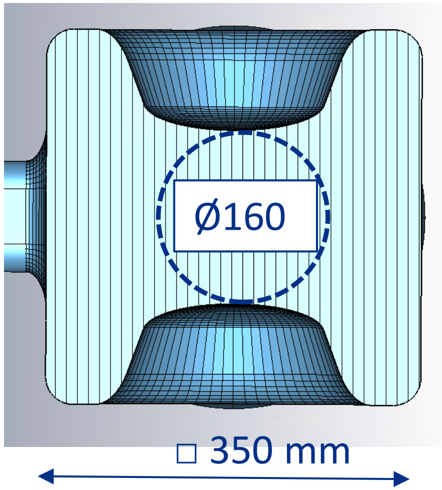
QMiR Cavity for EIC

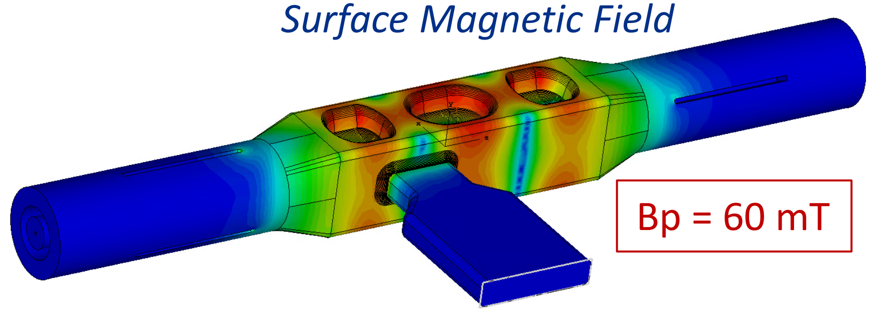
EIC Crab Cavity Aperture Limit: Ø103 mm [1]

[1] BNL-221006-2021-FORE

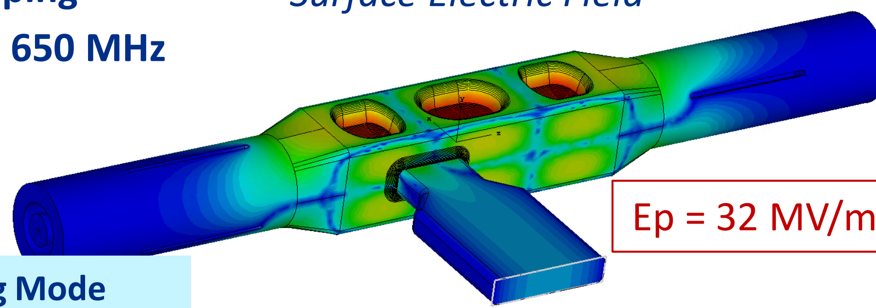


- ✓ **Low surface fields**
- ✓ **Strong HOM damping**
- ✓ **HOMs free at F > 650 MHz**

Surface Magnetic Field

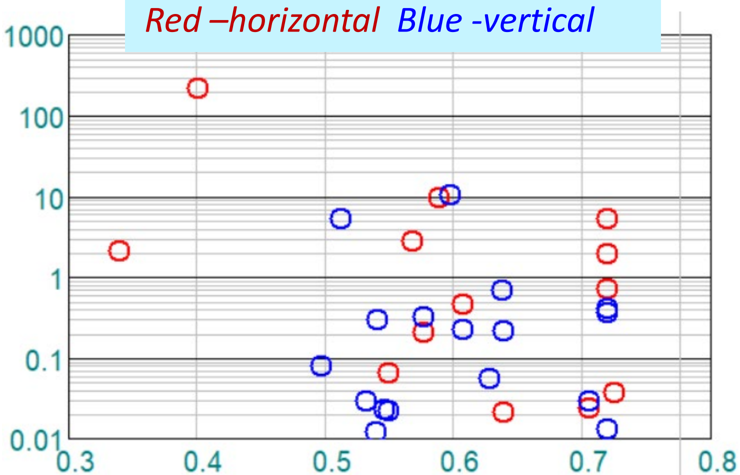


Surface Electric Field



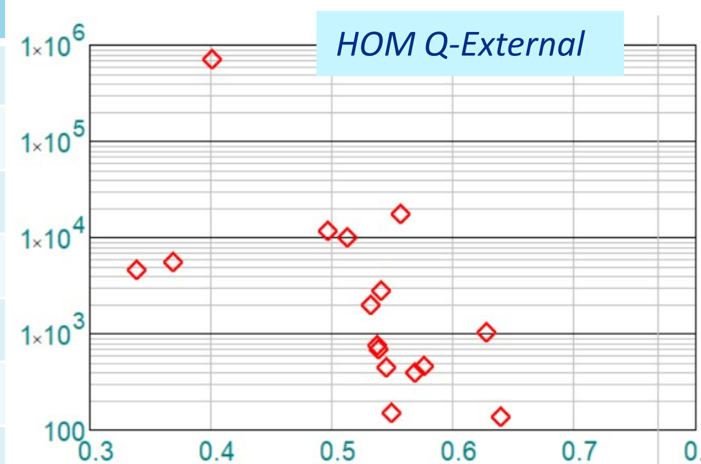
HOM Spectrum, $(R/Q)_{\perp}$ [Ω]

Red –horizontal *Blue -vertical*



Operating Mode	
Freq	**400 MHz**
$\mathbf{V_{kick}}$	**4.75 MV**
$\mathbf{(R/Q)_{\perp}}$	**225 Ω**
G-factor	**160**
Bp, max	**60 mT**
Ep, max	**32 MV/m**
$\mathbf{W_{STORED}}$	**40 J**
Length	**3000 mm**

HOM Q-External



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Operating Mode Cryogenic Budget

BCS surface resistance @2K

$$R_s(\omega,T) \propto A(\omega^2/T)e^{-[\Delta(T)/kT]}$$

Cavity Cryogenic Loss

$$P_c = \frac{\omega_0 W_0 R_s}{G}$$

Typical measured Q0 in 325 MHz Nb cavities (PIP-II)

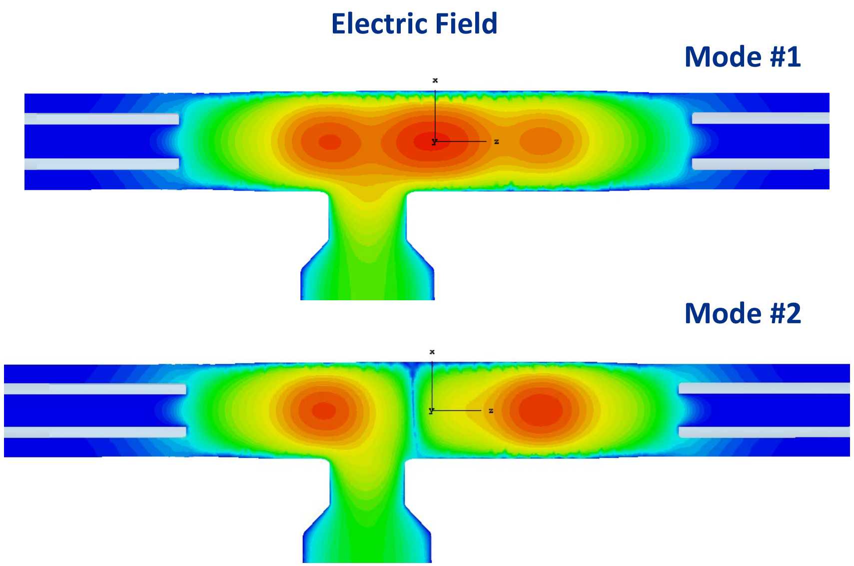
Material	Q0 @2K & 70mT	
	VTS	CM
Nb	> 1E10	> 1E10

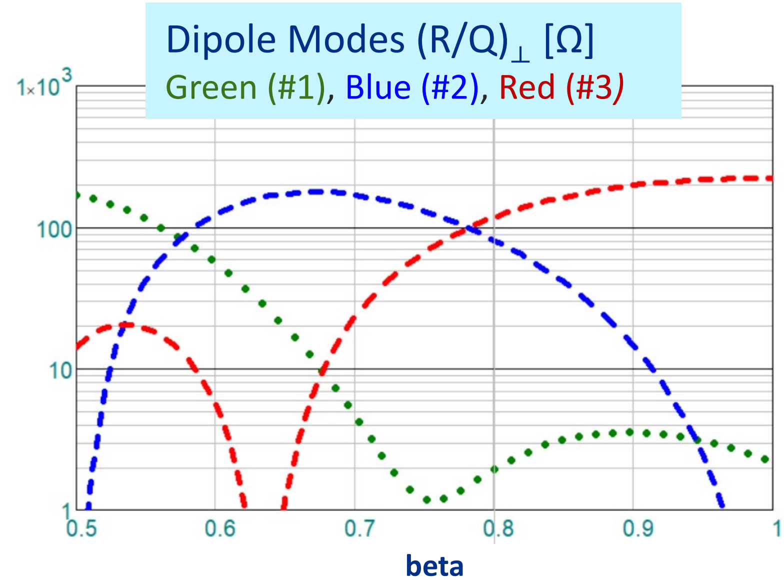
Expected Surface Resistance and 2K Cryo-load

Material	Rs, nΩ	CW-operation
		P_C , W
Nb	< 10	< 6

- **We consider CW RF operation of the cavity**
- **Nominal cryo-load is expected to be as low as 6 W**

Same Order Modes (SOM) Damping





1st Dipole SOM
F = 0.340 GHz
QE = 4500
$(R/Q)_{\perp}$ = 2 Ω

2nd Dipole SOM
F = 0.370 GHz
QE = 5500
$(R/Q)_{\perp}$ = 0.01 Ω

3rd Dipole Mode (operating)
F = 0.4 GHz
QE = 1E6
$(R/Q)_{\perp}$ = 225 Ω

- **SOM are coupled only to the input waveguide port**

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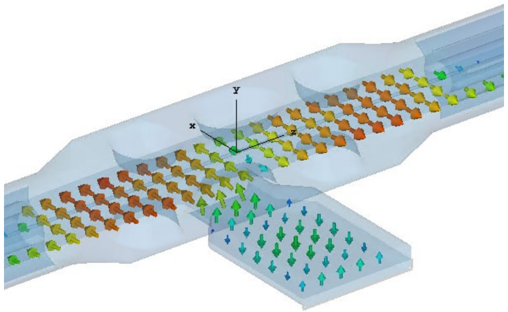
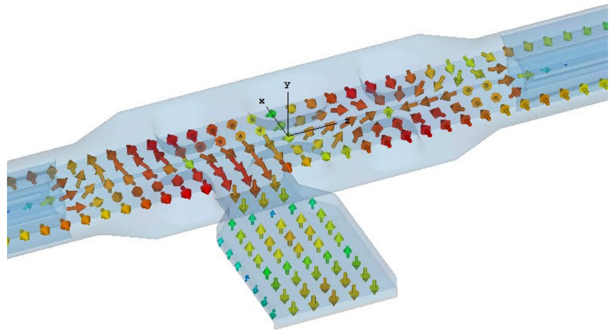
High Order Modes (HOM) Analysis

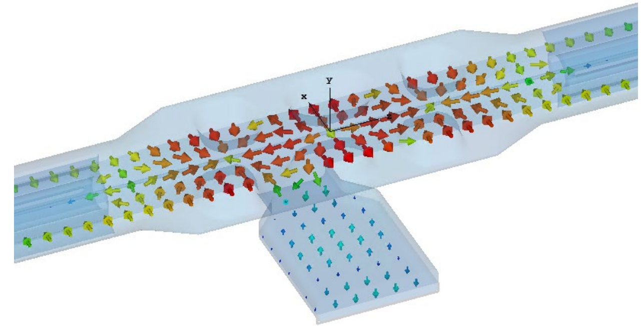
HOMs with highest (R/Q)*Q values



Dipole HOM
F = 0.512 GHz
QE = 1.0E4
$(R/Q)_x$ = 5 Ω



Monopole HOM
F = 0.545 GHz
QE = 440
$(R/Q)_z$ = 120 Ω



Monopole HOM
F = 0.556 GHz
QE = 1.8E4
$(R/Q)_z$ = 14 Ω

- **Monopole HOMs are mostly loaded onto coaxial line**

HOM Spectrum Summary

HOM with QE > 100

Frequency [MHz]	$(R/Q)_Z$	$(R/Q)_X$	$(R/Q)_Y$	Q_{ext}	P_{max} [W]
0.512	0.14	5.39	0.0028	10000	
0.532	9.77	0.029	0.0022	2000	
0.537	33.3	0.0043	0.0046	800	
0.545	122	0.023	0.00023	440	
0.549	14.4	0.022	0.066	150	
0.556	13.5	0.0056	0.0032	17500	
0.568	0.047	0.0043	2.83	393	

- **7 HOMs with QE > 100**
- **External coupling:** **QE < 2E4**
- **Dipole HOMs Impedance:** **$(R/Q)_\perp * Q * k < 5E5$ [Ω/m]**
- **Monopole HOMs Impedance:** **$(R/Q)_Z * Q * k < 2E5$ [Ω]**
- **HOM resonant excitation:** **$Pmax = (R/Q)_Z * Q * I_b^2 * DF$**

QMiR Cavity for EIC 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:

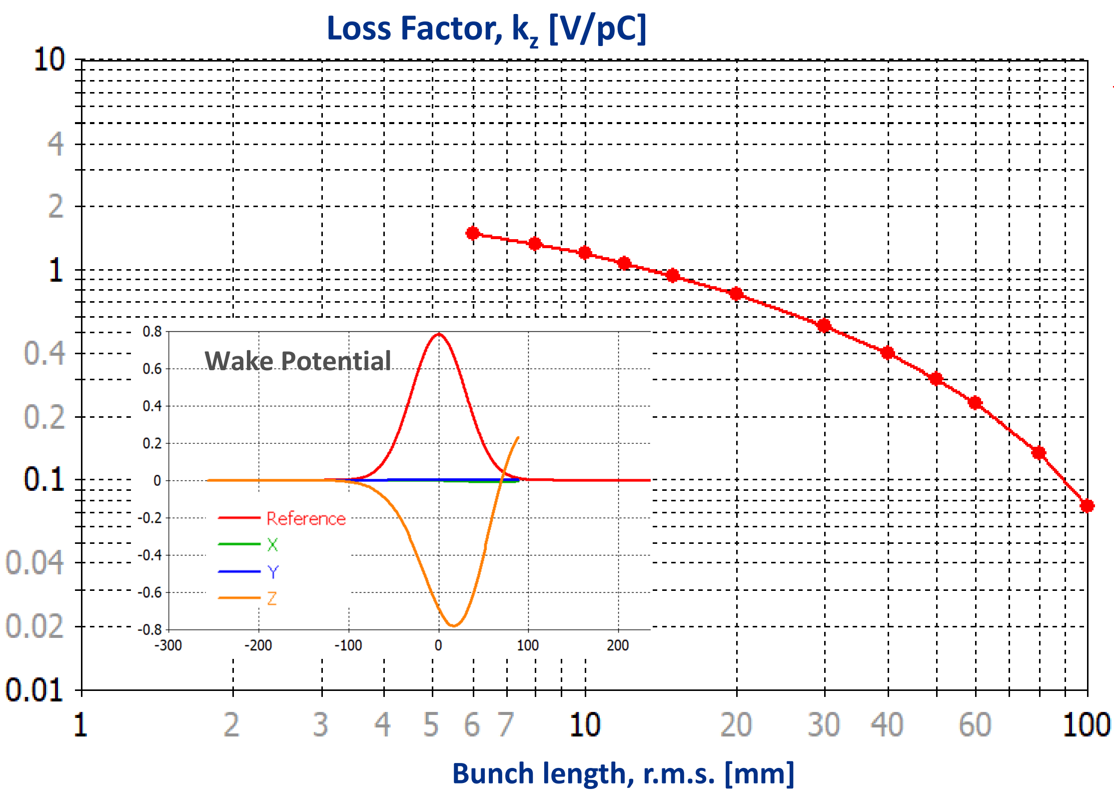
$$\boldsymbol{P = \frac{V_0^2}{4Q\left(\frac{r_\perp}{Q}\right)}\left[\left(1+\frac{I_p Q\left(\frac{r_\perp}{Q}\right)k_0 x_0}{U_0}\right)^2+\left(\frac{2Q\Delta\omega}{\omega_0}\right)^2\right]}$$

  - For max beam offset x_0 < 1 mm and Δf < 100 Hz (LFD, microphonics)

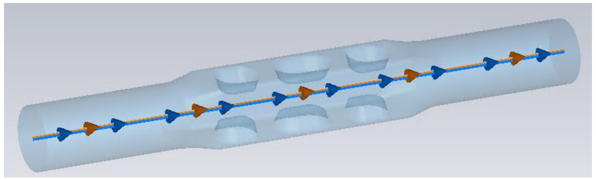
Beam OFF:	$P_{min} \approx$ 25 kW
Optimal Coupling:	$Q_L \approx$
Beam ON & Microphonics:	$P_{max} \approx$

- **~40 kW Solid State RF amplifier will be sufficient**

Incoherent HOM Excitation



CST Particle Studio Simulation



ParticleBeam2

Sigma	30 mm
Max. beam frequency (-20 dB)	3.41305 GHz
Beta	1
Charge	1e-09 C

Estimated Loss factors: k_z < 1 V/pC (e) and k_z < 0.2 V/pC (p)

Radiated wakefield power: $P = k_z q_0^2 N_b * f_{rep}$

Conclusions

- **QMIR is a good option for the EIC Crab Cavity**
  - design is radially compact (<0.35 m) and simple;
  - sparse HOM spectrum and small loss/kick factors;
- **QMiR re-optimized for 400 MHz with an aperture of 160 mm**
  - 1 QMiR can provide nominal 4.75 MV kick for EIC proton bunch;
  - Cavity has low operating surface fields: $E_p < 32$ MV/m and $B_p < 60$ mT
  - SOM/HOM are damped below EIC specifications;
- **Fermilab can design, build and test the QMIR cavity for EIC**
  - Further design optimization is possible to meet detailed requirements