Alternate Crab Cavity Design

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October 27, 2021

TRIUMF 2021 EIC Accelerator Partnership Workshop

The Electron-Ion Collider
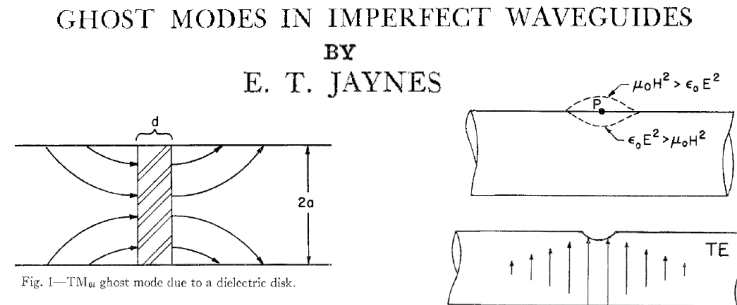
EIC2021, October 26-29, 2021
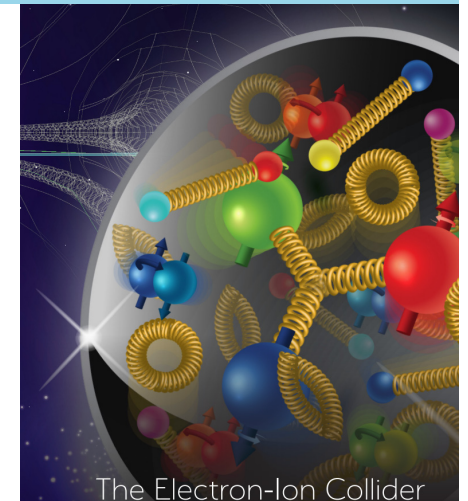
Outline

- **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. I—TM$_{01}$ ghost mode due to a dielectric disk.

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

Reprinted from the PROCEEDINGS OF THE IRE
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PRINTED IN THE U.S.A.

- 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 $\partial V_z / \partial x > 0$
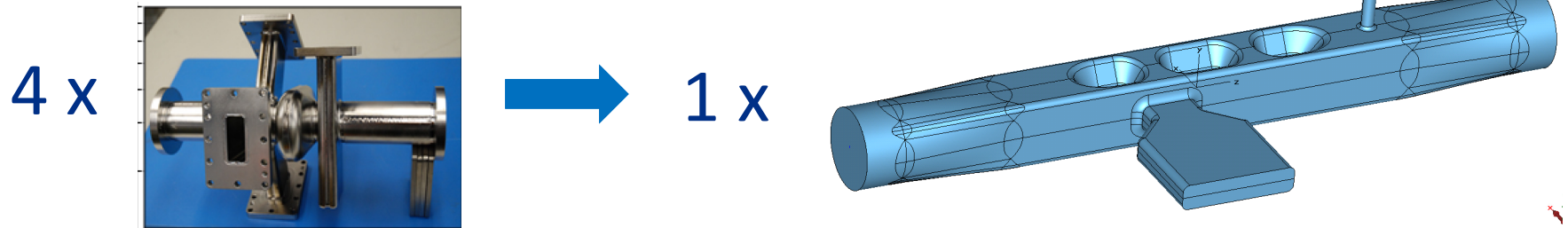 - no contradiction with the Panofsky/Wenzel theorem!

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

*Fermilab

Compact HOM-free Deflecting Cavity QMIR

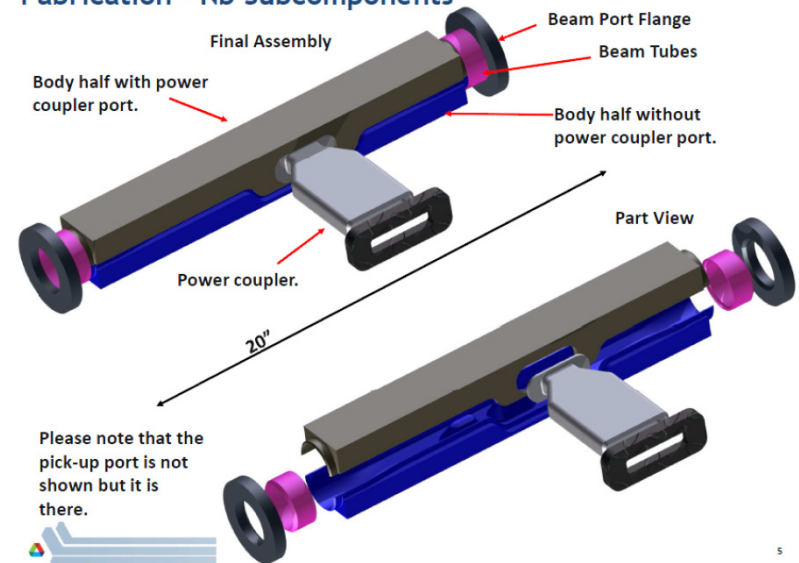## Quasi-Waveguide Multicell Deflecting Resonator [1]

- Proposed as replacement of Mark-II deflecting cavity for APS/SPX project
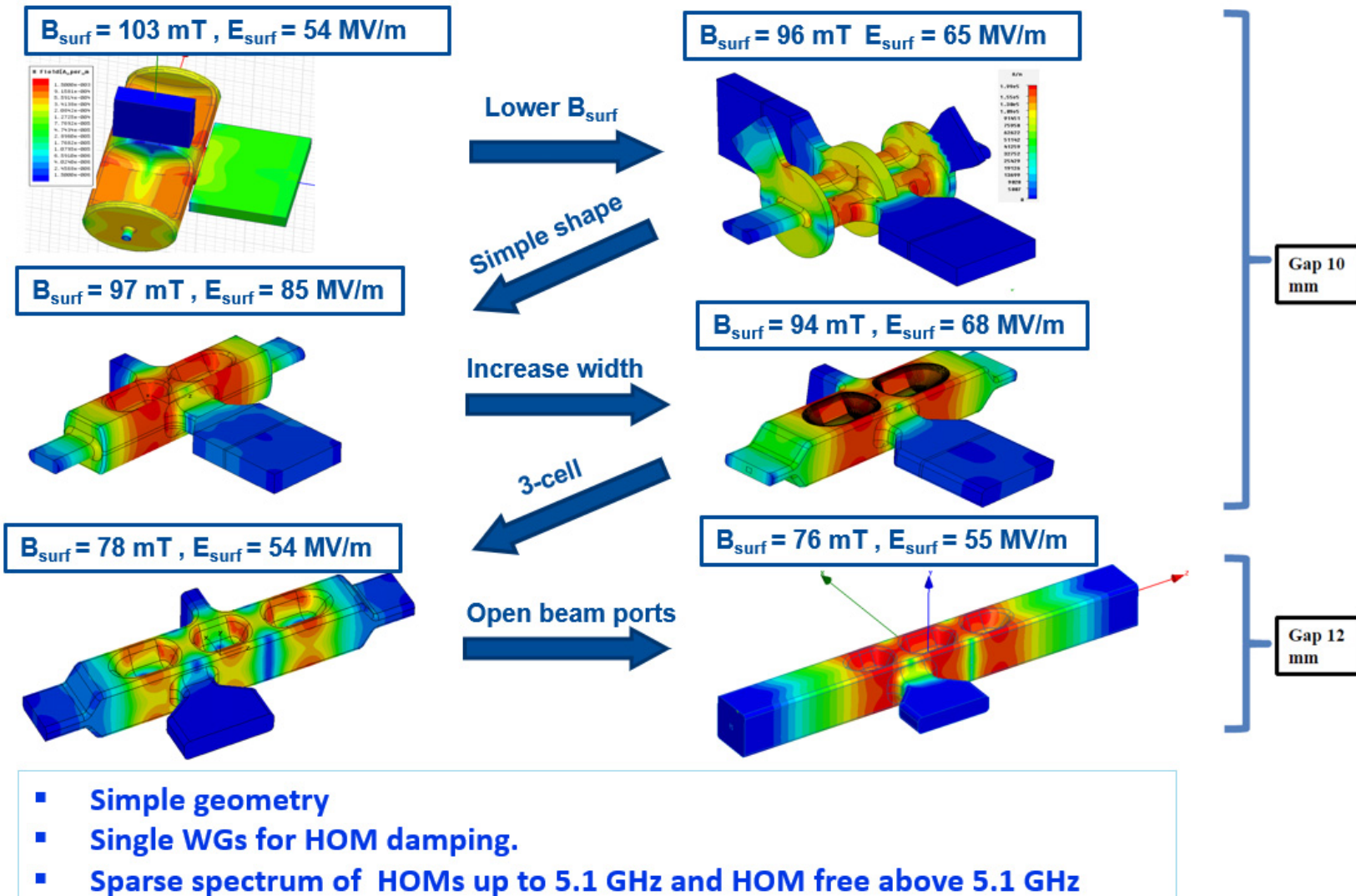
4 x ➡ 1 x

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

Fabrication - Nb Subcomponents

Final Assembly

Body half with power coupler port.

Beam Port Flange
Beam Tubes

Body half without power coupler port.

Power coupler.

Part View

20"

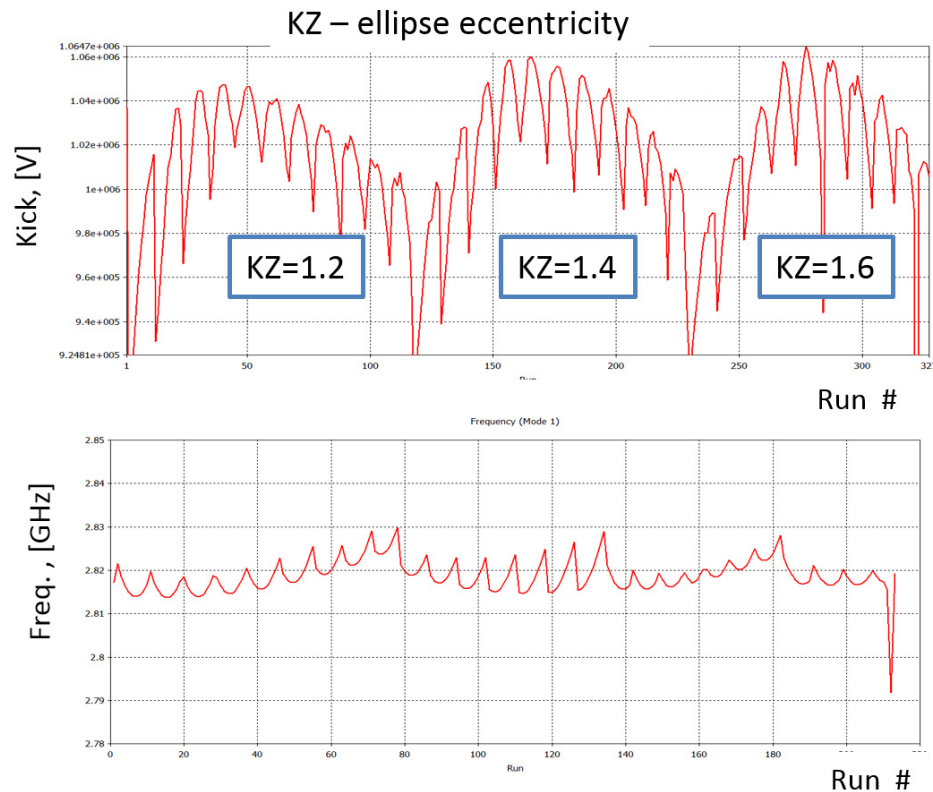Please note that the pick-up port is not shown but it is there.

[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

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R&D on Deflecting Cavity for ANL/SPX

$B_{surf} = 103$ mT , $E_{surf} = 54$ MV/m

$B_{surf} = 96$ mT $E_{surf} = 65$ MV/m

Lower B_{surf}

Simple shape

$B_{surf} = 97$ mT , $E_{surf} = 85$ MV/m

$B_{surf} = 94$ mT , $E_{surf} = 68$ MV/m

Increase width

3-cell

$B_{surf} = 78$ mT , $E_{surf} = 54$ MV/m

$B_{surf} = 76$ mT , $E_{surf} = 55$ MV/m

Open beam ports

Gap 10 mm

Gap 12 mm

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

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R&D on Deflecting Cavity for ANL/SPX

KZ – ellipse eccentricity

KZ=1.2   KZ=1.4   KZ=1.6

Kick, [V]

Run #

Freq., [GHz]

Run #

**Operating trapped mode surface electric (up) and magnetic (down) fields**
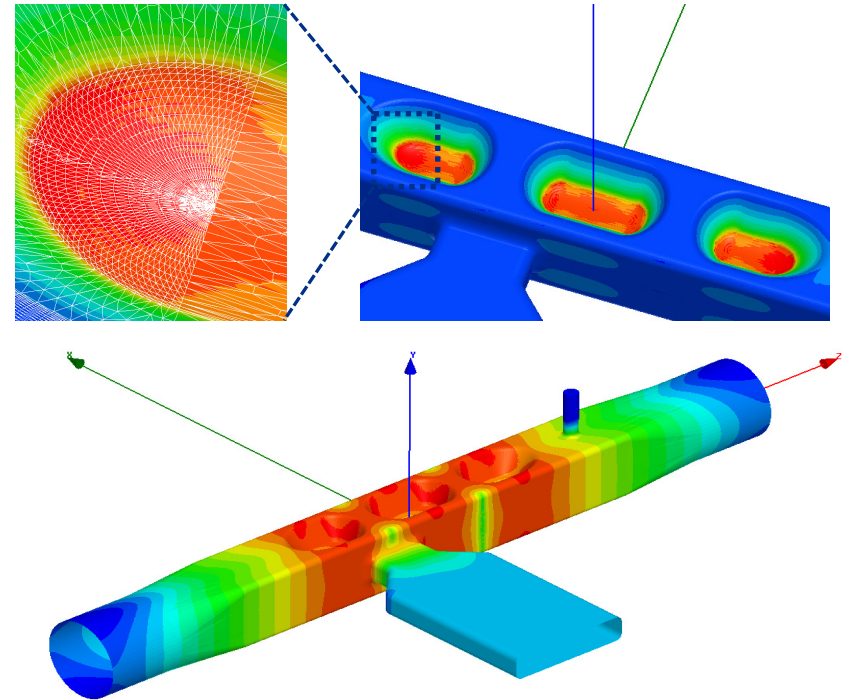
- Model is fully parameterized
- The frequency derivation was calculated for each parameter in order to preserve the operating mode frequency on the stage of geometry creation.
- General ellipsoid is used for hollow surface representation
- Global optimum search algorithm

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Operating Dipole Mode

a)

b)
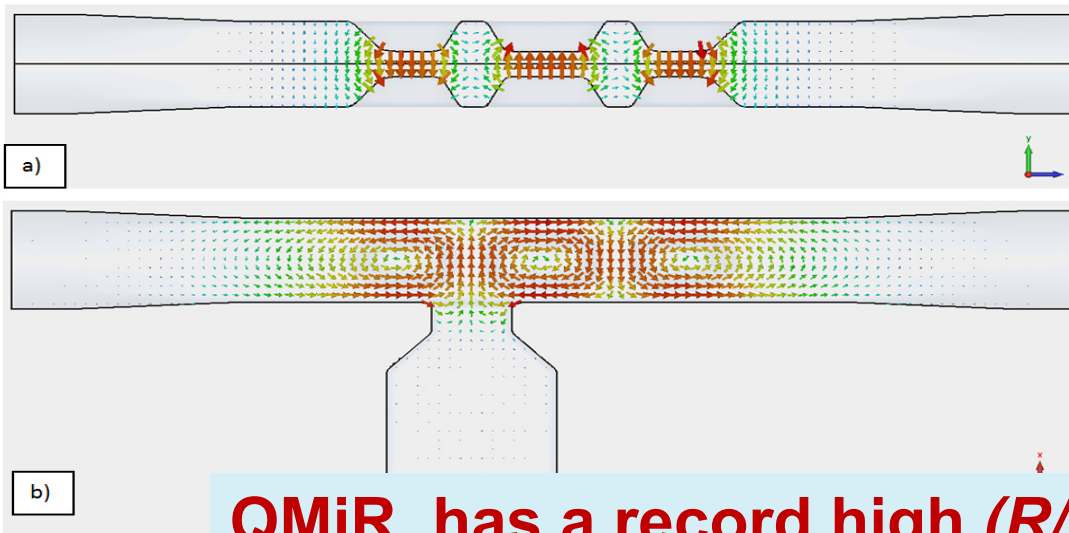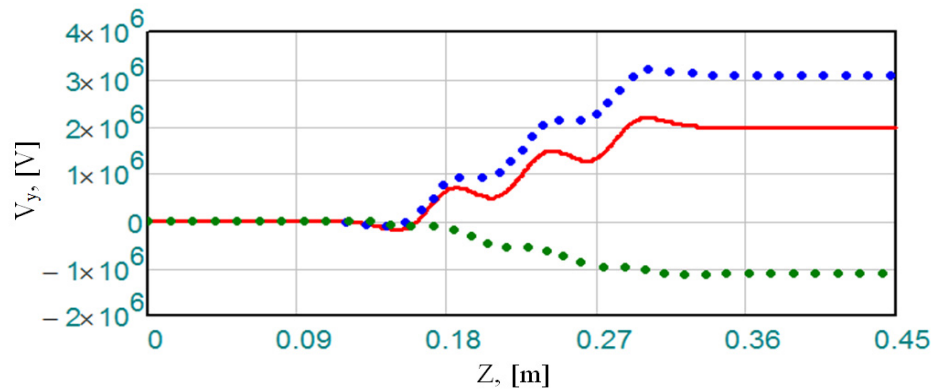
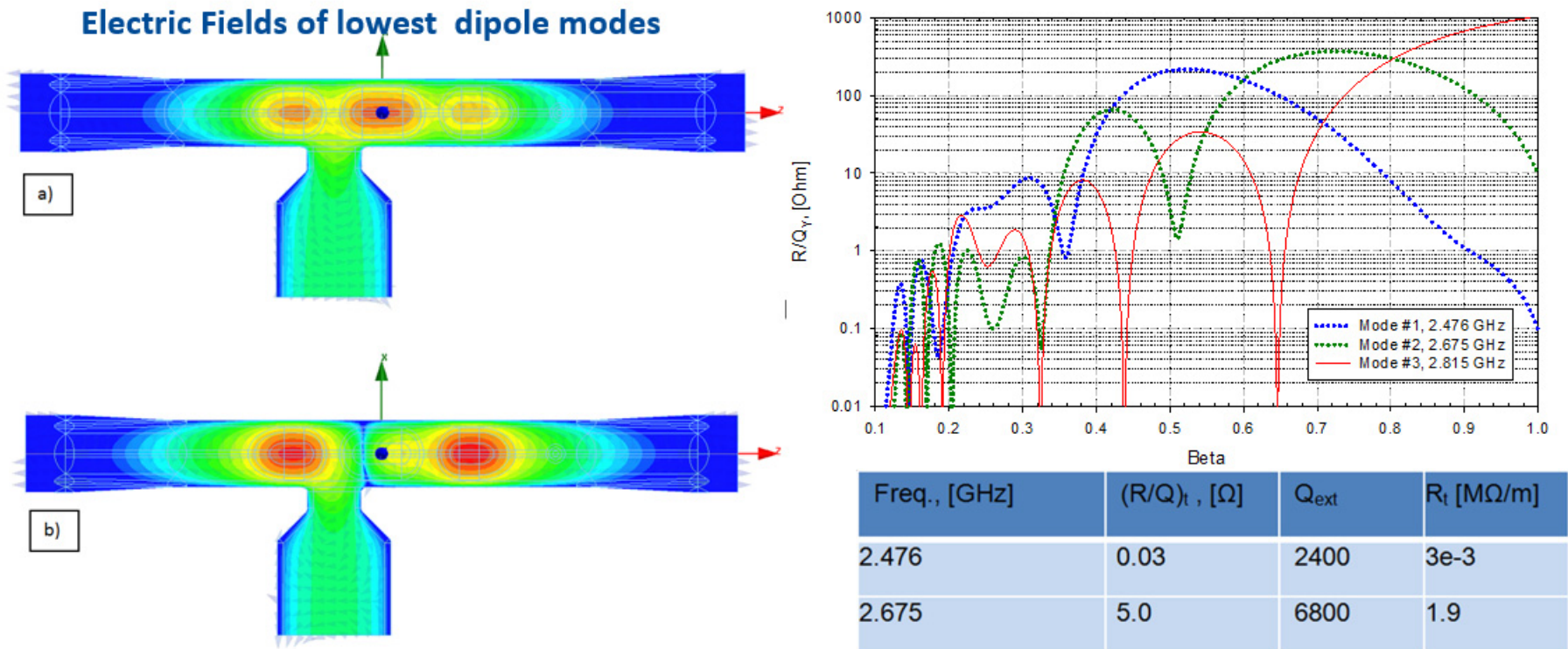Transverse electric (blue) and magnetic (red) field components along the cavity axis.
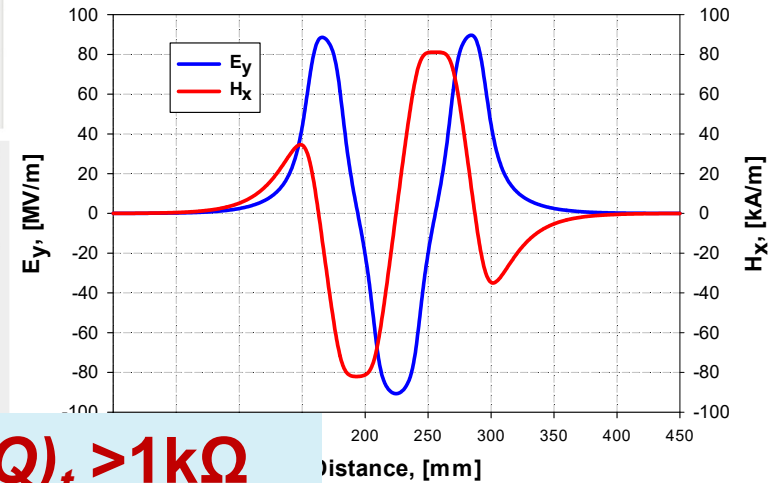
QMiR has a record high $(R/Q)_t$ >1kΩ

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

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Same Order Mode (SOM) Damping

Electric Fields of lowest dipole modes

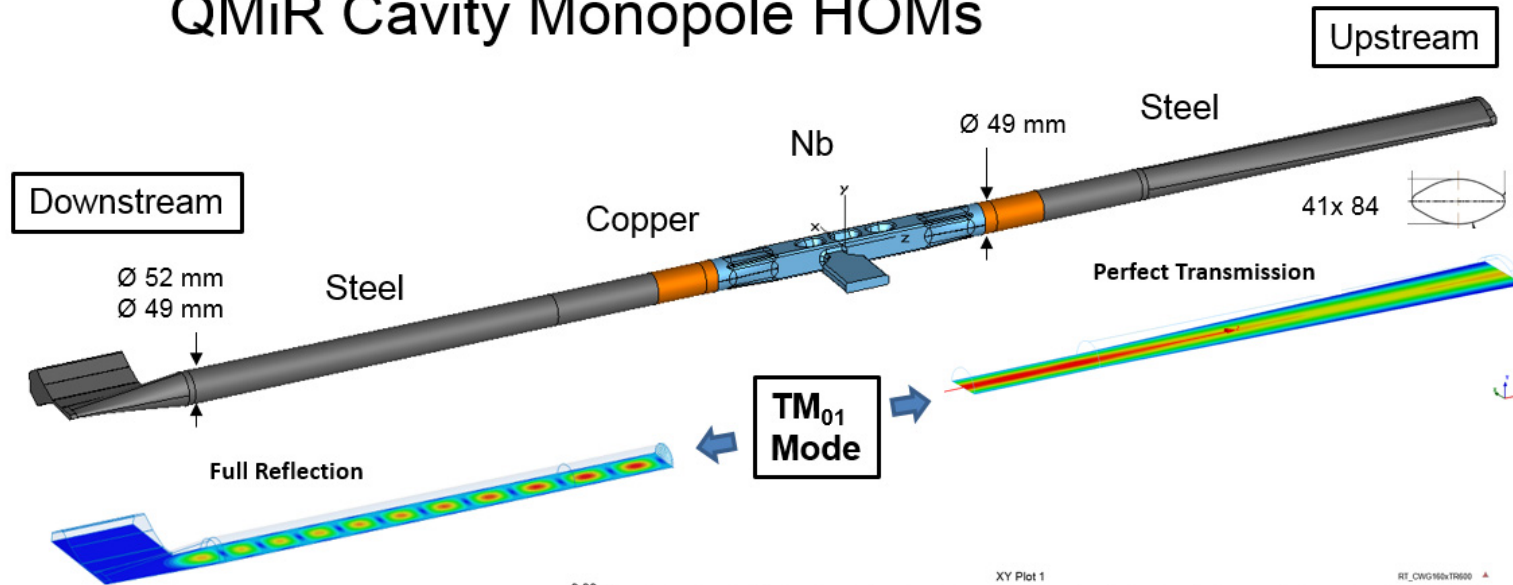| Freq., [GHz]	$(R/Q)_t$, [Ω]	Q_{ext}	R_t [MΩ/m]
2.476	0.03	2400	3e-3
2.675	5.0	6800	1.9

- 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

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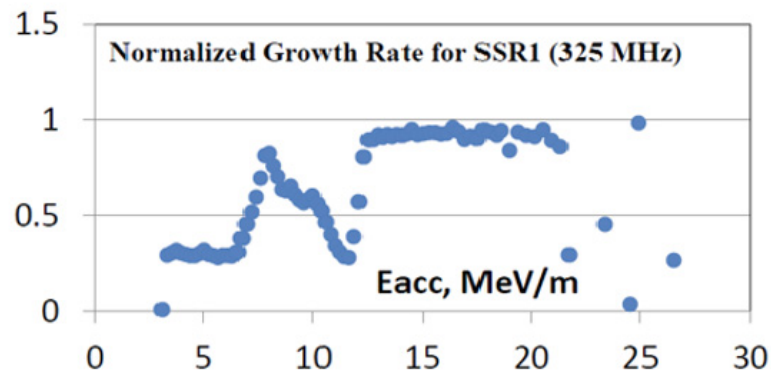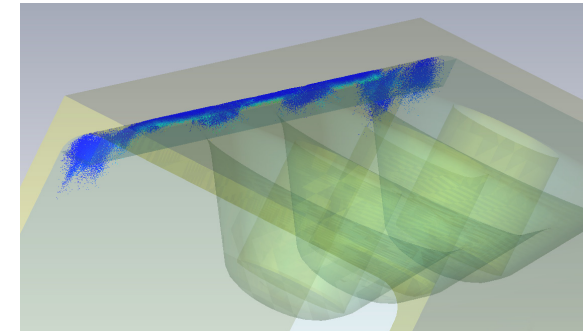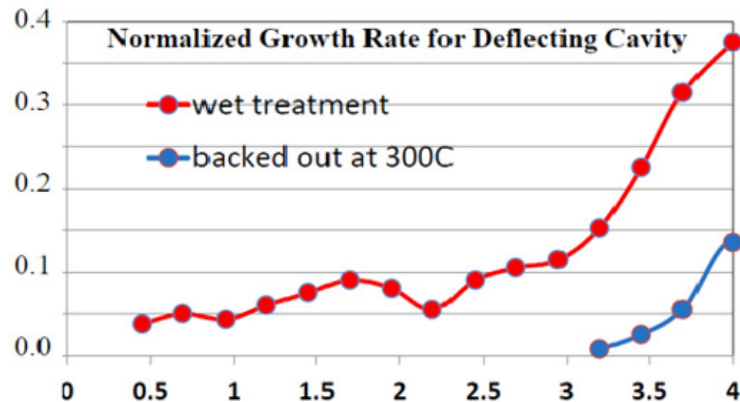
HOM Damping in the APS Ring

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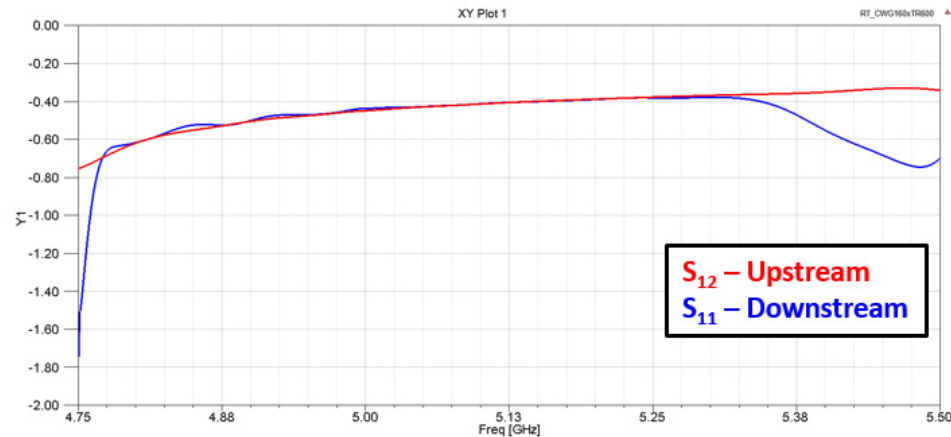
Monopole HOMs RF power is radiated to the Upstream beam pipe !

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Multipactor Analysis in QMiR

Multipactor Simulations with CST Studio

Normalized Growth Rate for Deflecting Cavity
- wet treatment
- backed out at 300C

Normalized Growth Rate for SSR1 (325 MHz)

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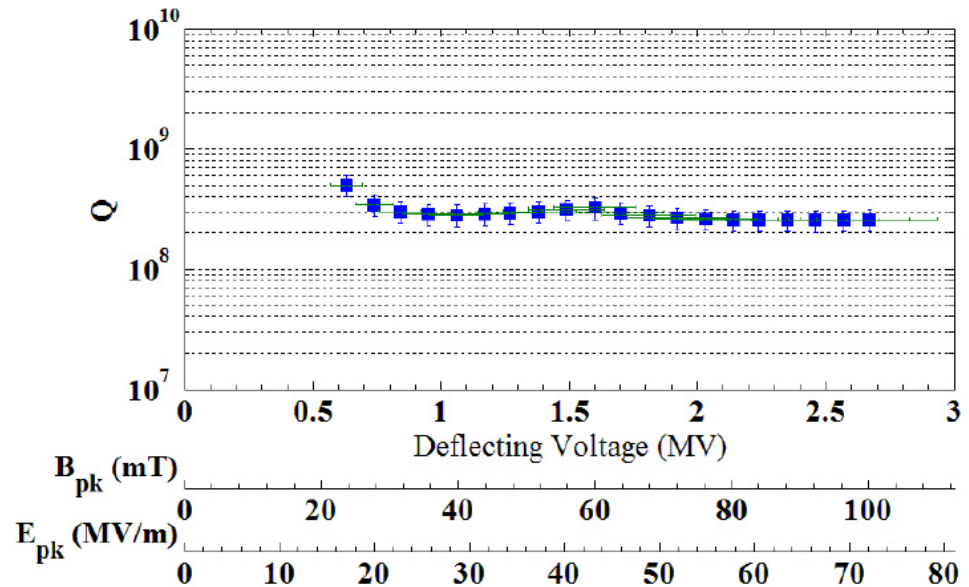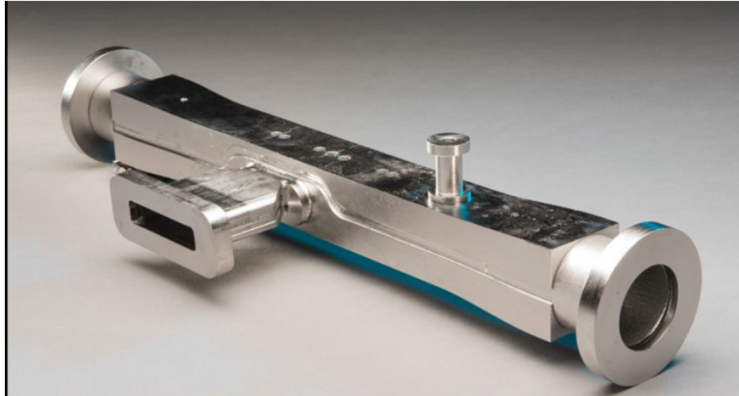
NG Rate in the SSR1 cavity are ~ 10 times higher and MP is successfully processed. QMiR cavity is practically free from MP in the operating RF field domain

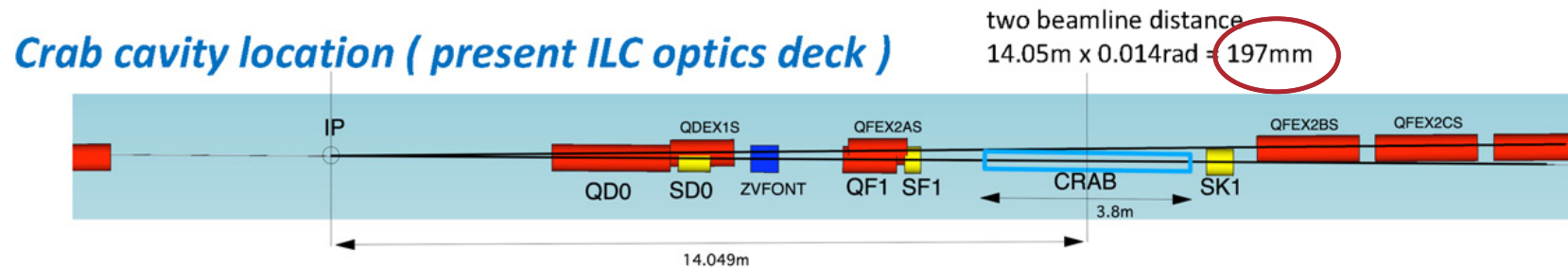**🔷 Fermilab**

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

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QMIR Application for ILC Crab Cavity

Crab cavity location (present ILC optics deck)

two beamline distance
14.05m x 0.014rad = 197mm

IP · QDEX1S · QFEX2AS · QFEX2BS · QFEX2CS

QD0 · SD0 · ZVFONT · QF1 SF1 · CRAB · SK1

3.8m

14.049m

- 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!**

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QMiR Cavity for ILC (scaled to 2.6 GHz)
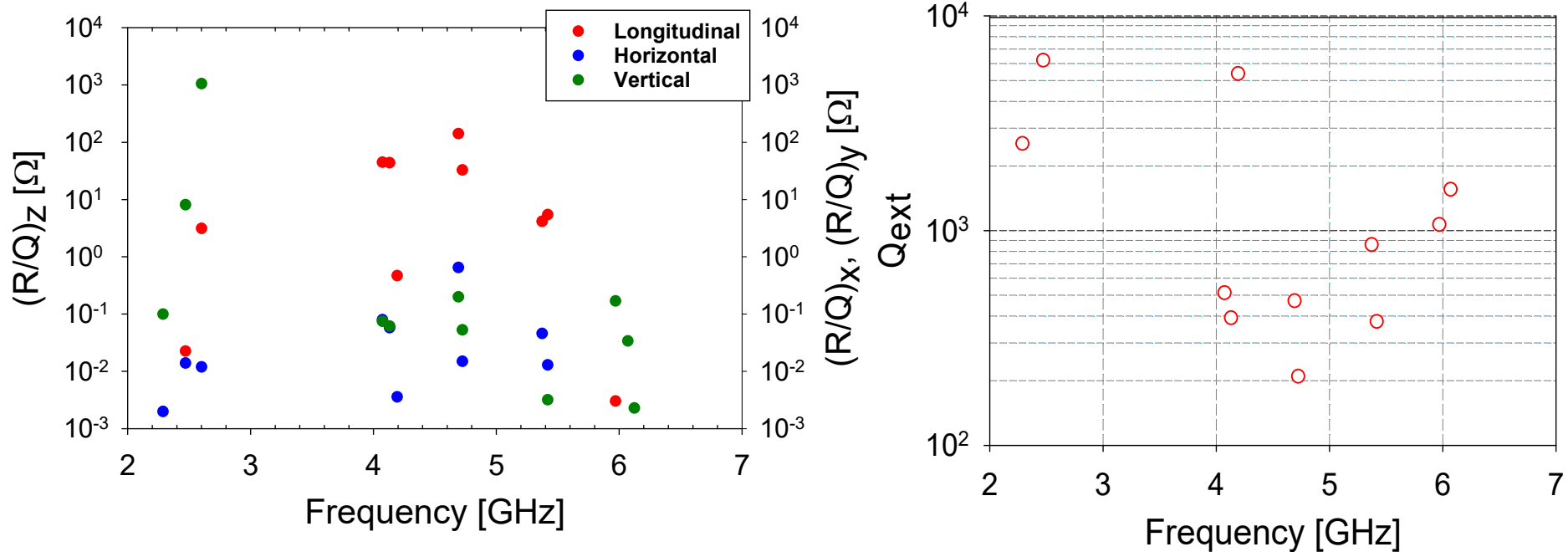
- There are two Same Order Modes (SOM) that have a low *(R/Q)*Q*

- 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**

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Mechanical Analysis LFD and dF/dP (by I. Gonin)
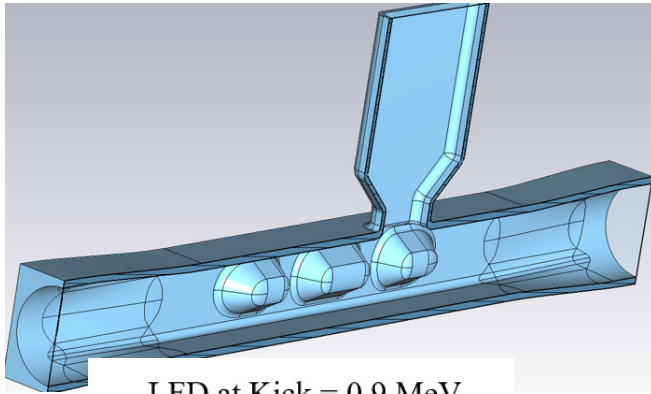
LFD at Kick = 0.9 MeV
Wall thickness 4 mm.
Δf ~ - 495 Hz

LFD < 500 Hz
dF/dP < 100 Hz
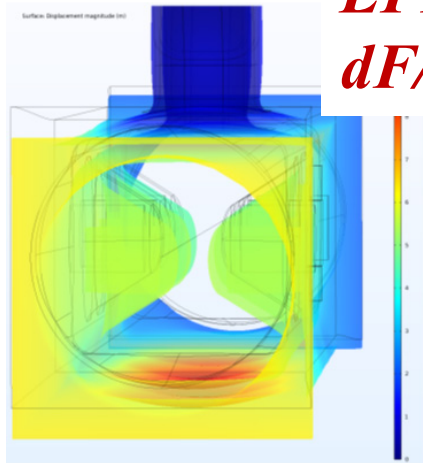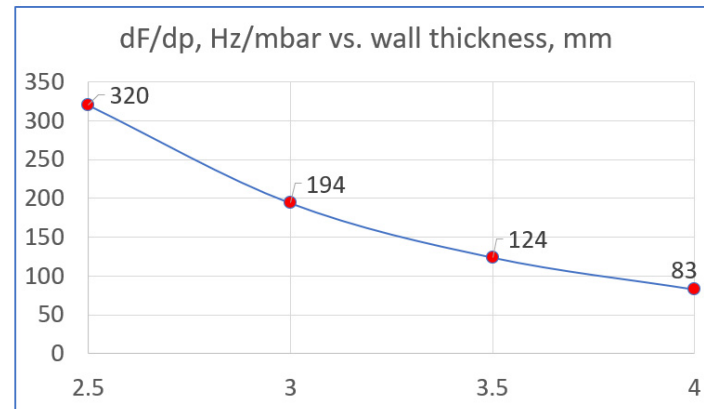

Deformation due to LFD
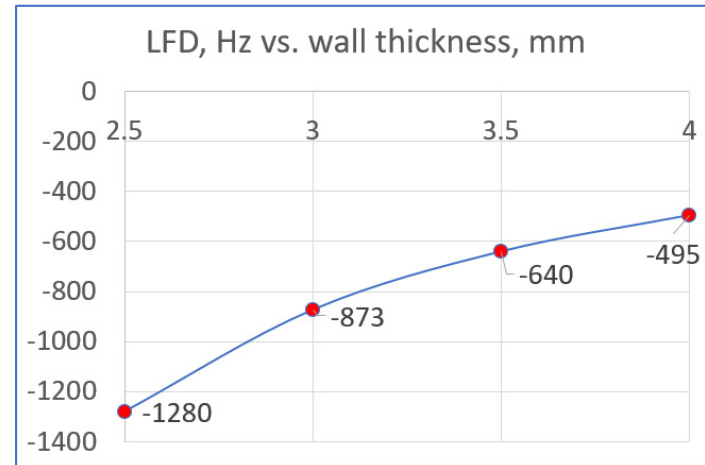
LFD in Hz at Kick = 0.9 MeV vs. cavity wall thickness

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

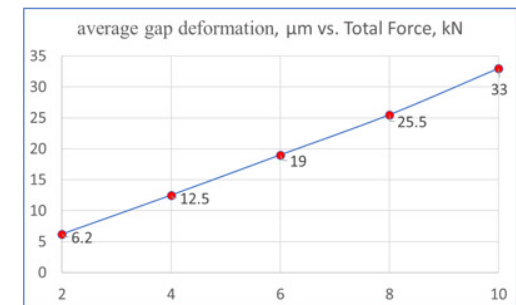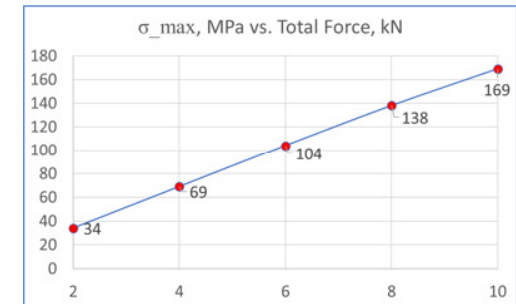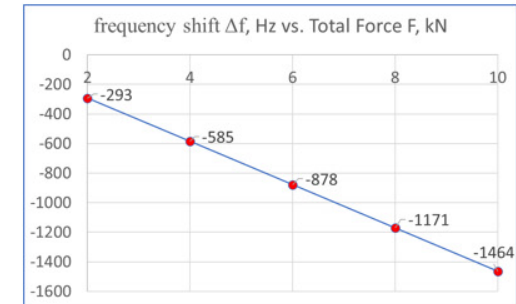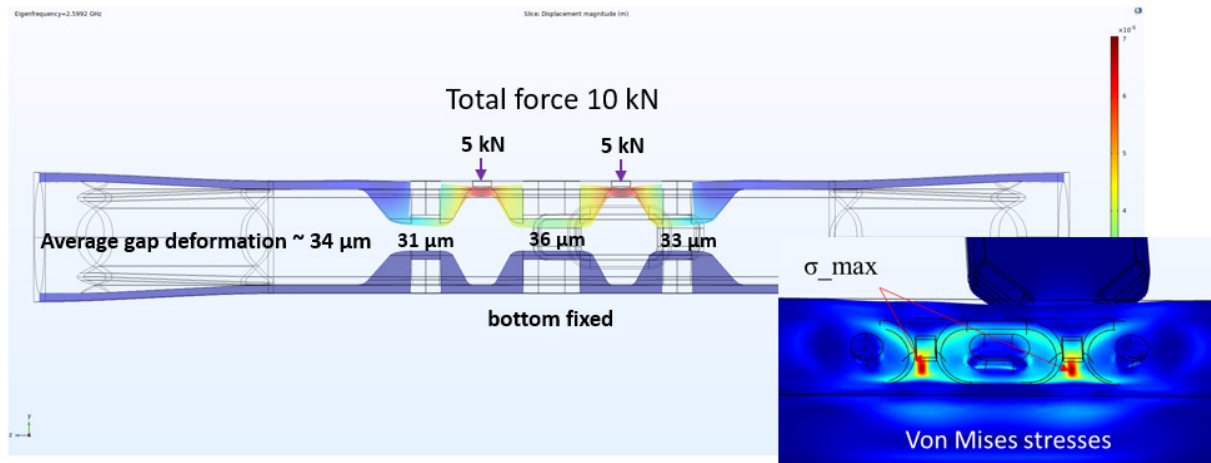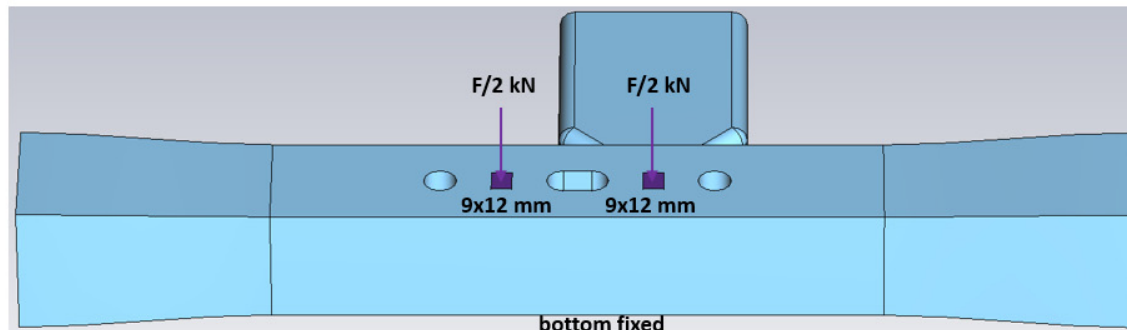- **QMiR LFD and dF/dP are less than the cavity bandwidth (few kHz)**

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Mechanical Analysis of Frequency Tuning (by I. Gonin)

Cavity shell deformations under external force. Wall thickness 4 mm

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

F/2 kN   F/2 kN

9x12 mm   9x12 mm

bottom fixed

Total force 10 kN

5 kN   5 kN

Average gap deformation ~ 34 μm   31 μm   36 μm   33 μm

bottom fixed

σ_max

Von Mises stresses

frequency shift Δf, Hz vs. Total Force F, kN

-293
-585
-878
-1171
-1464

σ_max, MPa vs. Total Force, kN

34
69
104
138
169

average gap deformation, μm vs. Total Force, kN
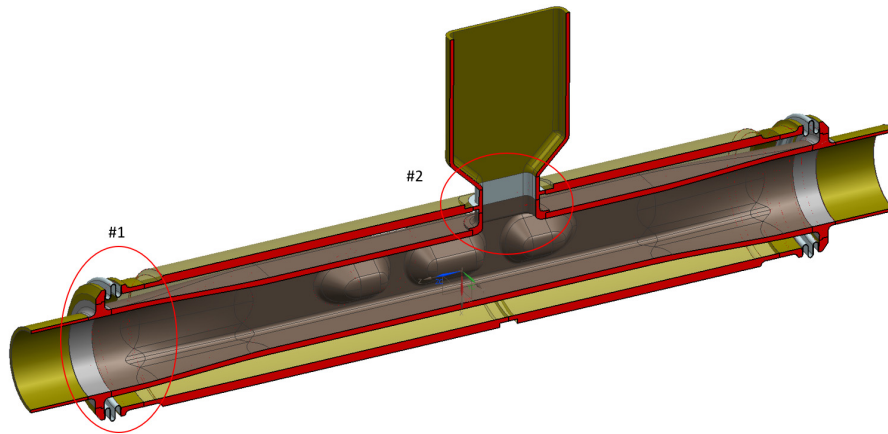
6.2
12.5
19
25.5
33

Maximum frequency tuning range: ~ 1..2 MHz

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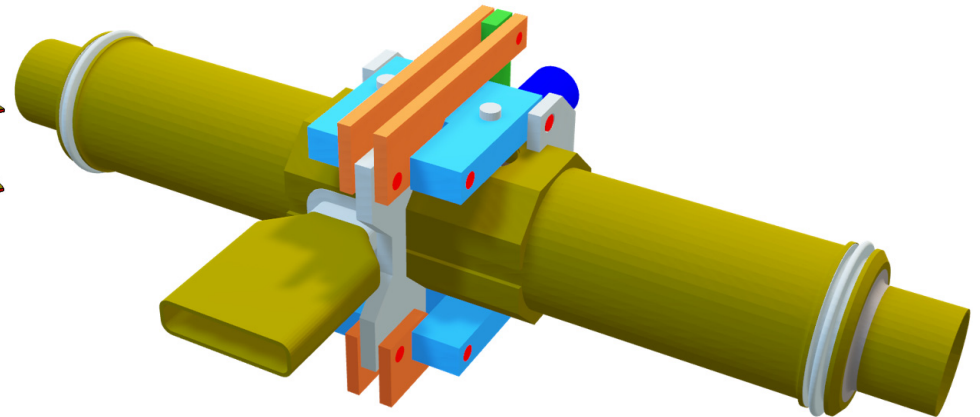
QMiR Cavity Slow Tuner Design (by V. Polubotko)

Compact lever-type frequency tuner
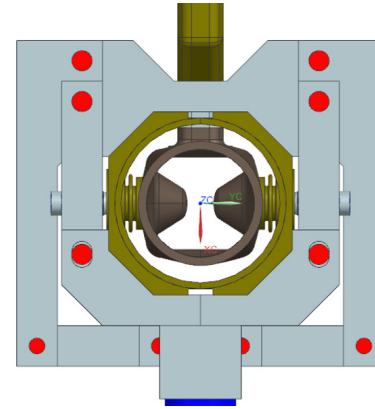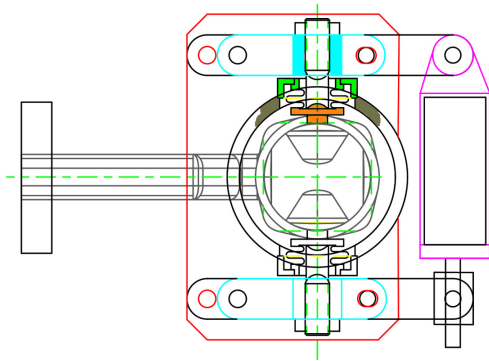
LHe Vessel

Dressed QMiR Cavity

Design of frequency tuner integrated with dressed cavity is ongoing

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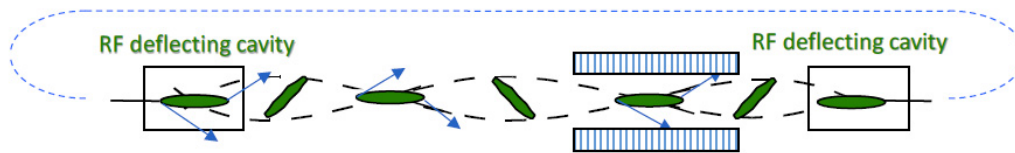# QMiR Cavity for ELLETRA-II Upgrade (ST Trieste)

Original scheme for ANL/SPX[1]

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

SPX 2-Frequency scheme

Two frequencies:
$f_1 = nf_0$,
$f_2 = \left(n + \frac{1}{2}\right)f_0$
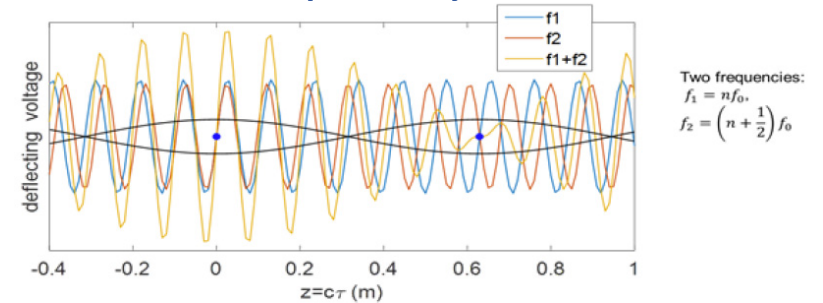
Figure 1-3. Alternating kicked and un-kicked buckets with 2-frequency crab cavities.

Deflecting System for ST Trieste [2]

RF amplifier
Circulator
SOM absorber
Cryostat
RF window
Beam line
BLA (optional)
Cavities
1.5 m
2.0 m

Large aperture

Variant B (3 GHz)

13.9 mm

Low B-field

$B_s \leq 16\ mT$
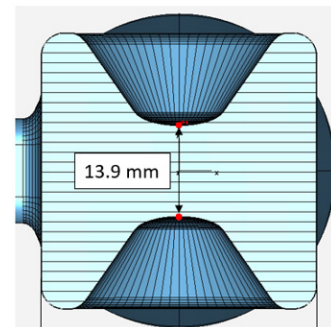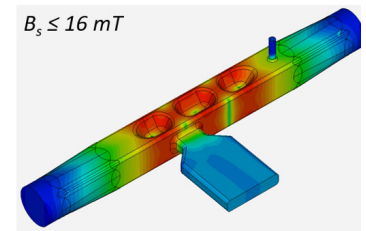
MAC for ST Trieste recommended to proceed with the QMiR type Crab Cavities, 3 GHz and 3.25 GHz for ELLETRA-II upgrade

[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.

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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

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Backup Slides

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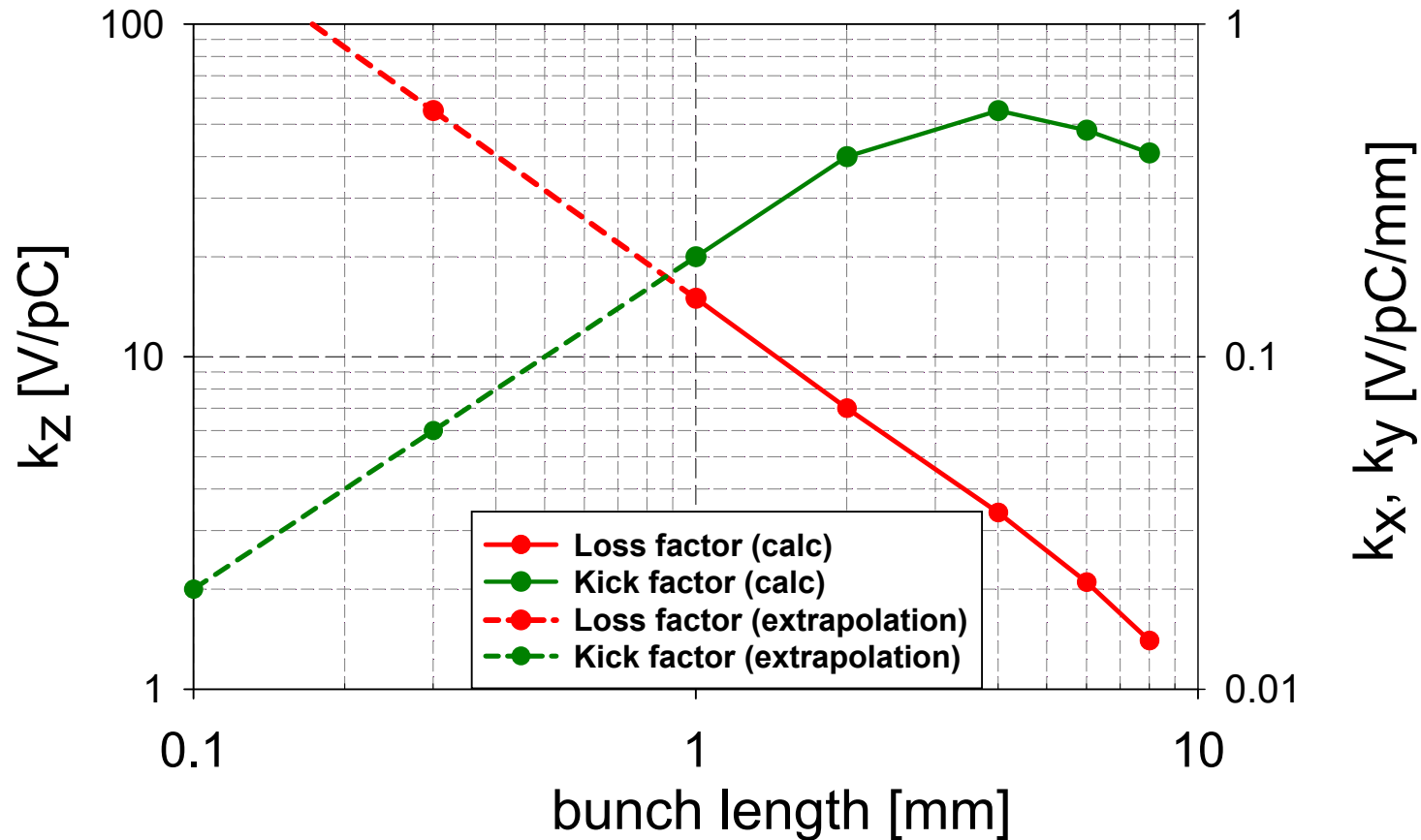
For the ILC bunch length (0.3 mm rms), the loss and kick factors:
k_loss <= 50 V/pC and k_kick <= 0.1 V/pC/mm

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High Order Mode (HOM) Damping

K_{LOSS} = 0.66 V/pC

~ 50 % of HOM RF is radiated downstream

~ 50 % of HOM RF is radiated upstream

Port3: 3 modes →
- TE$_{11-HOR}$
- TE$_{11-VER}$
- TM$_{01}$

Port2: 3 modes

Port1: 1 mode

1

2

3

4

Monopole HOMs

R/Q, [Ω] vs Freq., [GHz]

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

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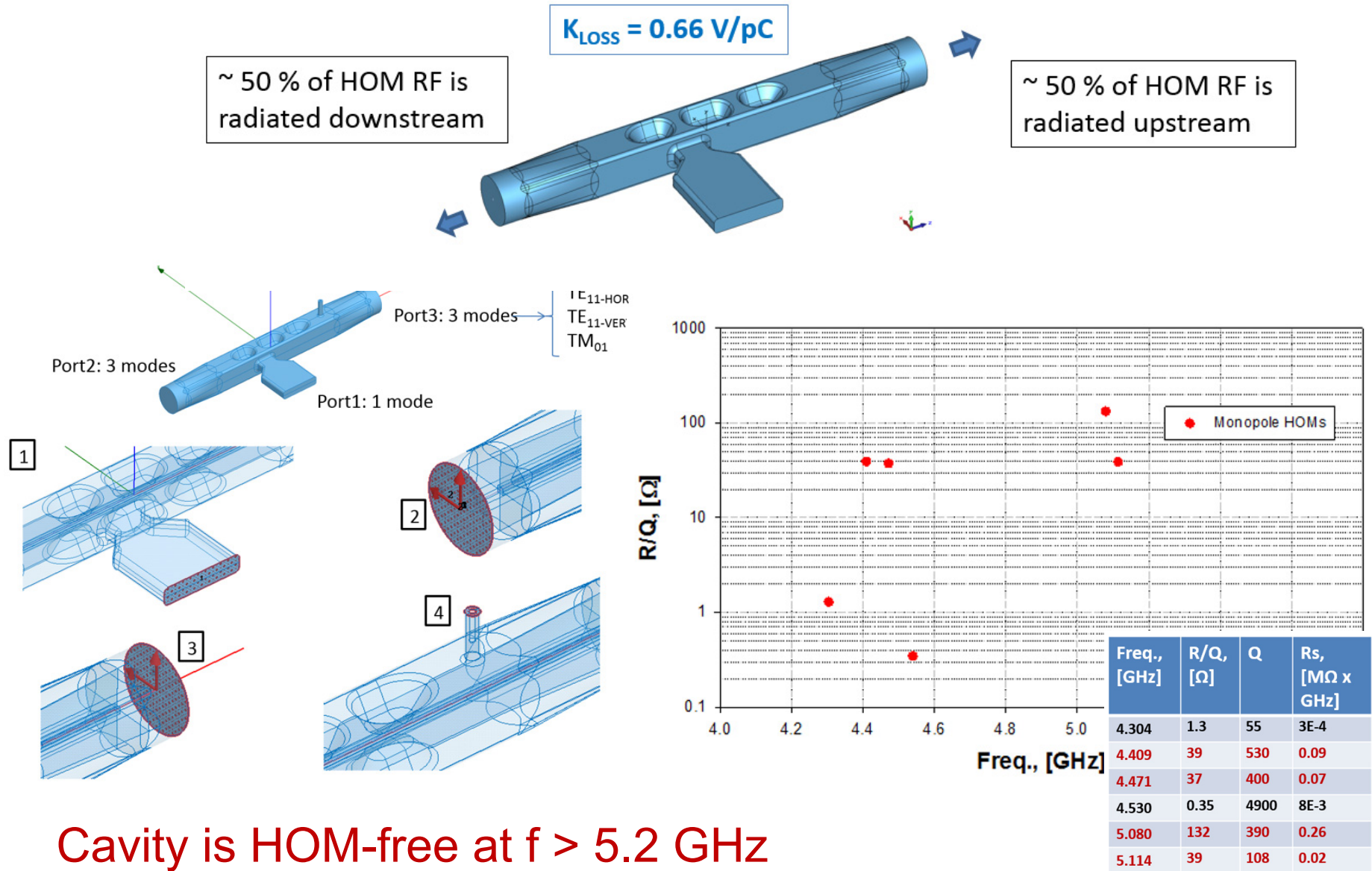
QMiR Cavity for ILC (scaled to 2.6 GHz)

Operation mode $\qquad \left(\frac{r_\perp}{Q}\right) = 1040$ Ohm (@2.6 GHz)

Maximal dipole *horizontal* HOM $\quad \left(\frac{r_\perp}{Q}\right)_x < 10$ Ohm (@2.5 GHz);

$\qquad\qquad\qquad\qquad\qquad\qquad Q < 1 \times 10^5$ ($< Q_{max} \approx 2.4 \times 10^6$)

Maximal dipole *vertical* HOM $\qquad \left(\frac{r_\perp}{Q}\right)_y < 10$ Ohm (@4 GHz);

$\qquad\qquad\qquad\qquad\qquad\qquad Q < 1 \times 10^4$ ($< Q_{max} \approx 1.7 \times 10^6$)

Horizontal kick factor* $\qquad\qquad k_x = 100$ (< 2300) V/pC/m

Vertical kick factor* $\qquad\qquad\quad k_y = 400$ (< 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**

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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:	$P_{min} \approx$ 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

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