Alternate Crab Cavity Design

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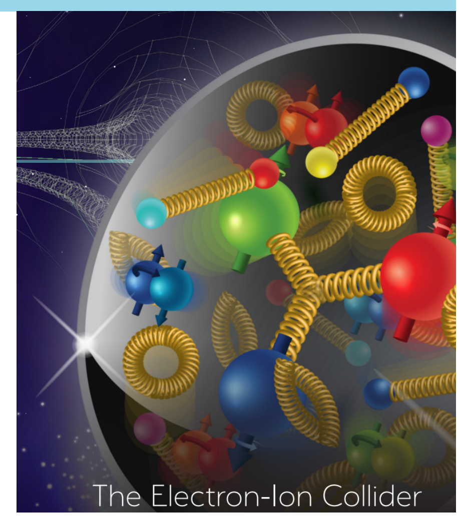
TRIUMF 2021 EIC Accelerator Partnership Workshop



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EIC2021, October 26-29, 2021

Outline

- Concept of the HOM-free deflecting cavity
- QMiR (2.815 GHz) deflecting cavity for ANL/SPX project
  - EM design
  - Production and Testing
- QMiR (2.6 GHz) for ILC Crab Cavity
  - HOM Analysis
  - Mechanical Analysis (LFD and dF/dP)
  - Frequency Tuner and Dressed Cavity Design
- QMiR (3 GHz and 3.25 GHz) for ELLETRA-II upgrade
- Conclusions

HOM-free Deflecting Cavity Concept

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

GHOST MODES IN IMPERFECT WAVEGUIDES

BY

E. T. JAYNES

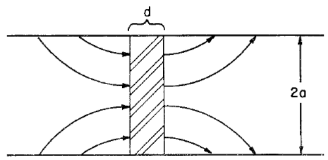
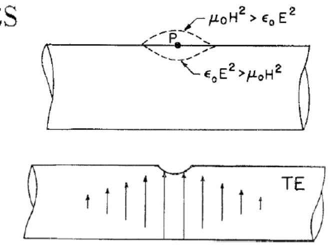


Fig. 1—TM_{01} ghost mode due to a dielectric disk.



$$\Delta p_x(x,y,t_0) = -\frac{i\cdot e}{\omega}\cdot\frac{d}{dx}\int_{-\infty}^{+\infty} dz\cdot E_z(x,y,z,t=z/v+t_0) = -\frac{i\cdot e}{\omega}\cdot\frac{\partial V_z}{\partial x}$$

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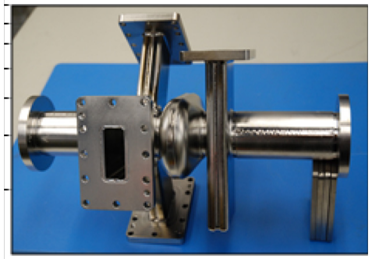
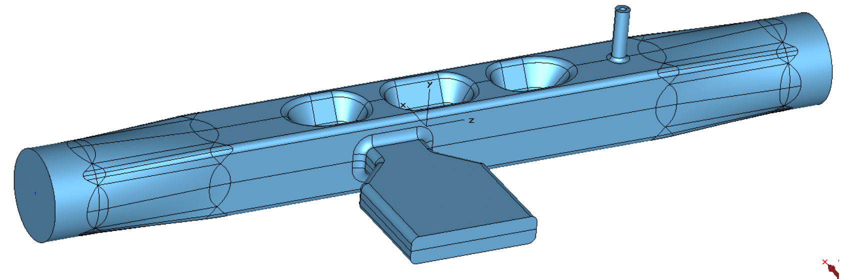
- Rediscovered in 1990s by G. Stupakov and S. Kurennoy [1]
- Further development of RFD at ODU (J. Delayen) [2]
- Transverse kick is produced by Quasi-TE modes which form transition zones with $\partial V_z/\partial x > 0$
  - no contradiction with the Panofsky/Wenzel theorem!

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

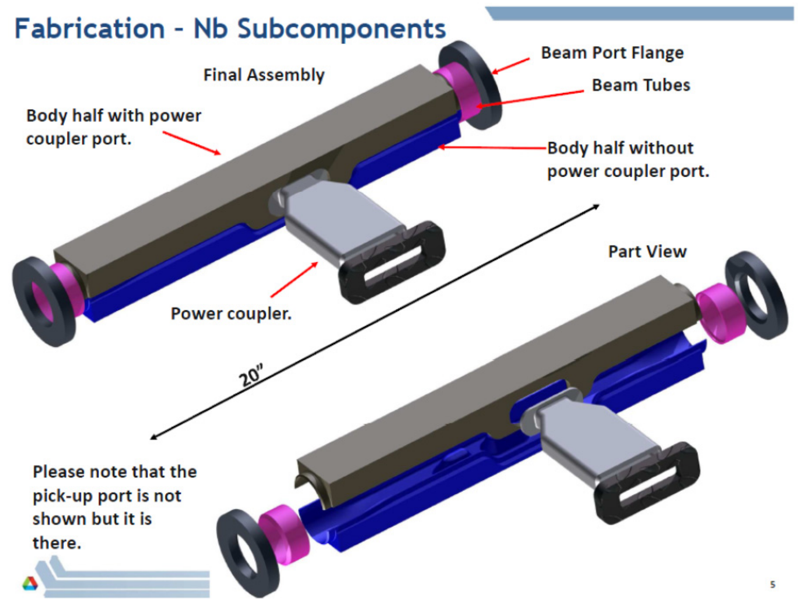
Compact HOM-free Deflecting Cavity QMIR

Quasi-Waveguide Multicell Deflecting Resonator [1]

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

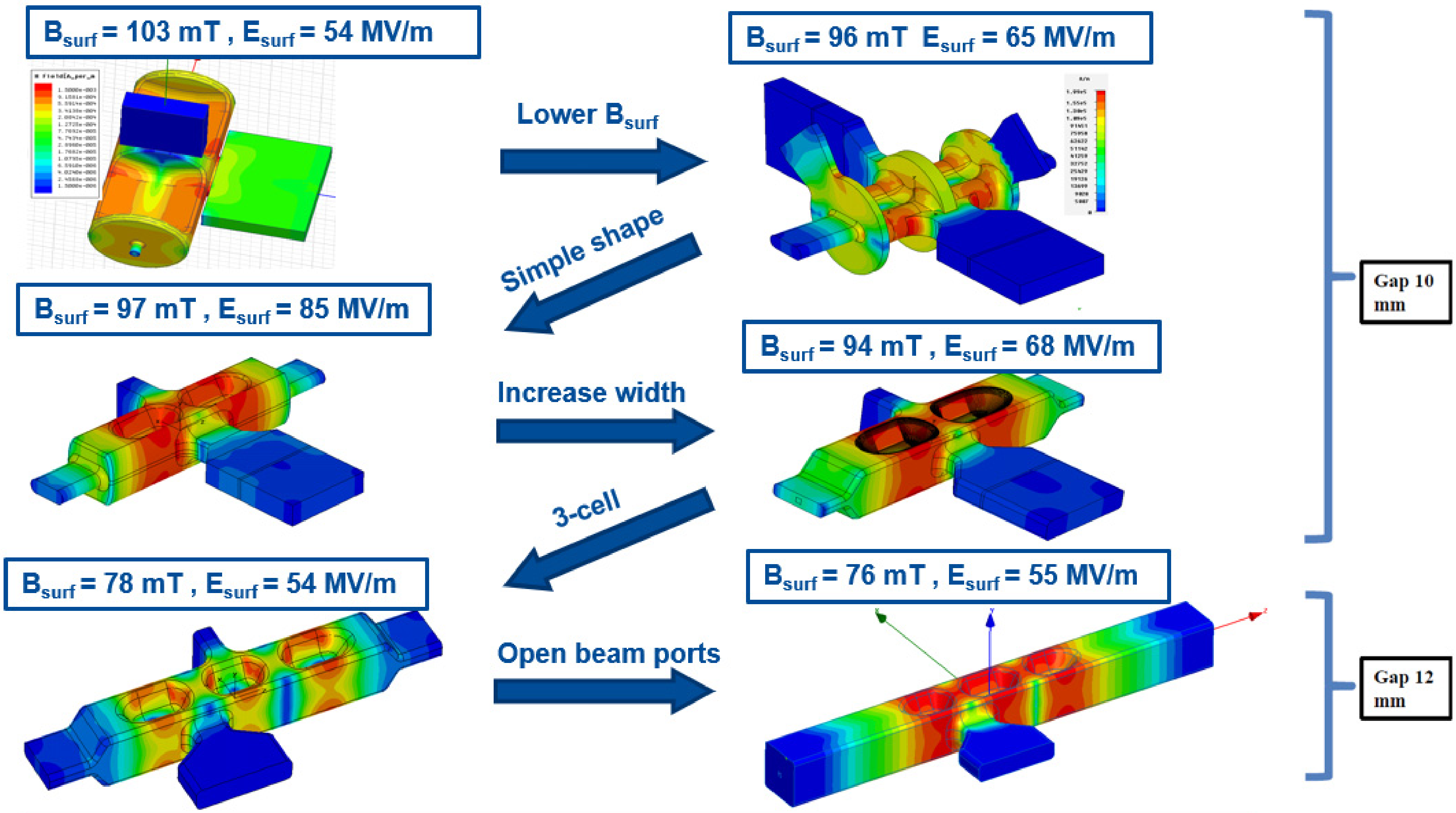
4 x  → 1 x 

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



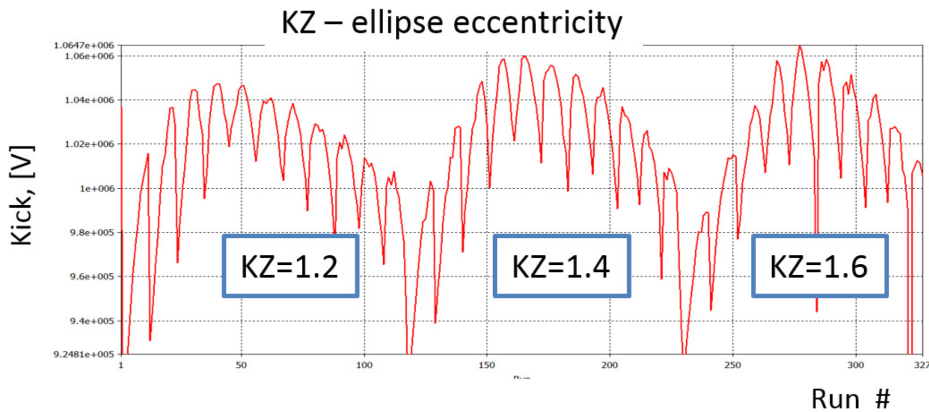
[1] A. Lunin, I. Gonin, M. Awida, T. Khabiboulline, V. Yakovlev, A. Zholents, Physics Procedia 79 (2015) 54 – 62
[2] Zachary Conway on behalf of ANL PHY LINAC Development Group, 04/23/2013

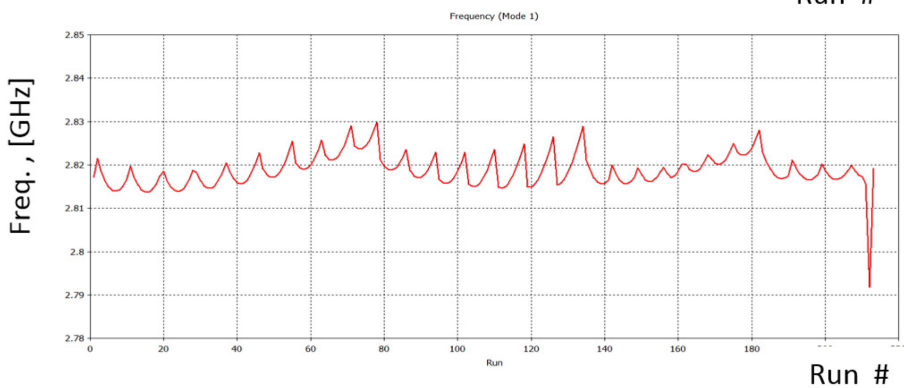
R&D on Deflecting Cavity for ANL/SPX



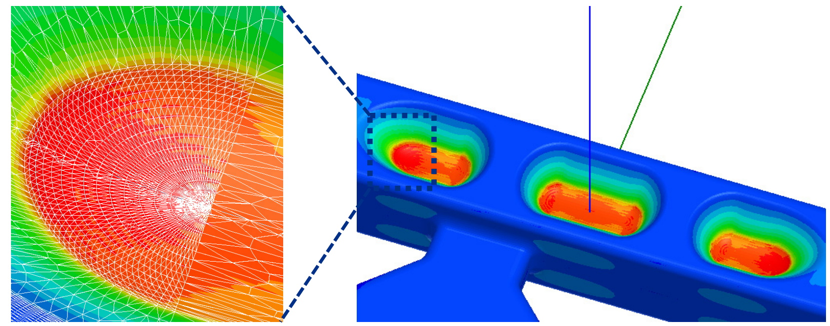
- Simple geometry
- Single WGs for HOM damping.
- Sparse spectrum of HOMs up to 5.1 GHz and HOM free above 5.1 GHz

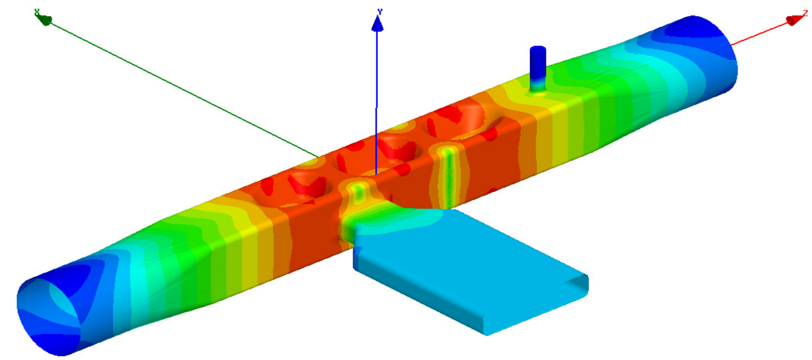
R&D on Deflecting Cavity for ANL/SPX





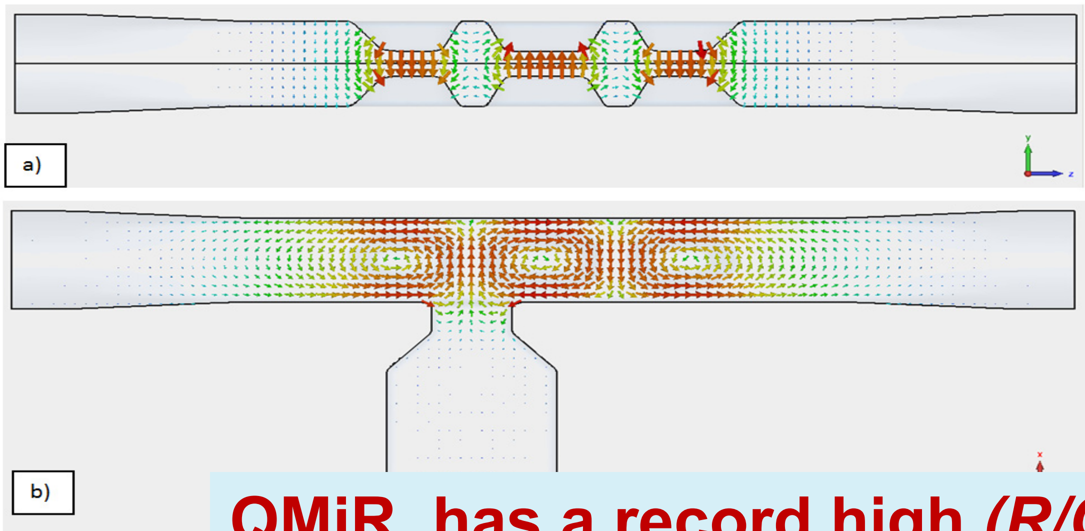
Operating trapped mode surface electric (up) and magnetic (down) fields



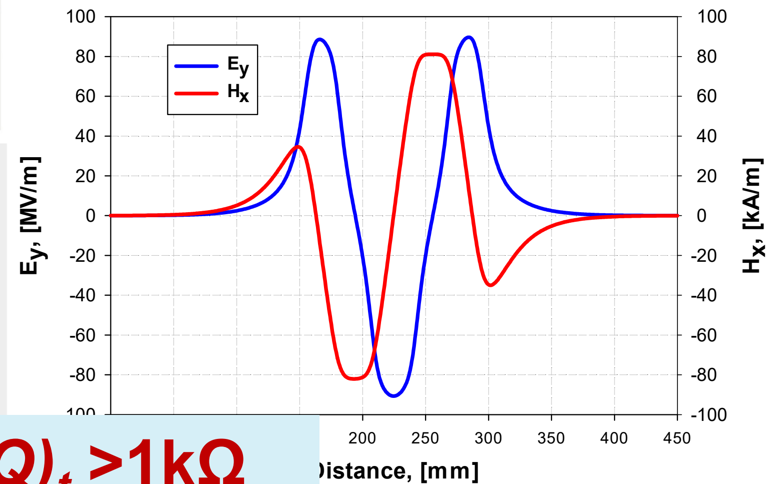


- Model is fully parameterized
- The frequency derivation was calculated for each parameter in order to preserve the operating mode frequency on the stage of geometry creation.
- General ellipsoid is used for hollow surface representation
- Global optimum search algorithm

Operating Dipole Mode

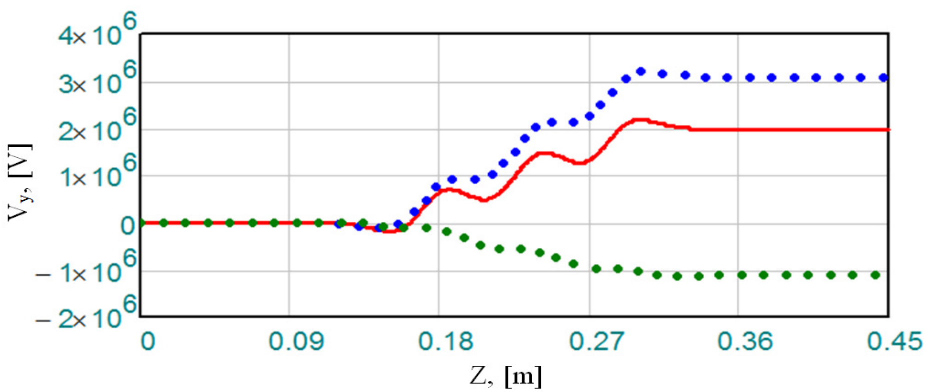


Transverse electric (blue) and magnetic (red) field components along the cavity axis.



QMiR has a record high $(R/Q)_t$ >1kΩ

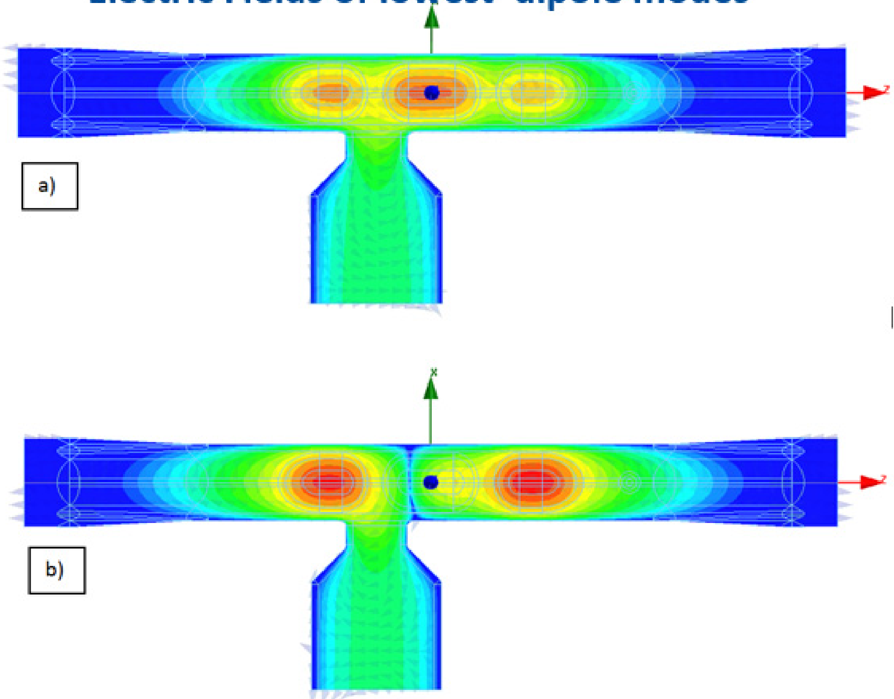
Integrated vertical kick along the cavity axis (solid red curve is the overall kick, dotted blue and green curves are electric and magnetic kicks).

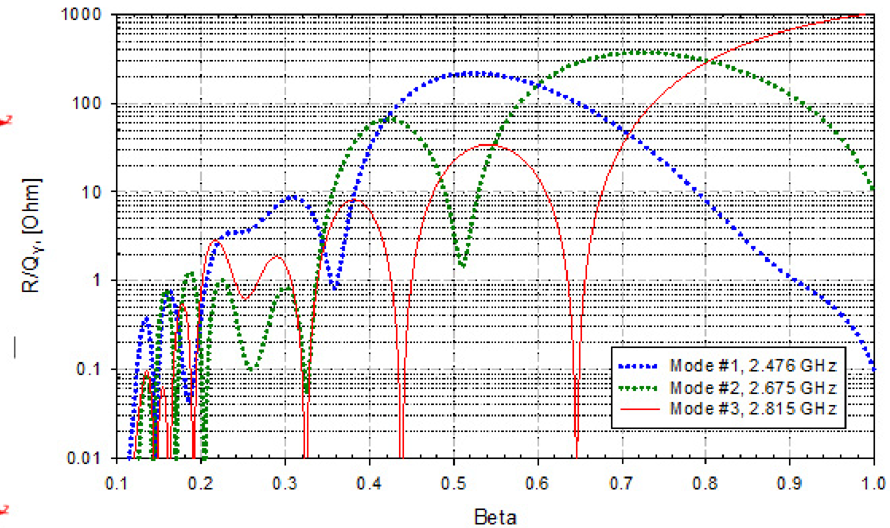


Freq	2815 MHz
V_{kick}	2 MV
E_{max}	55 MV/m
B_{max}	76 mT
$(R/Q)_Y$	1040 Ω
G	130
W_{STOR}	0.23 J

Same Order Mode (SOM) Damping

Electric Fields of lowest dipole modes



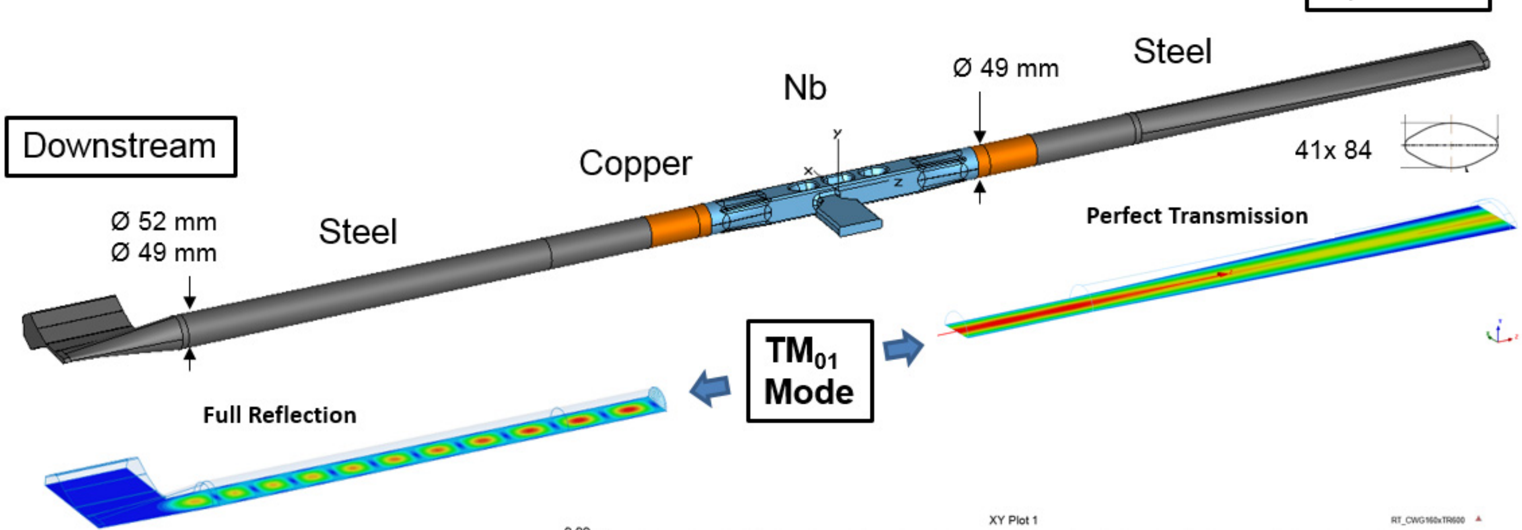


Freq., [GHz]	$(R/Q)_t$, [Ω]	Q_{ext}	R_t [MΩ/m]
2.476	0.03	2400	3e-3
2.675	5.0	6800	1.9

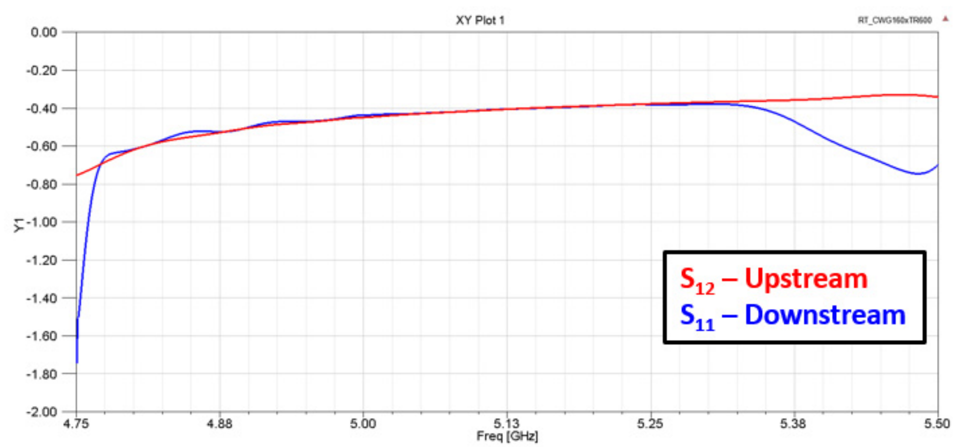
- The fundamental coupler waveguide is used to suppress SOM modes
- The FPC is purposely shifted from the cavity center in order to provide external coupling for the operating mode and damping lower frequency dipole modes simultaneously

HOM Damping in the APS Ring

QMiR Cavity Monopole HOMs



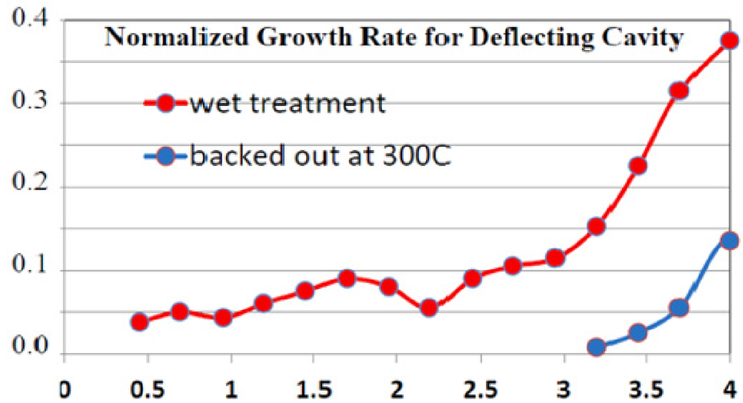
Cross Section	TM_{01} Cut Off
Ø 52 mm	4.4 GHz
Ø 49 mm	4.7 GHz
Upstream	4.5 GHz

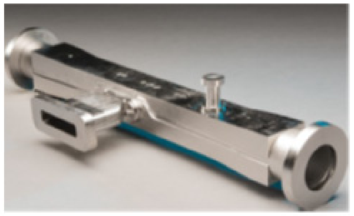


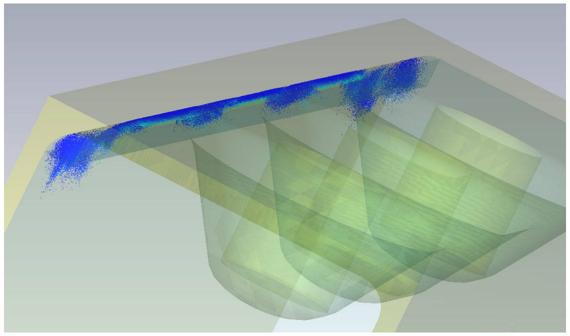
Monopole HOMs RF power is radiated to the Upstream beam pipe !

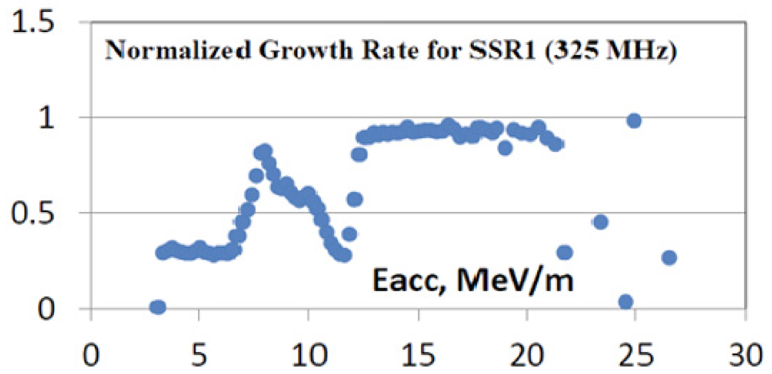
Multipactor Analysis in QMiR

Multipactor Simulations with CST Studio





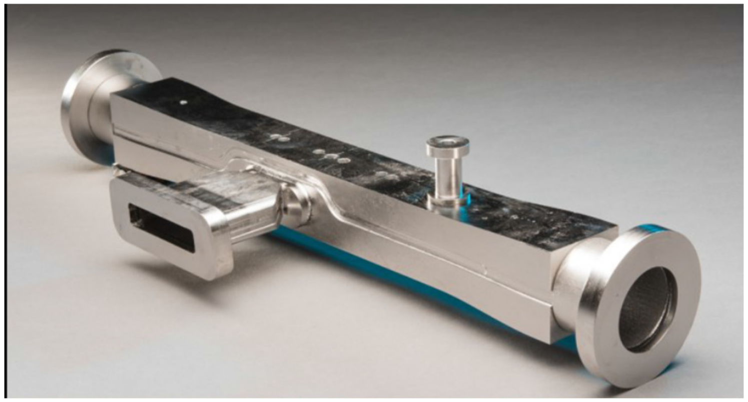


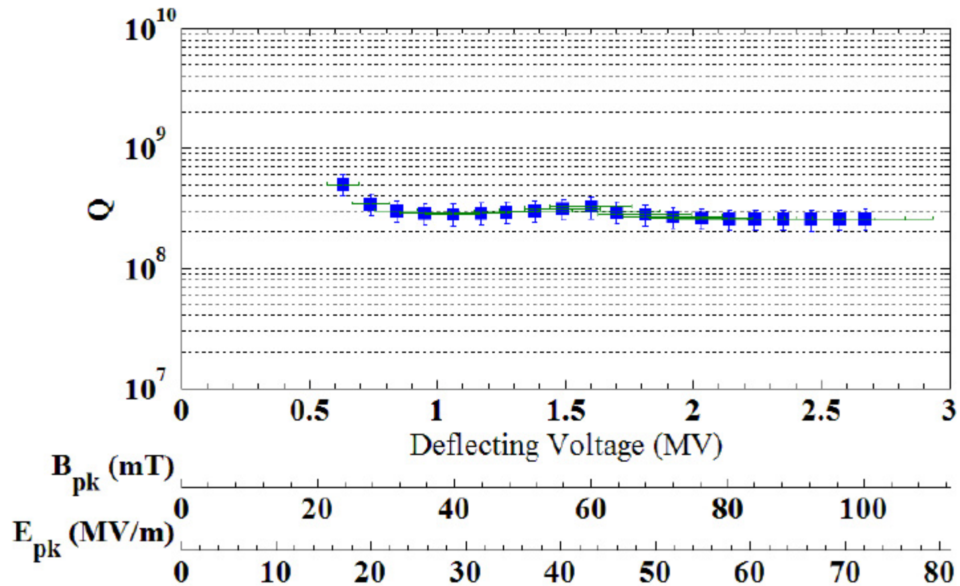


NG Rate in the SSR1 cavity are ~ 10 times higher and MP is successfully processed.
QMiR cavity is practically free from MP in the operating RF field domain

QMIR Prototype Production and Testing

Bare QMiR (21.75' Long) cavity





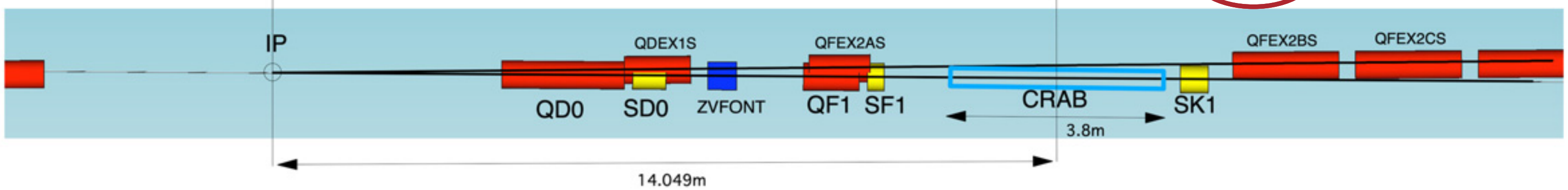
- Cavity received EP-treatment before the test
- Measured maximal deflecting voltage of 2.7 MV exceeded the design goal of 2.0 MV @2K vertical test of QMiR prototype [1]
- Relatively low Q_0 (3E8) is due to extra RF losses at covering flanges
- Further QMiR development was stopped due to the cancelation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

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

QMIR Application for ILC Crab Cavity

Crab cavity location (present ILC optics deck)

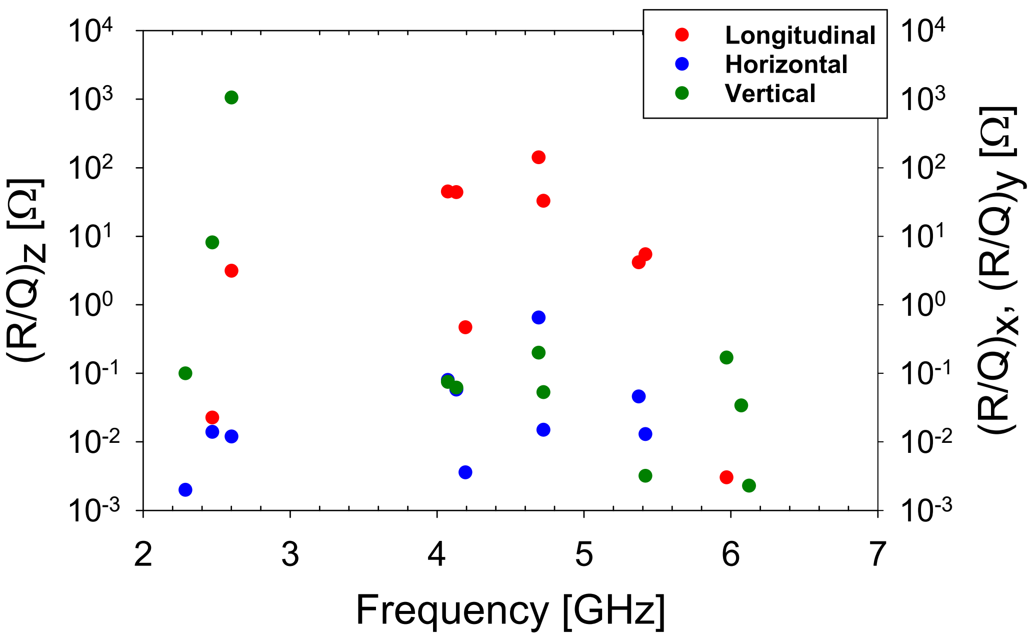
two beamline distance
14.05m x 0.014rad = 197mm

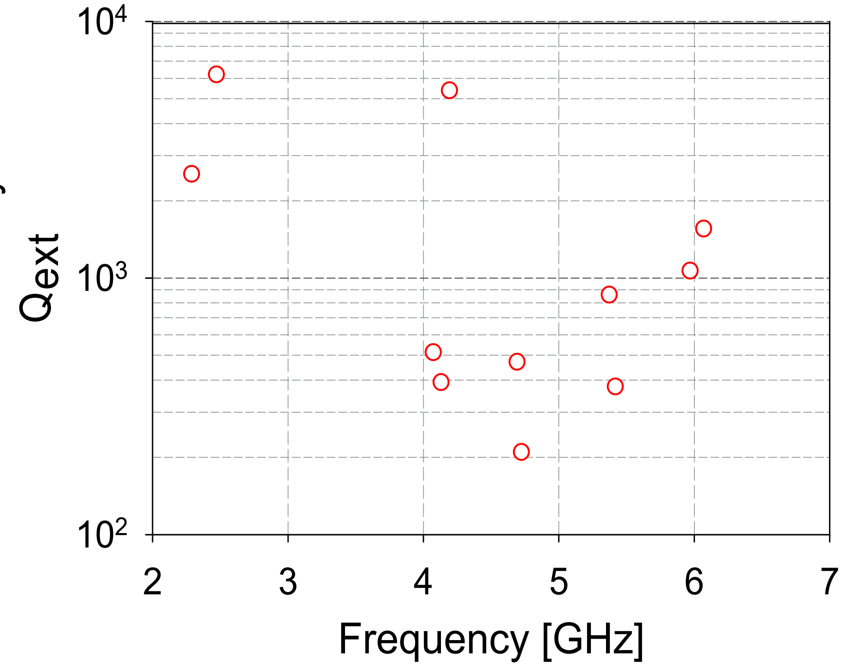


- **The kick voltage is inverse proportional to frequency ($V_t \sim f^{-1}$)**
- **The CC space is limited by a close beamlines distance (< 0.2 m)**
- **For the deflecting voltage of about 0.9 MV the cavity has considerably small surface fields, Ep ≈25 MV/m, Bp ≈ 35 mT**

- **QMiR cavity @2.6 GHz looks a good choice!**

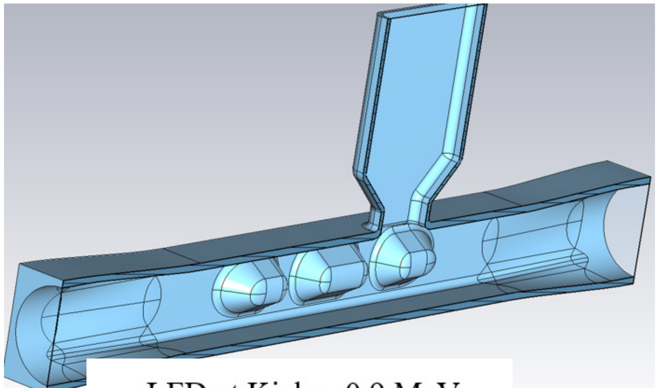
QMiR Cavity for ILC (scaled to 2.6 GHz)





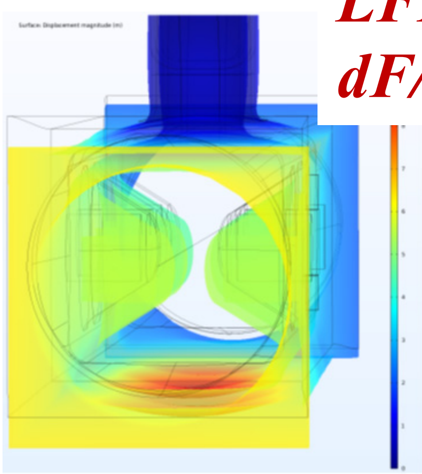
- There are two Same Order Modes (SOM) that have a low *(R/Q)*Q*
- SOM/HOM external couplings Qext < 10^4
- SOM/HOMs longitudinal and transverse impedances (@1mm):
  (R/Q)z <= 100 Ω, *(R/Q)x* <= 1 Ω and *(R/Q)y* <= 10 Ω
- **SOM/HOM spectrum is sparse and strongly damped**

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

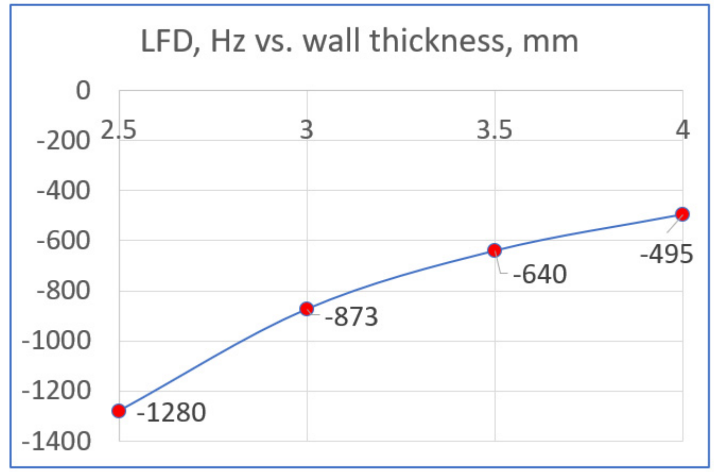


LFD at Kick = 0.9 MeV
Wall thickness 4 mm.
Δf ~ - 495 Hz

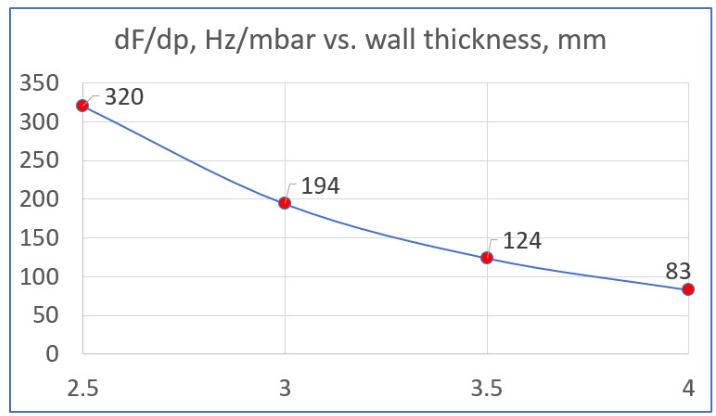
LFD < 500 Hz
dF/dP < 100 Hz



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

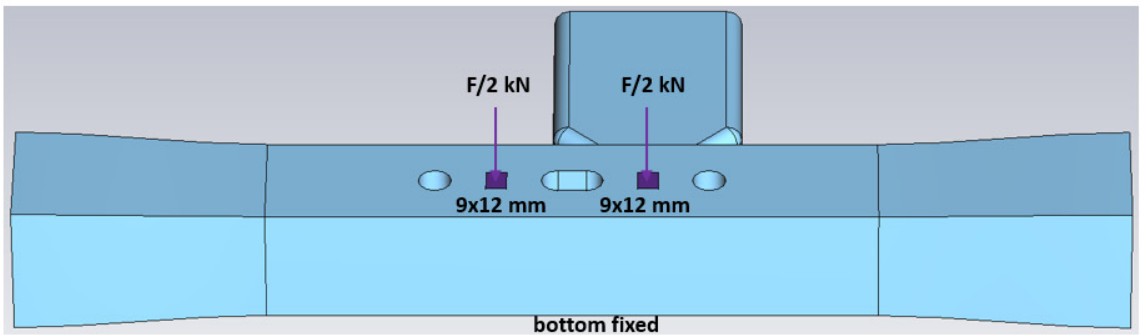
- **QMiR LFD and dF/dP are less than the cavity bandwidth (few kHz)**

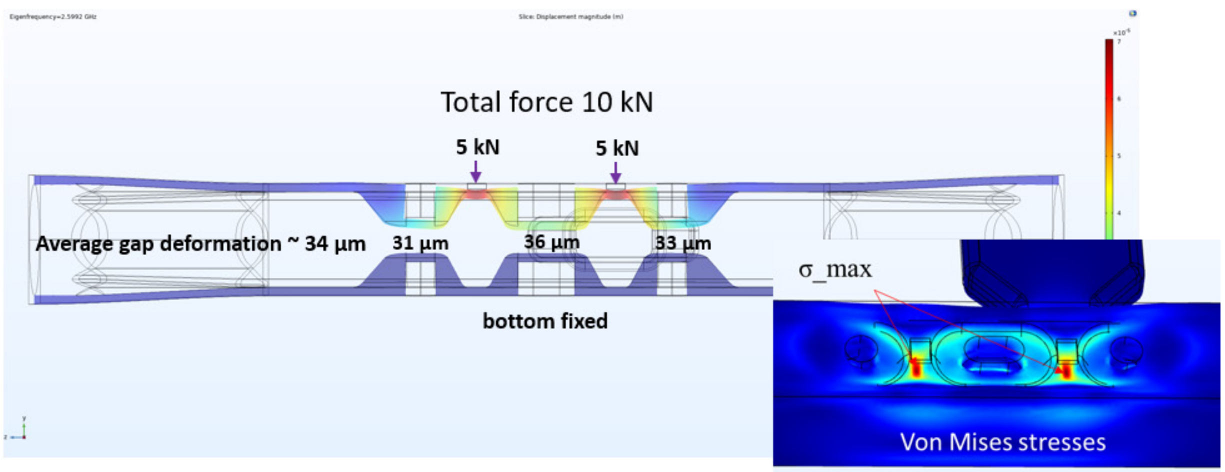
Mechanical Analysis of Frequency Tuning (by I. Gonin)

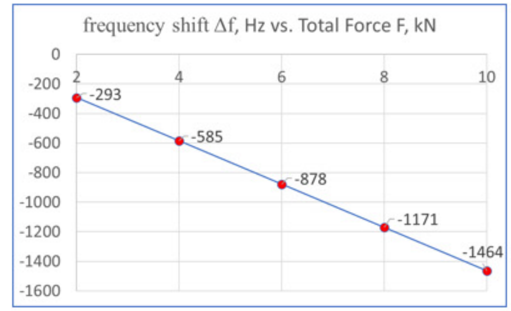
Cavity shell deformations under external force. Wall thickness 4 mm

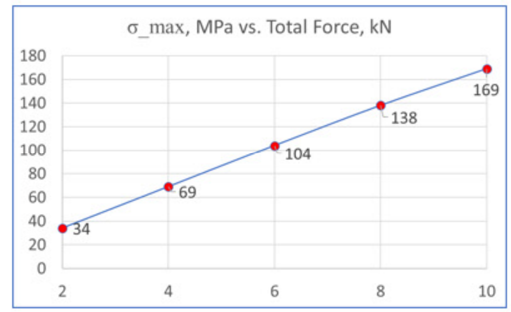
$\Delta f / \Delta L \sim - 45$ kHz/µm

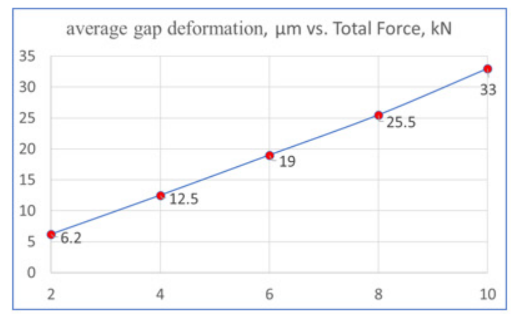
$\Delta \sigma / \Delta Force \sim 17.3$ MPa/kN









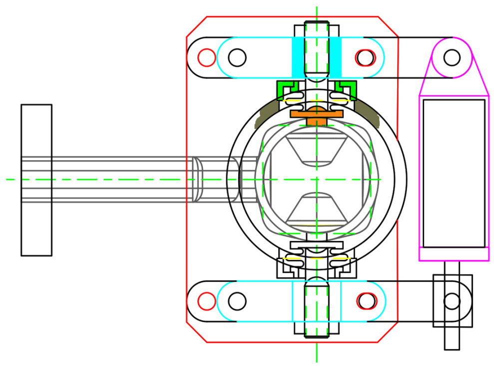


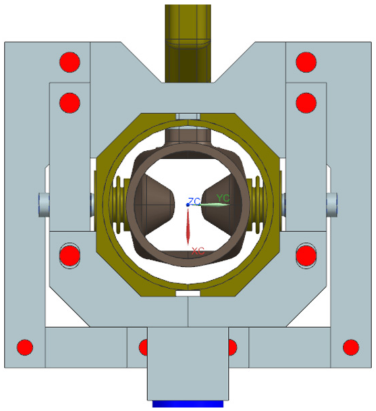
Maximum frequency tuning range: ~ 1..2 MHz

Fermilab

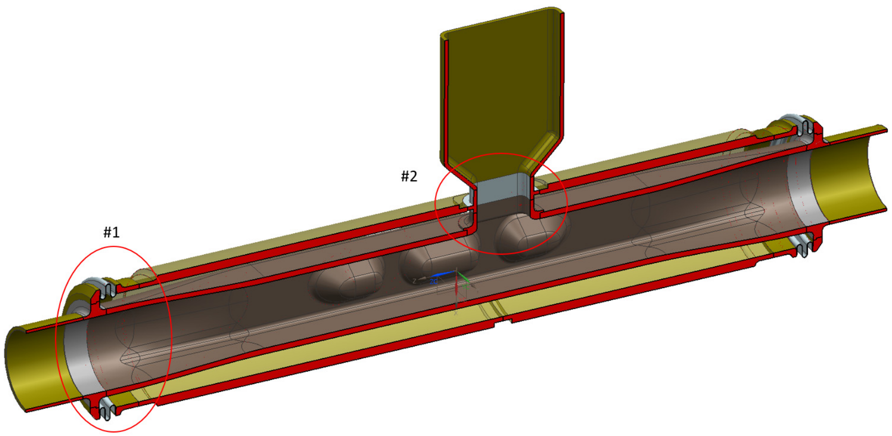
QMiR Cavity Slow Tuner Design (by V. Polubotko)

Compact lever-type frequency tuner

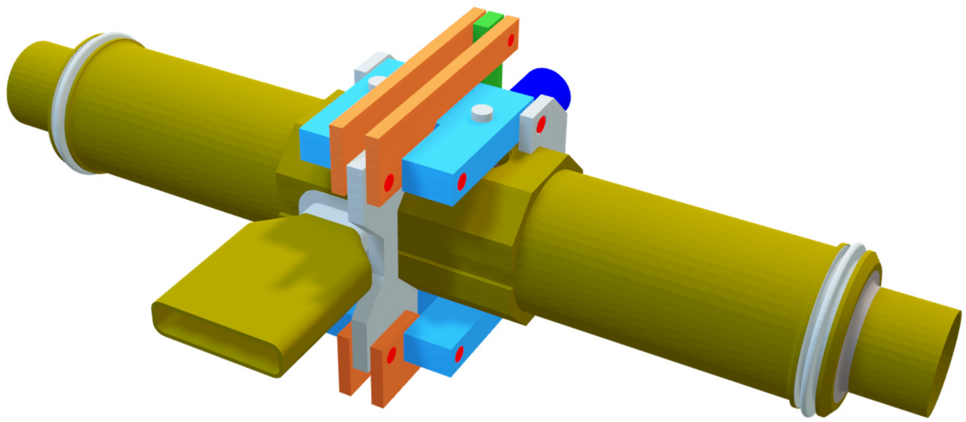




LHe Vessel



Dressed QMiR Cavity



Design of frequency tuner integrated with dressed cavity is ongoing

QMiR Cavity for ELLETRA-II Upgrade (ST Trieste)

Original scheme for ANL/SPX[1]

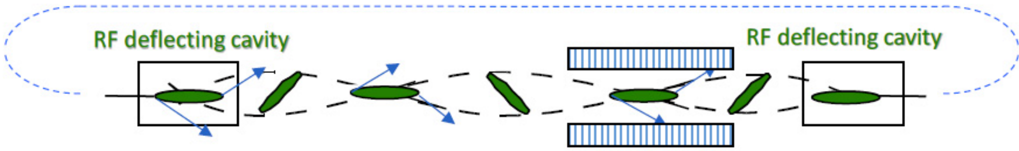


Figure 1-1. Tilt-and-cancel scheme for producing short bunches.

SPX 2-Frequency scheme

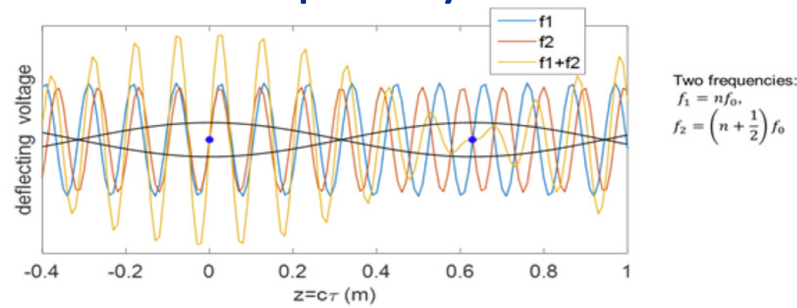
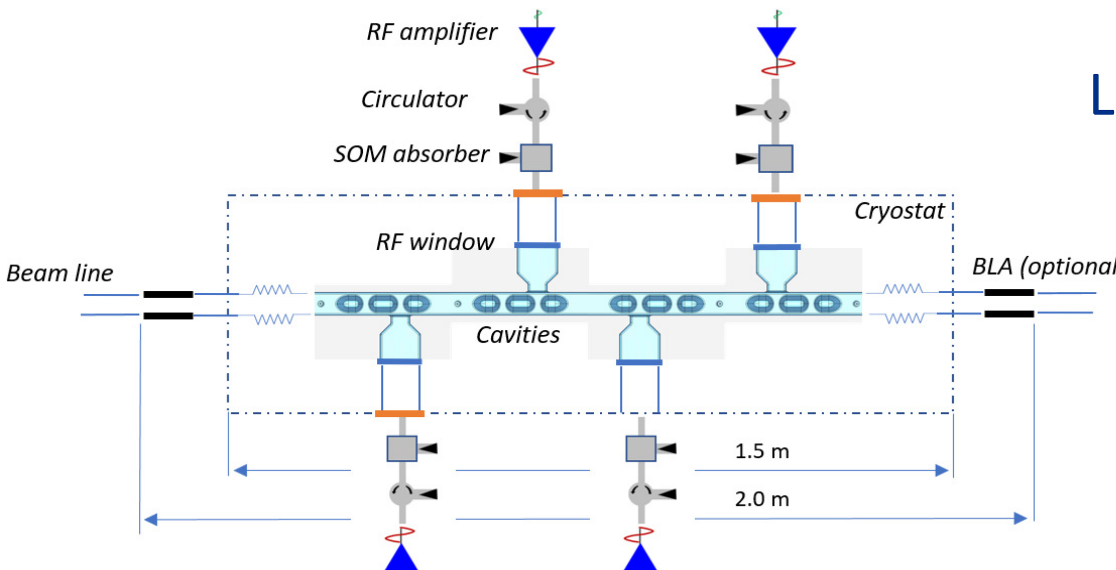


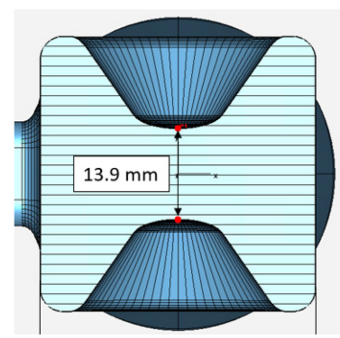
Figure 1-3. Alternating kicked and un-kicked buckets with 2-frequency crab cavities.

Deflecting System for ST Trieste [2]

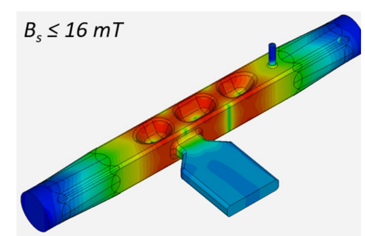


Large aperture

Variant B (3 GHz)



Low B-field



MAC for ST Trieste recommended to proceed with the QMiR type Crab Cavities, 3 GHz and 3.25 GHz for ELLETRA-II upgrade

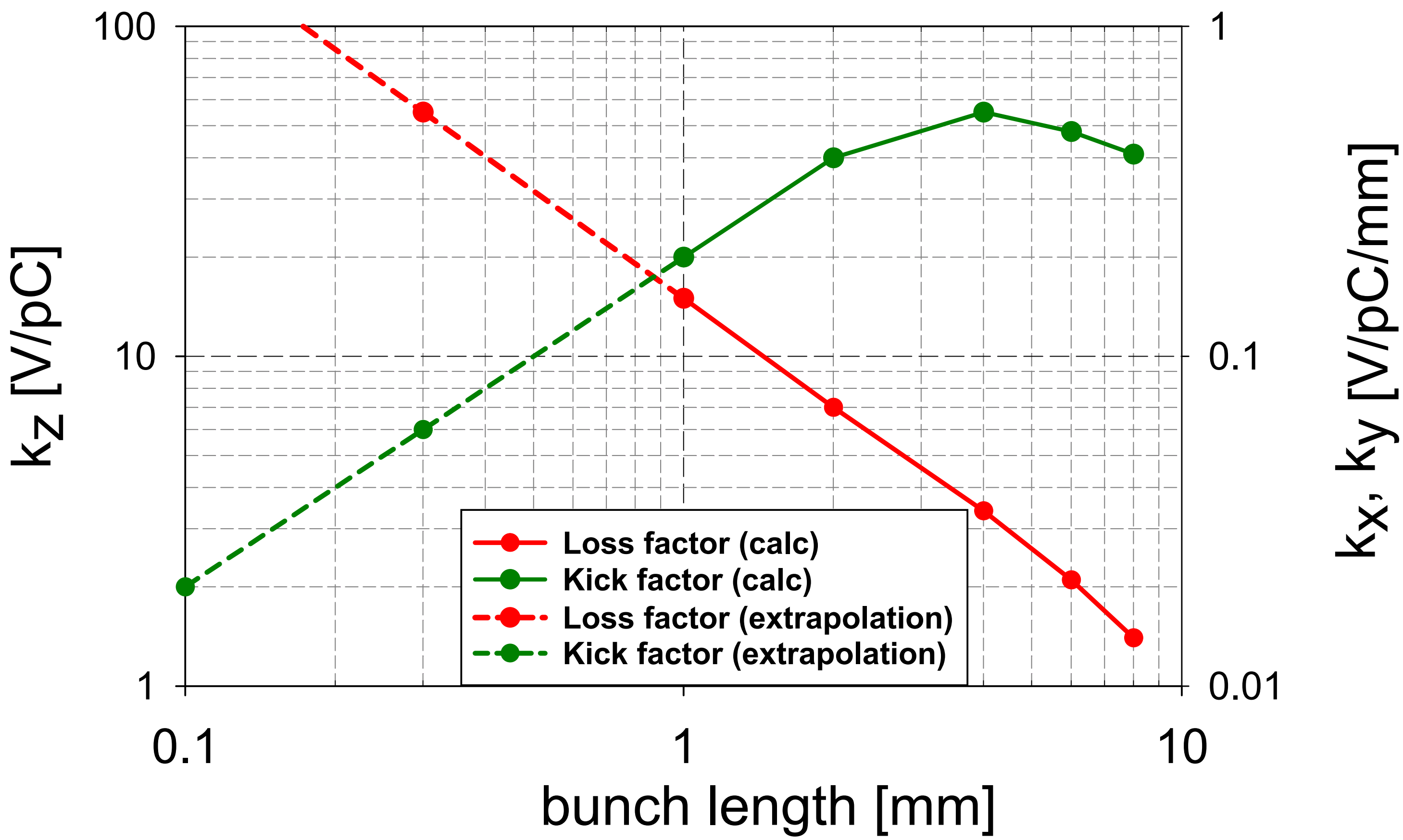
[1] A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM in Physics Research Section A 425(1-2), 1999.
[2] A. Lunin, T. Khabiboulline, V. Yakovlev, FERMILAB-TM-2756-TD, Technical Note, Fermilab, 2021.

Conclusions

- ❑ A Quasi-Waveguide Multicell Deflecting Resonator (QMIR) is a viable option for Crab and Deflecting Cavities applications
  - QMIR is very compact and simple (no HOM-couplers)
  - It has sparse HOM spectrum
  - It has acceptable loss/kick factors
  - No MP in operation voltage domain.
- ❑ QMIR cavity is now being considered for the Elletra-2 and ILC projects.
  - It meets all the project requirements
- ❑ Fermilab can design, build and test QMIR cavities for a variety of particle accelerator applications

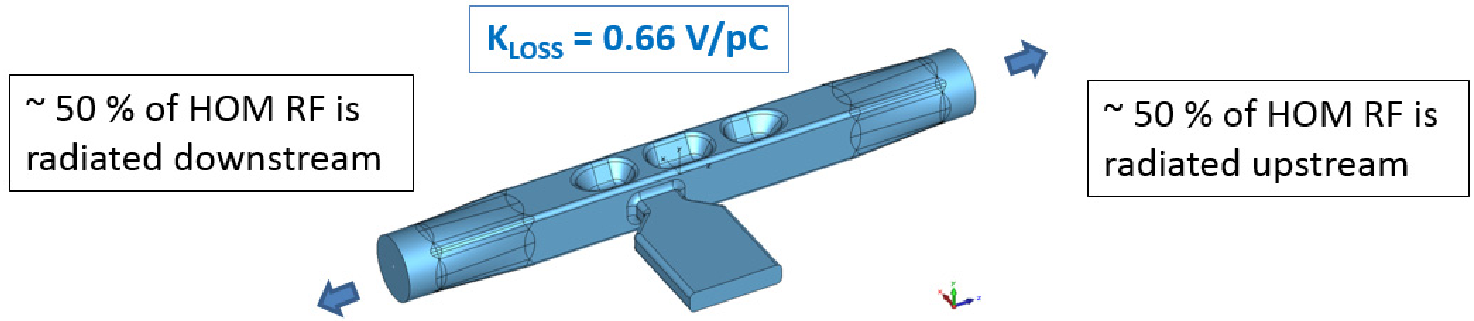
Backup Slides

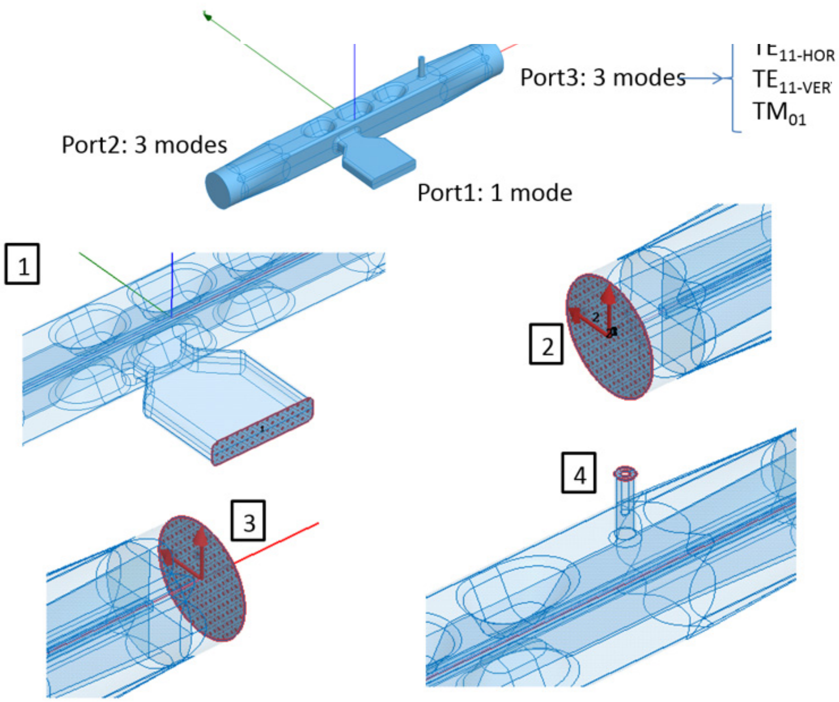
2.6 GHz QMiR for ILC Crab Cavity

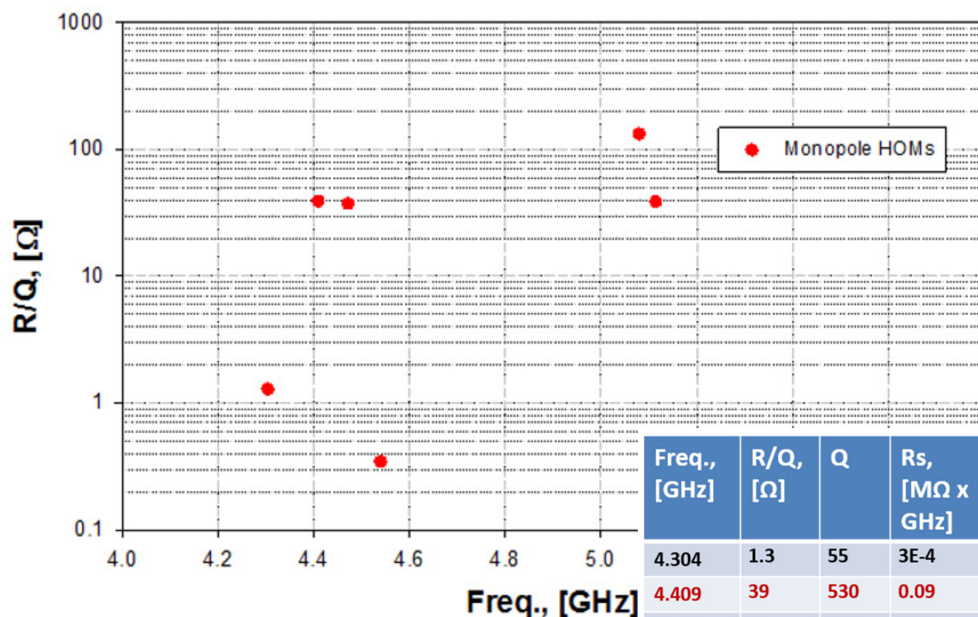


For the ILC bunch length (0.3 mm rms), the loss and kick factors:
k_loss <= 50 V/pC and k_kick <= 0.1 V/pC/mm

High Order Mode (HOM) Damping







Freq., [GHz]	R/Q, [Ω]	Q	Rs, [MΩ x GHz]
4.304	1.3	55	3E-4
4.409	39	530	0.09
4.471	37	400	0.07
4.530	0.35	4900	8E-3
5.080	132	390	0.26
5.114	39	108	0.02

Cavity is HOM-free at f > 5.2 GHz

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 *vertica*l HOM $\left(\frac{r_\perp}{Q}\right)_y < 10$ Ohm (@4 GHz);

$Q < 1\times10^4$ ($< Q_{max} \approx 1.7\times10^6$)

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

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

$P_{gen} < 1$ kW

Fermilab