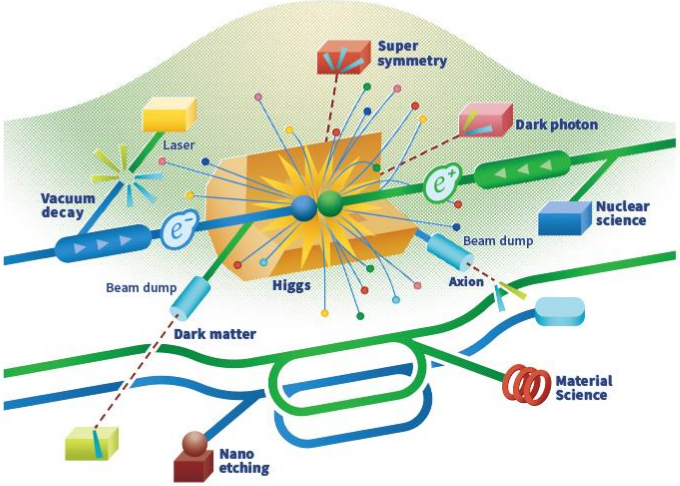
QMiR Crab Cavity for ILC

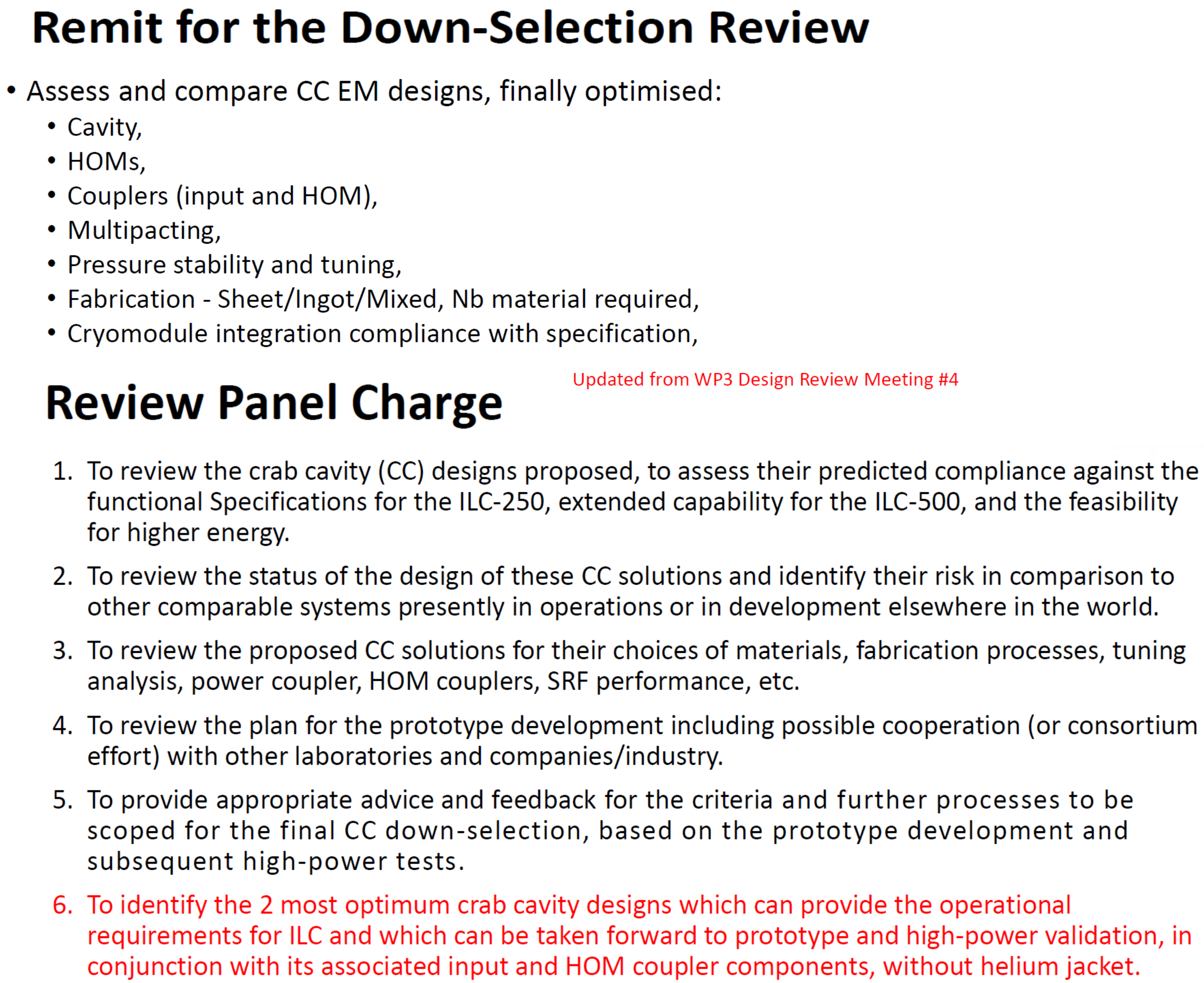
Andrei Lunin, Vyacheslav Yakovlev

April 04-06, 2023

WP3 Crab Cavity Design Down-selection Review



Meeting Goals



Remit for the Down-Selection Review

- Assess and compare CC EM designs, finally optimised:
  - Cavity,
  - HOMs,
  - Couplers (input and HOM),
  - Multipacting,
  - Pressure stability and tuning,
  - Fabrication - Sheet/Ingot/Mixed, Nb material required,
  - Cryomodule integration compliance with specification,

Review Panel Charge

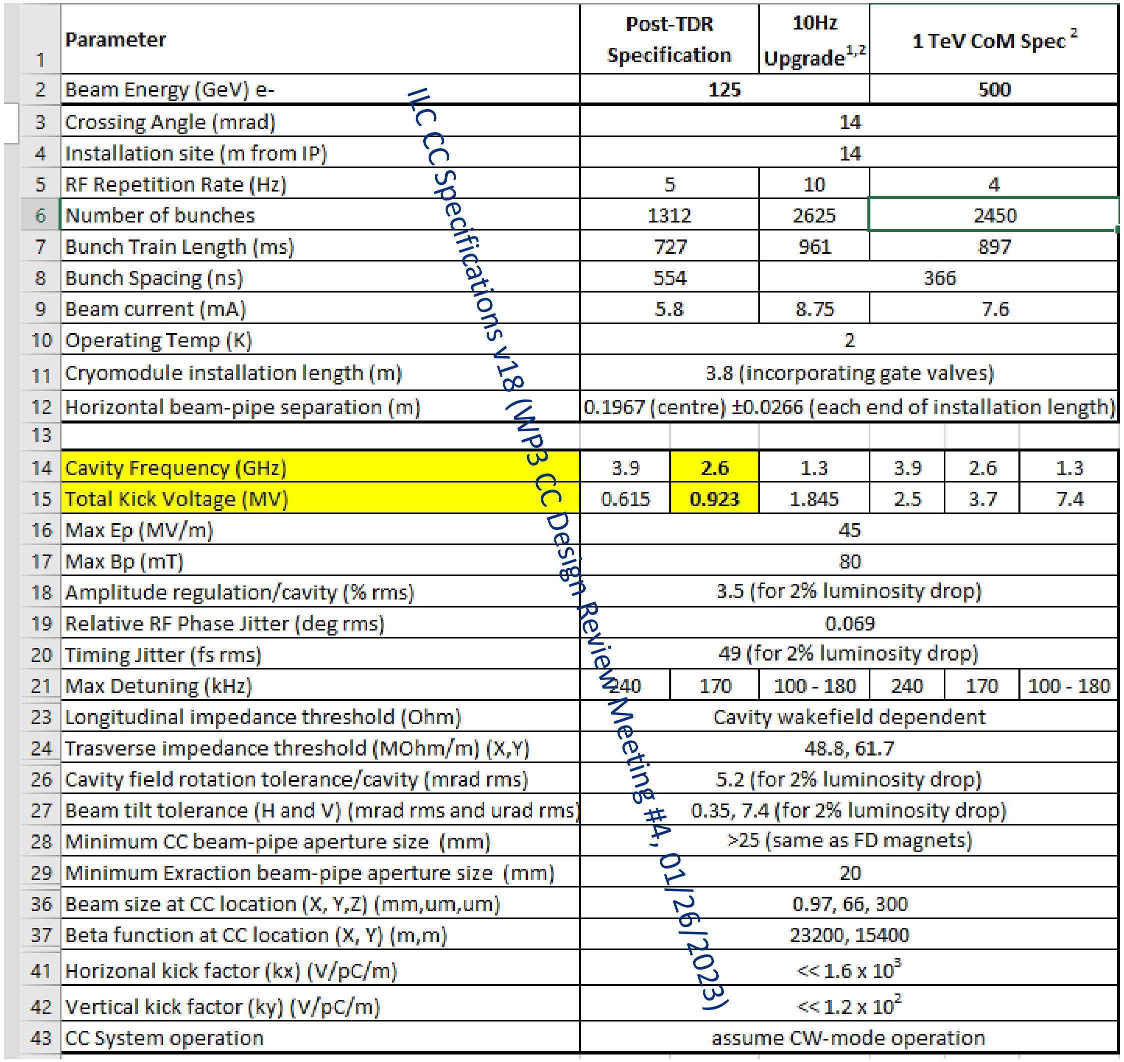
Updated from WP3 Design Review Meeting #4

1. To review the crab cavity (CC) designs proposed, to assess their predicted compliance against the functional Specifications for the ILC-250, extended capability for the ILC-500, and the feasibility for higher energy.
2. To review the status of the design of these CC solutions and identify their risk in comparison to other comparable systems presently in operations or in development elsewhere in the world.
3. To review the proposed CC solutions for their choices of materials, fabrication processes, tuning analysis, power coupler, HOM couplers, SRF performance, etc.
4. To review the plan for the prototype development including possible cooperation (or consortium effort) with other laboratories and companies/industry.
5. To provide appropriate advice and feedback for the criteria and further processes to be scoped for the final CC down-selection, based on the prototype development and subsequent high-power tests.
6. To identify the 2 most optimum crab cavity designs which can provide the operational requirements for ILC and which can be taken forward to prototype and high-power validation, in conjunction with its associated input and HOM coupler components, without helium jacket.

Outline

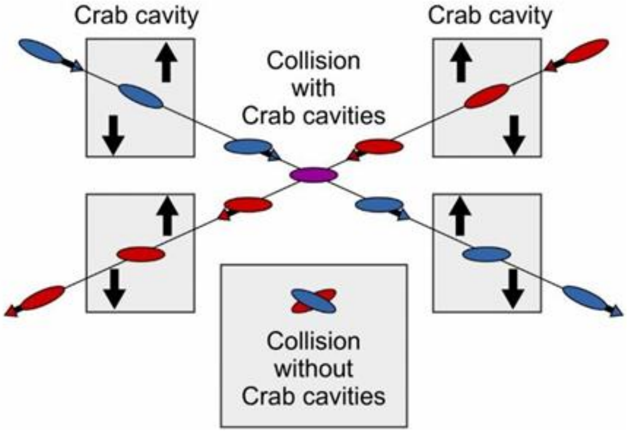
- General Requirements for the ILC Crabbing System
  - Total kick voltage and surface fields
  - HOM impedance and wakefield thresholds
  - Available space limitations
- QMiR Cavity (2.6 GHz) RF Design
  - Electrode profile and surface fields optimization
  - SOM, HOM and Wakefields Simulations
  - Statistical HOM Analysis
  - Cryogenic loss budget and RF power requirements
  - Multipactor analysis
- Cavity Mechanical Design
  - Cavity mechanical simulations (LFD and dF/dP)
  - Frequency Tuner and Dressed Cavity Design
- QMiR Cryomodule Conceptional Design
- Future R&D Plans

Specifications for the ILC Crab Cavities (CC)



	Parameter	Post-TDR Specification		10Hz Upgrade[1,2]	1 TeV CoM Spec[2]			
2	Beam Energy (GeV) e-	125			500			
3	Crossing Angle (mrad)	14						
4	Installation site (m from IP)	14						
5	RF Repetition Rate (Hz)	5		10	4			
6	Number of bunches	1312		2625	2450			
7	Bunch Train Length (ms)	727		961	897			
8	Bunch Spacing (ns)	554		366				
9	Beam current (mA)	5.8		8.75	7.6			
10	Operating Temp (K)	2						√
11	Cryomodule installation length (m)	3.8 (incorporating gate valves)						
12	Horizontal beam-pipe separation (m)	0.1967 (centre) ±0.0266 (each end of installation length)						√
13								
14	**Cavity Frequency (GHz)**	3.9	**2.6**	1.3	3.9	2.6	1.3	
15	**Total Kick Voltage (MV)**	0.615	**0.923**	1.845	2.5	3.7	7.4	√
16	Max Ep (MV/m)	45						√
17	Max Bp (mT)	80						
18	Amplitude regulation/cavity (% rms)	3.5 (for 2% luminosity drop)						
19	Relative RF Phase Jitter (deg rms)	0.069						
20	Timing Jitter (fs rms)	49 (for 2% luminosity drop)						
21	Max Detuning (kHz)	240	170	100 - 180	240	170	100 - 180	√
23	Longitudinal impedance threshold (Ohm)	Cavity wakefield dependent						
24	Trasverse impedance threshold (MOhm/m) (X,Y)	48.8, 61.7						√
26	Cavity field rotation tolerance/cavity (mrad rms)	5.2 (for 2% luminosity drop)						
27	Beam tilt tolerance (H and V) (mrad rms and urad rms)	0.35, 7.4 (for 2% luminosity drop)						
28	Minimum CC beam-pipe aperture size (mm)	>25 (same as FD magnets)						√
29	Minimum Exraction beam-pipe aperture size (mm)	20						
36	Beam size at CC location (X, Y,Z) (mm,um,um)	0.97, 66, 300						
37	Beta function at CC location (X, Y) (m,m)	23200, 15400						
41	Horizonal kick factor (kx) (V/pC/m)	<< 1.6 x 10^3						√
42	Vertical kick factor (ky) (V/pC/m)	<< 1.2 x 10^2						
43	CC System operation	assume CW-mode operation						√

ILC CC Specifications v18 (WP3 CC Design Review Meeting #4, 01/26/2023)

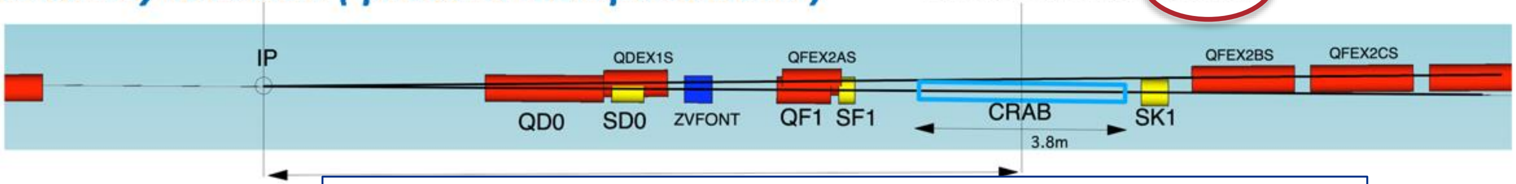


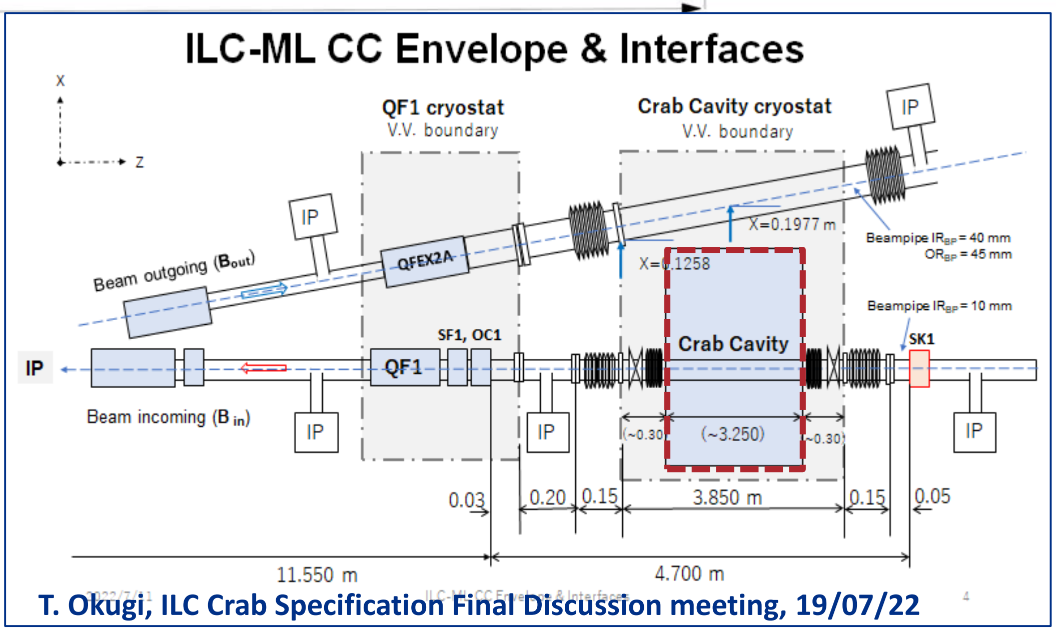
- **ILC CC key specifications adopted**
- **QMiR Cavity meets ALL SPECs (to be continued)**

Space Requirements for the ILC Crabbing System

Crab cavity location (present ILC optics deck)

two beamline distance
14.05m x 0.014rad = 197mm





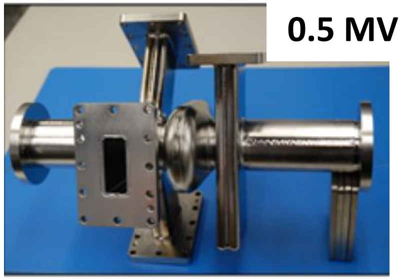
ILC-ML CC Envelope & Interfaces

T. Okugi, ILC Crab Specification Final Discussion meeting, 19/07/22

- **The available space for ILC/CC system is limited**
- **The kick voltage is inverse proportional to frequency ($V_t \sim f^{-1}$)**
- **Crab cavity @2.6 GHz looks like a good compromise to provide the necessary kick and fit into the space**

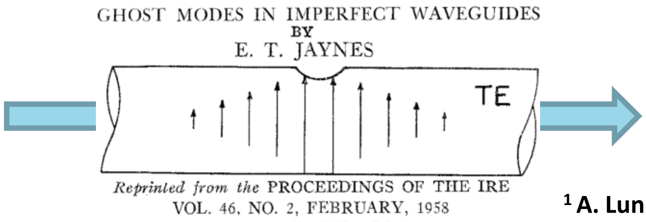
Superconducting Quasi-Waveguide Multicell Resonator (QMiR) for the Advanced Photon Source SPX Project

Original ANL deflecting cavity



0.5 MV kick

The idea

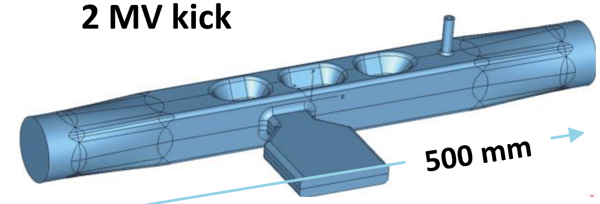


GHOST MODES IN IMPERFECT WAVEGUIDES
BY
E. T. JAYNES

Reprinted from the PROCEEDINGS OF THE IRE
VOL. 46, NO. 2, FEBRUARY, 1958
PRINTED IN THE U.S.A.

QMiR deflecting cavity[1,2]

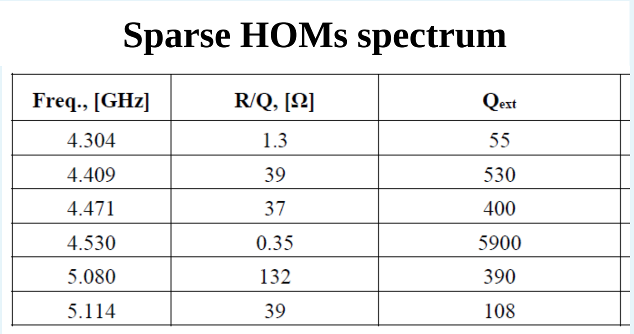
2 MV kick



[1] A. Lunin, et. al., Physics Procedia Vol. 79, 54 –62, 2015

[2] Z. Conway, et. al., WEPR050, IPAC14, Dresden, Germany, 2014

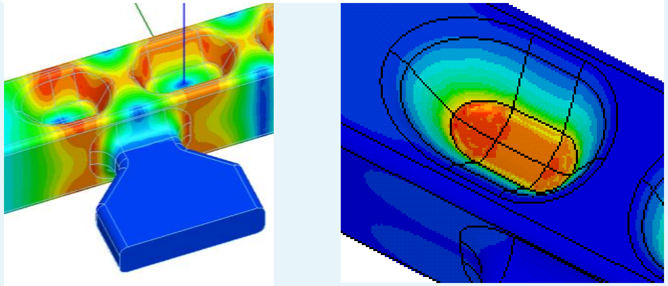
Sparse HOMs spectrum



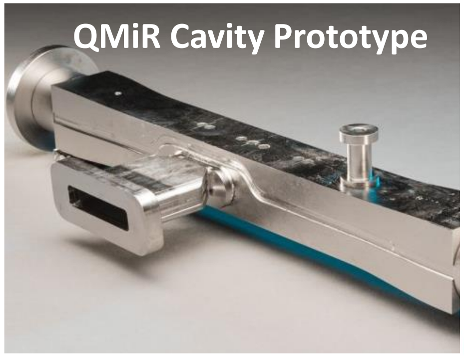
Freq., [GHz]	R/Q, [Ω]	Q_{ext}
4.304	1.3	55
4.409	39	530
4.471	37	400
4.530	0.35	5900
5.080	132	390
5.114	39	108

Freq	2815 MHz
V_{kick}	2 MV
E_{max}	55 MV/m
B_{max}	76 mT
$(R/Q)_Y$	1 kΩ
G	130

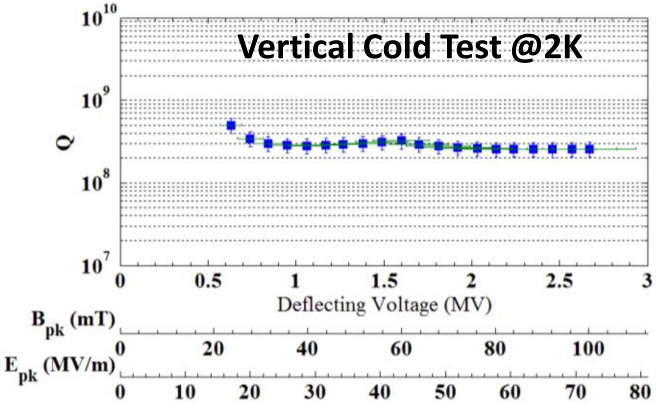
Highly optimized surface EM-fields



- ✓ High efficiency single cavity
- ✓ Simple and compact
- ✓ NO HOM-couplers (!)
- ✓ Sparse, low-Q HOMs
- ✓ NO issues with SOM
- ✓ Simple WG coupler



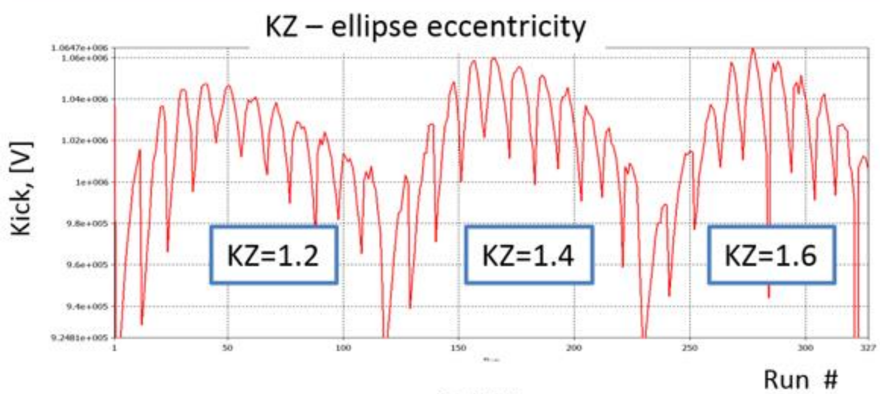
QMiR Cavity Prototype

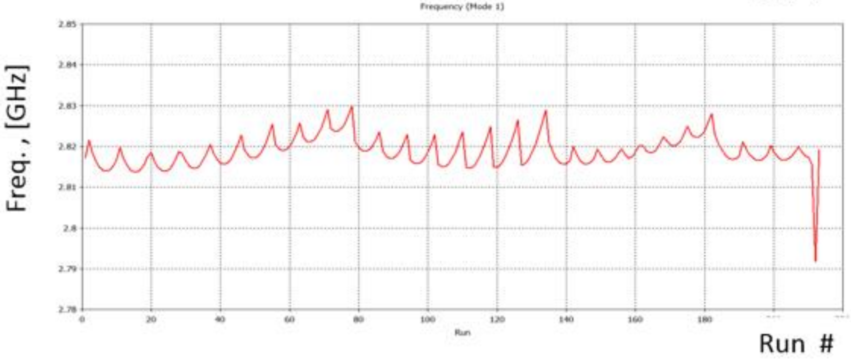


Vertical Cold Test @2K

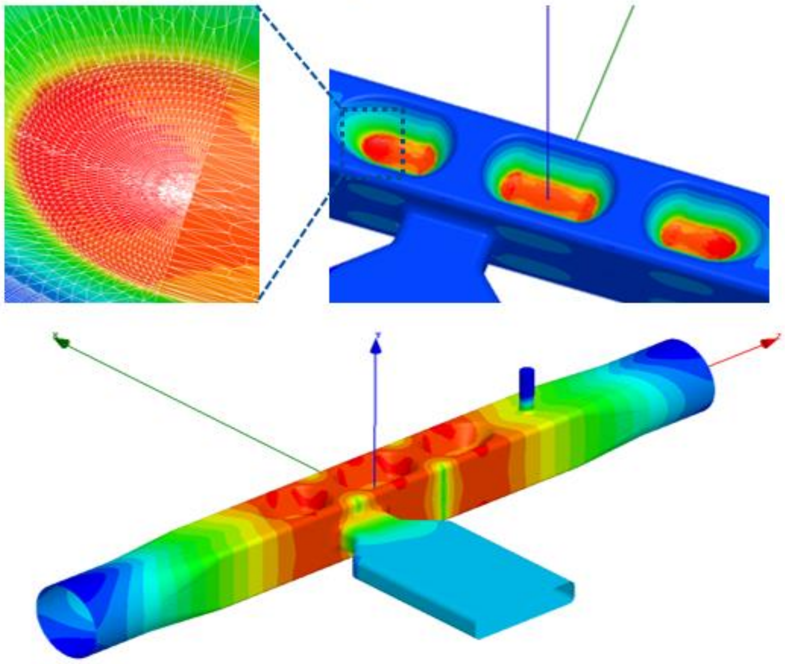
- **World record in VTS test : 2.7 MV kick, no quench, no MP**

QMiR Cavity EM Design





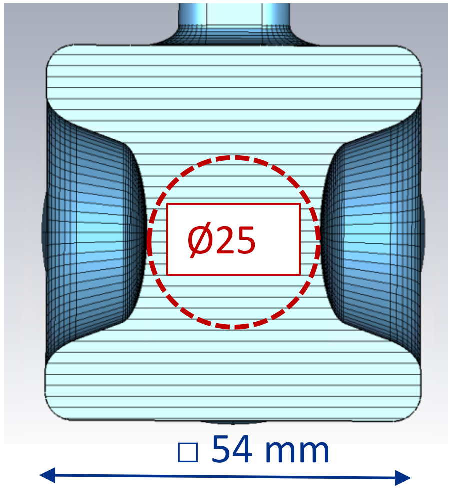
Operating trapped mode surface electric (up) and magnetic (down) fields



- ✓ **Fully parametrized model**
- ✓ **General ellipsoid geometry of the electrodes**
- ✓ **Frequency derivations pre-calculated for each parameter**
- ✓ **Operating mode frequency preserved constant**
- ✓ **Global optimum search algorithm (~10k variations)**

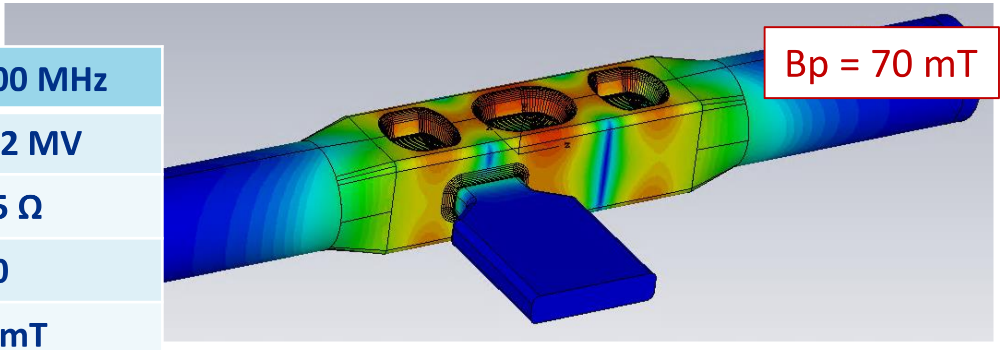
QMiR Cavity for ILC (2.6 GHz with increased aperture)

ILC Crab Cavity Aperture Limit: Ø25 mm

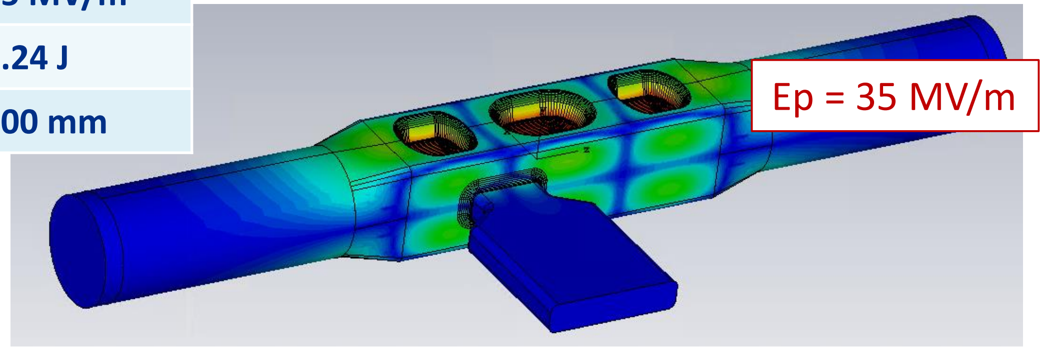


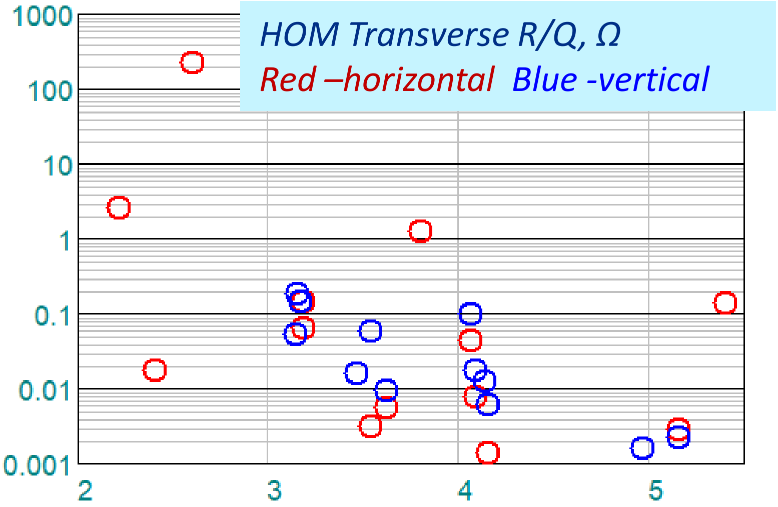
Freq	2600 MHz
V_{kick}	0.92 MV
$(R/Q)_t$	225 Ω
G-factor	160
Bp, max	70 mT
Ep, max	35 MV/m
W_{STORED}	0.24 J
Length	500 mm

Surface Magnetic Field



Surface Electric Field





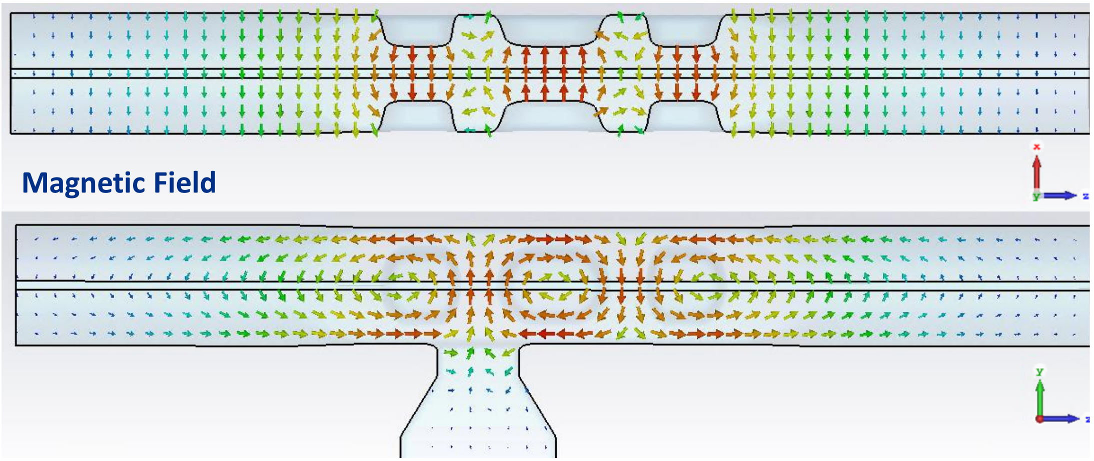
QMiR KEY FACTS

- ✓ **Low surface fields**
- ✓ **Strong SOM and HOM damping to WG and BP ports**
- ✓ **HOM spectrum is sparse with low R/Q and Q**
- ✓ **4 QMiR cavities can provide 3.7 MV Kick (1 TeV option)**

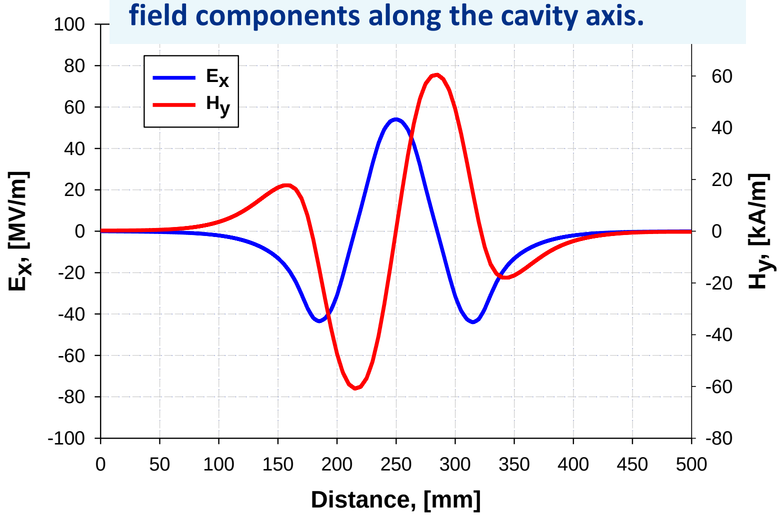
Operating Dipole Mode

Electric Field

Magnetic Field



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



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)

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

(R/Q)	
$(R/Q)_Z$ @r_0= 1 mm	0.68 Ω
$(R/Q)_X$, LF	223 Ω
$(R/Q)_X$, PW	225 Ω
$(R/Q)_Y$, PW	8E-6 Ω

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 1.3 GHz Nb cavities (XFEL, LCLS-II)

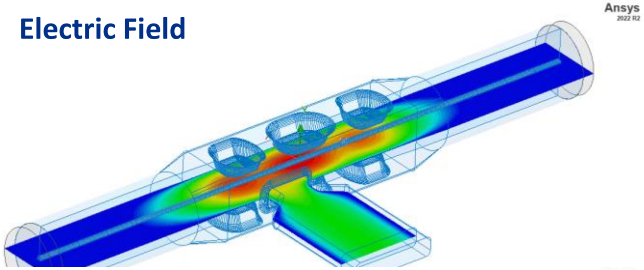
Material	Q0 @2K & 70mT	
	VTS	CM
Nb		> 1E10
Nb, N-dopped		> 3E10

Expected Surface Resistance and 2K Cryo-load

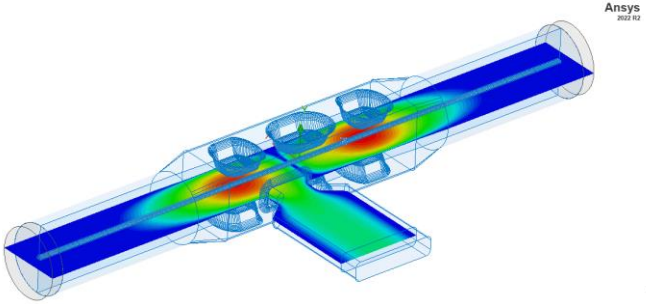
Material	Rs, nΩ	CW-operation
		P_C , W
Nb	< 120	< 2.7
Nb, N-dopped	< 40	< 1

- **We consider CW RF operation of the cavity with pulsed beam**
- **QMiR nominal cryo-load is expected to be as low as 1W with N-doping Nb treatment**

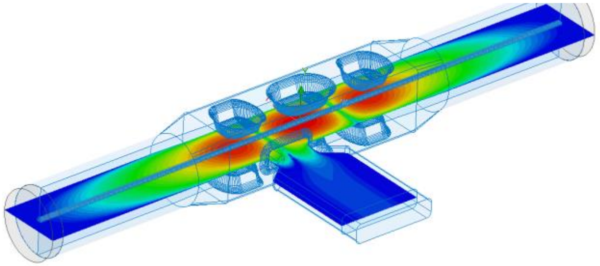
Same Order Modes (SOM) Damping



1^{st} Dipole SOM
F = 2.210 GHz
QE = 4300
$(R/Q)_t$ = 2.5 Ω



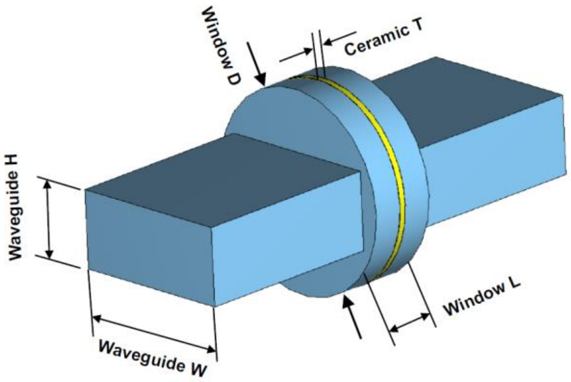
2^{nd} Dipole SOM
F = 2.400 GHz
QE = 7400
$(R/Q)_t$ = 0.02 Ω



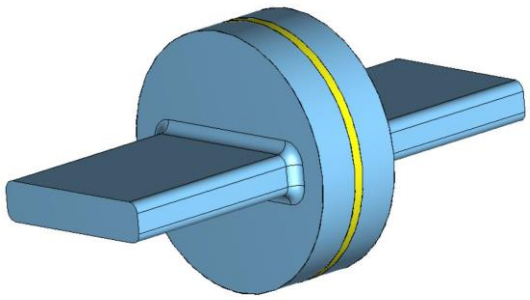
3^{rd} Dipole SOM
F = 2.600 GHz
QE = 1.3E6
$(R/Q)_t$ = 225 Ω

- **SOM are coupled to the input waveguide port**
- **The input coupler shall not compromise the SOM coupling**

Design of the Input Ceramic RF Window (by S. Kazakov)

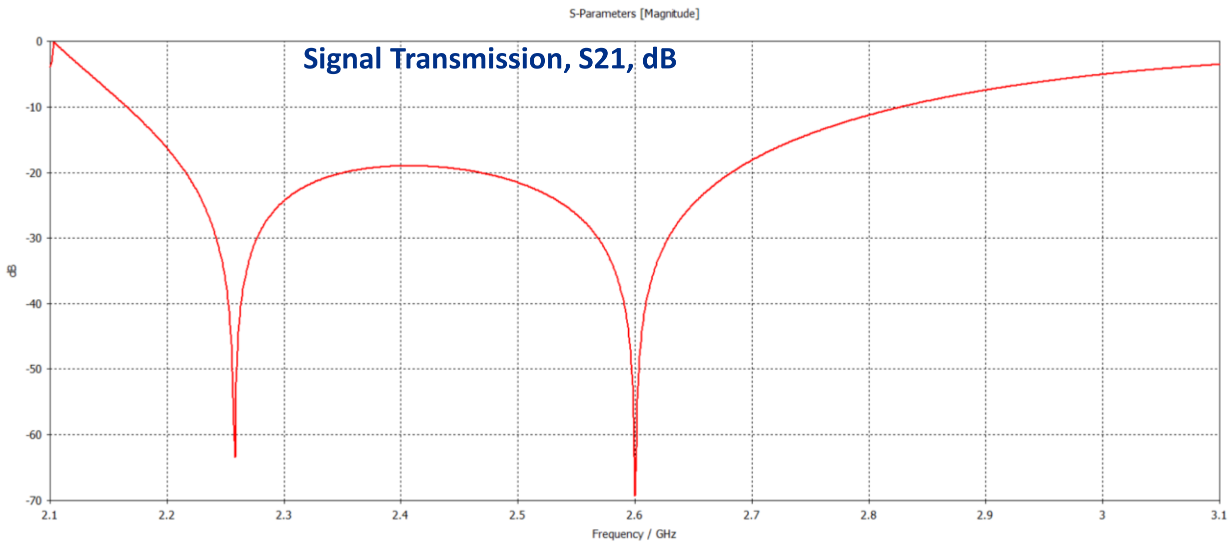


Parameter	Value, mm
Window D	83
Window L	35.2
Ceramic T	4
Ceramic Eps	9.8
Waveguide W	71.14
Waveguide H	16

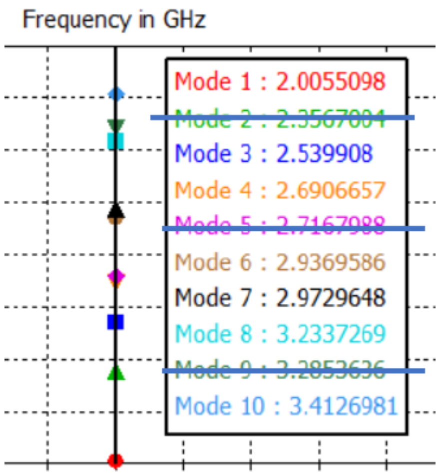


CC Window, waveguide 16mm.

S. Kazakov, 02/21/2023



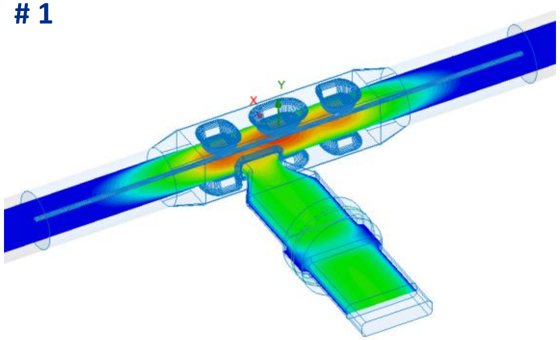
Ghost Modes in Ceramic



- **Pillbox cylindrical λ/2 RF window**
- **Coupler “-10 dB” bandwidth > 650 MHz**

SOM Damping with Input RF Coupler

1



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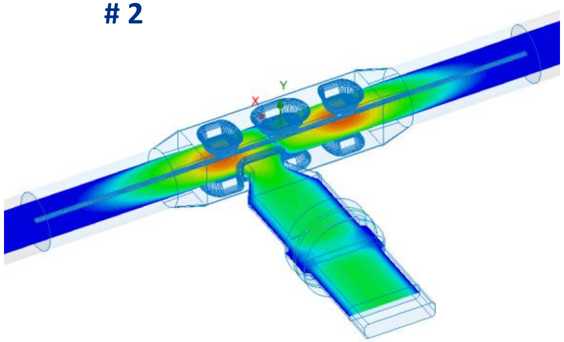

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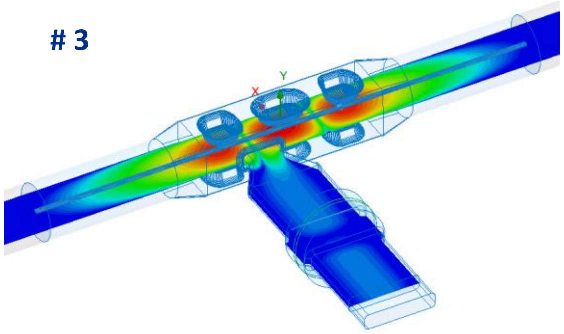
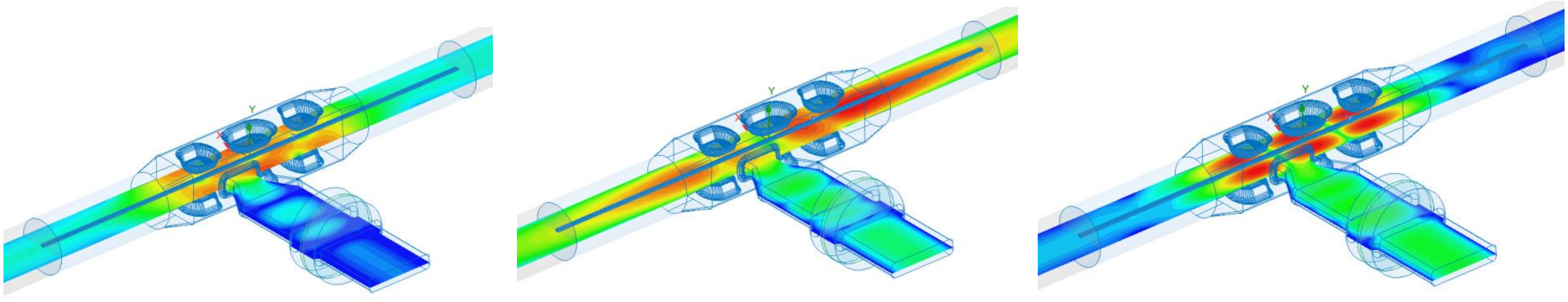


SOM #	External Coupling, QE	
	w/o coupler	with coupler
1	4300	6000
2	7400	8400
3	1.3E6	1.3E6

- Broadband design of the input ceramic window provides SOM coupling QE < 1E4

High Order Modes (HOM) Analysis

HOM with the highest quality factor



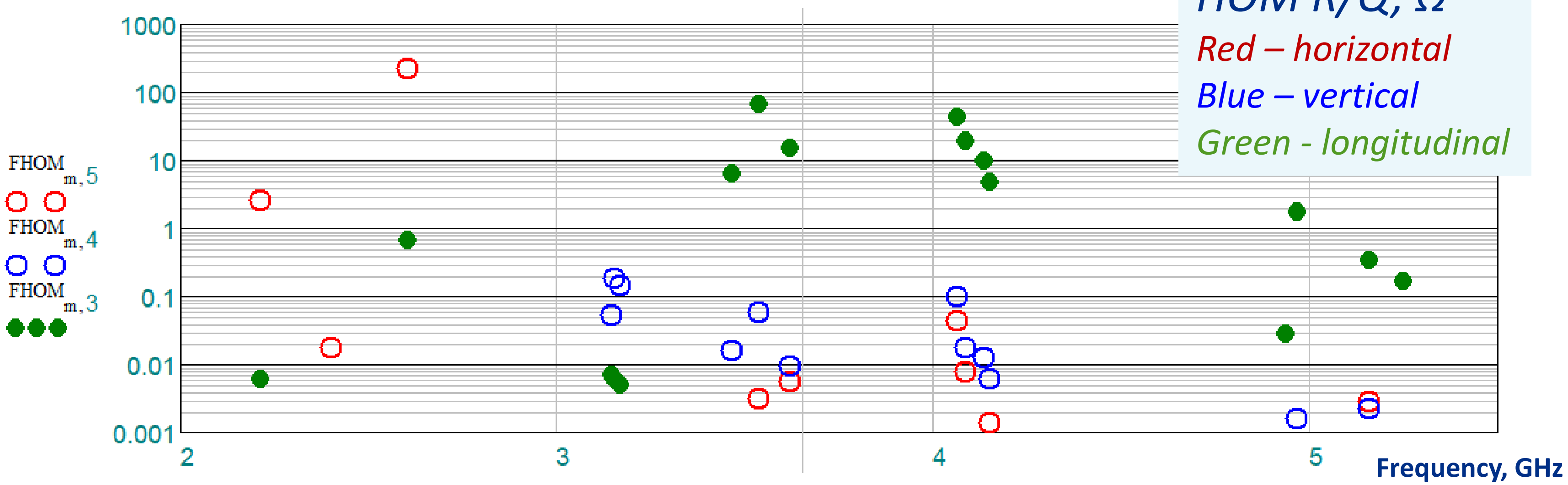
Monopole HOM
F = 3.617 GHz
QE = 4.3E4
$(R/Q)_Z$ = 15.6 Ω

Monopole HOM
F = 4.085 GHz
QE = 12.3E4
$(R/Q)_Z$ = 20 Ω

Quadruple HOM
F = 5.112 GHz
QE = 5.5E4
$(R/Q)_t$ = 1E-4 Ω

- Only 20 HOMs with QE > 100 below 6 GHz frequency
- Maximum HOM QE < 6E4
- Maximum dipole HOMs $(R/Q)_t < 0.2$ Ω
- Monopole HOMs are mostly loaded the beam-pipe

QMiR HOM Spectrum Summary

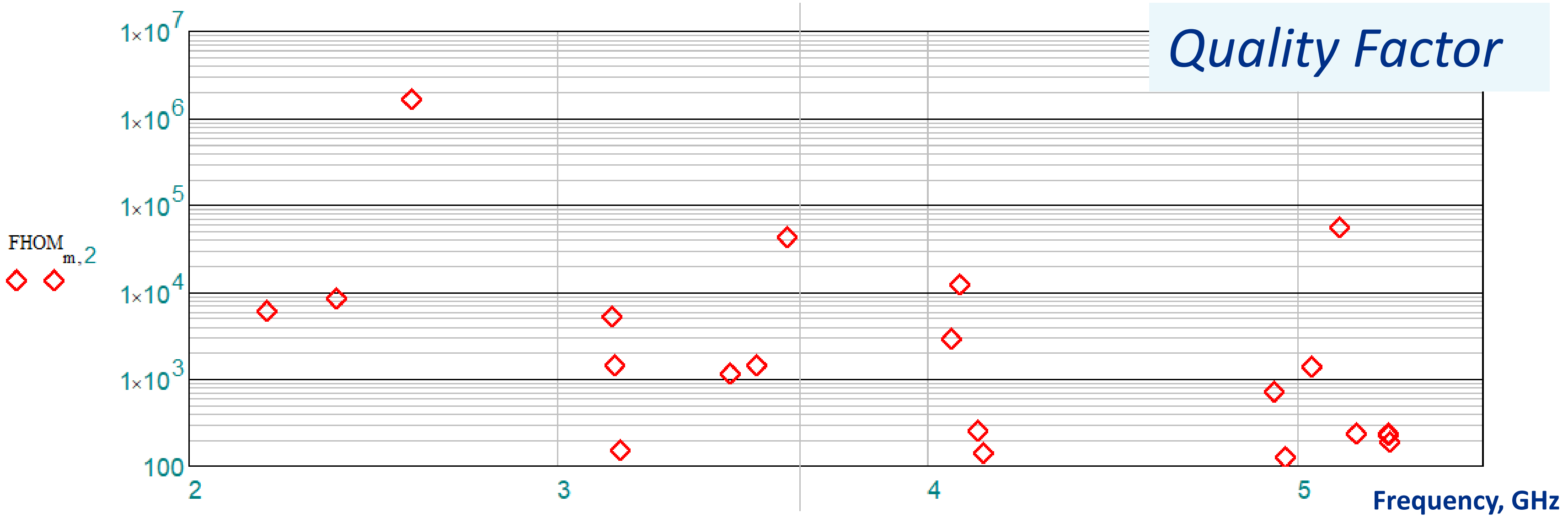


HOM R/Q, Ω

Red – horizontal

Blue – vertical

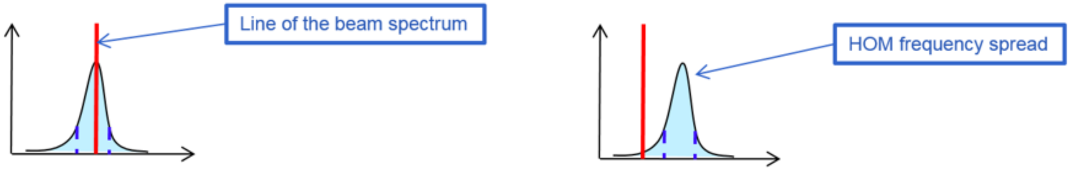
Green - longitudinal



Quality Factor

QMiR HOM Resonant Beam Excitation

Stochastic HOM excitation by the pulsed beam*



* A. Lunin, et. al., Phys. Rev. Accel. Beams **21**, 022001

Resonant steady-state HOM power and transverse voltage

$$\langle P\rangle_{max} = \frac{(R_{\parallel}/Q)\omega_0 q_0^2}{4t_b}\left(\frac{e^{\alpha}+1}{e^{\alpha}-1}\right), \qquad |V_{\perp}|_{max}^{r=r_0} = \frac{(R_{\perp}/Q)\omega_0 q_0 r_0 k}{4}\left(\frac{e^{\alpha}+1}{e^{\alpha}-1}\right)$$

where $\alpha = t_b/\tau$, t_b is the bunch spacing, $\tau = 2Q_L/\omega_0$ is the HOM signal decay time,

Resonant excitation condition: $t_b << \tau$ ------> $Q >> t_b\omega_0/2$

For ILC beam: t_b = 550 ns and **$Q_{RESONANT}$ > 5000**

- **NO high-Q resonant excitation of HOMs with QL < 1E4**

QMiR HOM Spectrum Summary

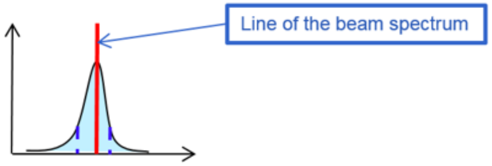
HOM with QE > 5000

Frequency [MHz]	$(R/Q)_x$	$(R/Q)_y$	$(R/Q)_z$	Q_{ext}	P_{max} [W]
2121	2.5	-	6.1E-3	6000	3E-6
2400	0.02	-	1E-5	8400	-
2600	225	-	0.68	1.3E6	0.13
3144	-	0.05	7.1E-3	5200	-
3618	-	-	15.6	4.3E4	0.1
4085	-	-	19.9	1.2E4	0.03
5112	1E-4	-	1E-4	5.5E4	-
5954	2E-4	-	2E-4	6300	-

- HOM resonant excitation: $P_{max} = (R/Q)_Z * Q * I_b^2 * DF$
- Maximum HOM power $P_{max} < 0.1$ W

QMiR HOM Statistical Analysis

Stochastic HOM excitation by the pulsed beam*



* A. Lunin, et. al., Phys. Rev. Accel. Beams **21**, 022001

Off-resonance HOM excitation

$$\langle P\rangle = \frac{(R_{\parallel}/Q)\omega_0 q_0^2}{4t_b}A_\infty \qquad |V_\perp|_{x=x_0} = \frac{(R_\perp/Q)\omega_0 q_0 x_0 k}{4}A_\infty$$

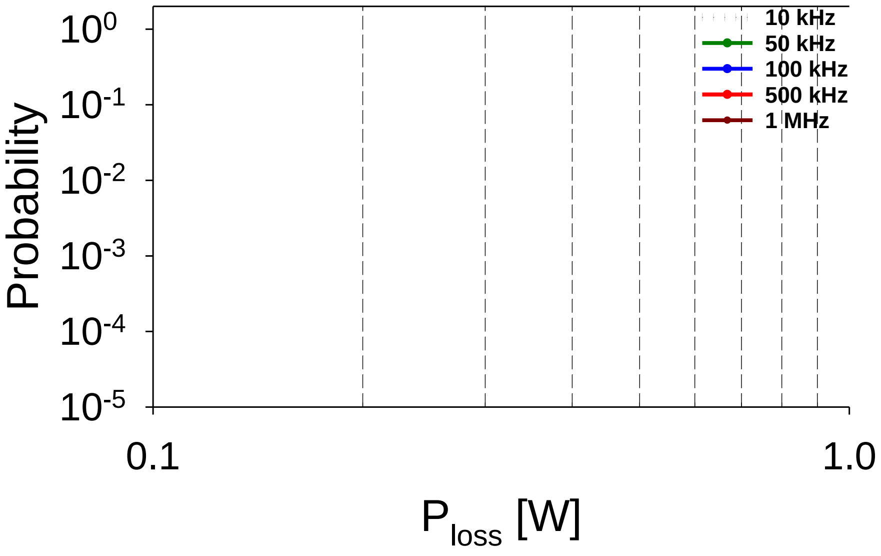
$A_\infty=2(e^{2a}-2e^{a}\cos(\omega_0/f_b)+1)^{-0.5}+1$ is the resonant form-factor

- **We calculated 100k cavities with random HOM spectra**
- **Statistic parameters with a normal distribution:**

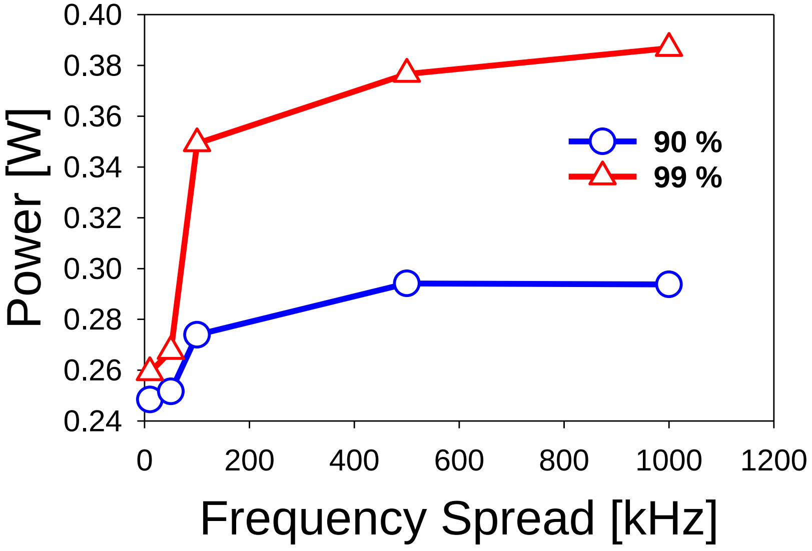
Freq, Q-factor, R/Q

QMiR HOM Statistical Analysis

HOM Frequency Deviation, σ_f , rms



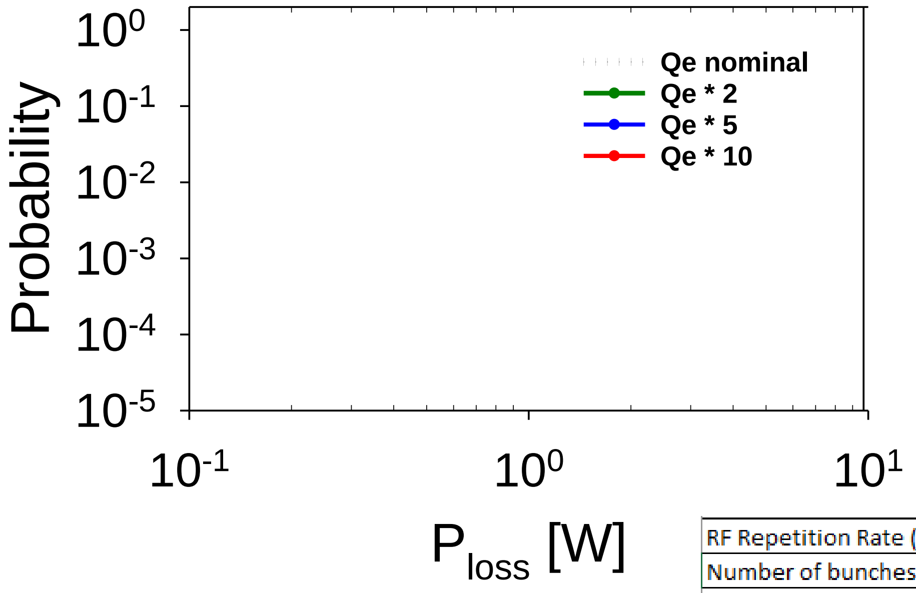
HOM Power Probability



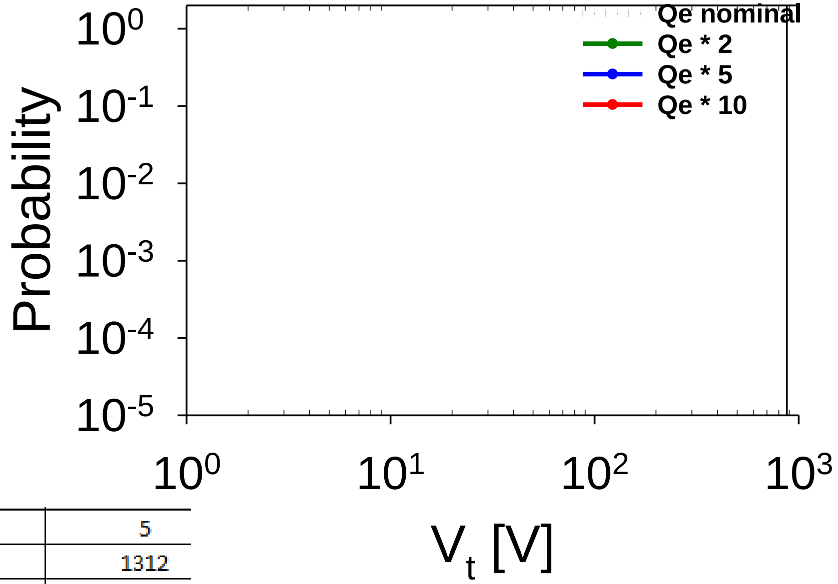
- **Probability depends on HOM frequency spread and Q-factors**
- **For high-Q modes, the probability saturates if $1/\sigma_f > t_b/2$**
- **We conservatively consider σ_f = 1 MHz**

QMiR HOM Statistical Analysis

HOM Power vs Q-factor



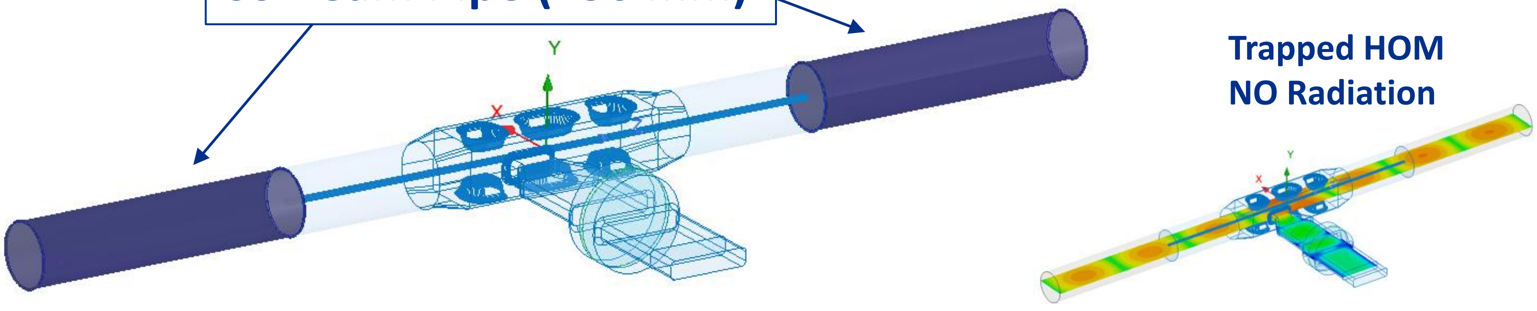
HOM Voltage vs Q-factor



RF Repetition Rate (Hz)	5
Number of bunches	1312
Bunch Train Length (ms)	727
Bunch Spacing (ns)	554
Beam current (mA)	5.8

- **HOM parameters deviation : $\sigma_{R/Q} = 0.2*(R/Q)$, $\sigma_F = 1$ MHz**
- **HOMs probability calculated only for external coupling (Qe)**
- **Beam offset taken +1mm**
- **With 99% probability: $P_{HOM} < 0.7$ W and $VT_{HOM} < 40$ V**

QMiR HOM Damping by Stainless Steel Sections



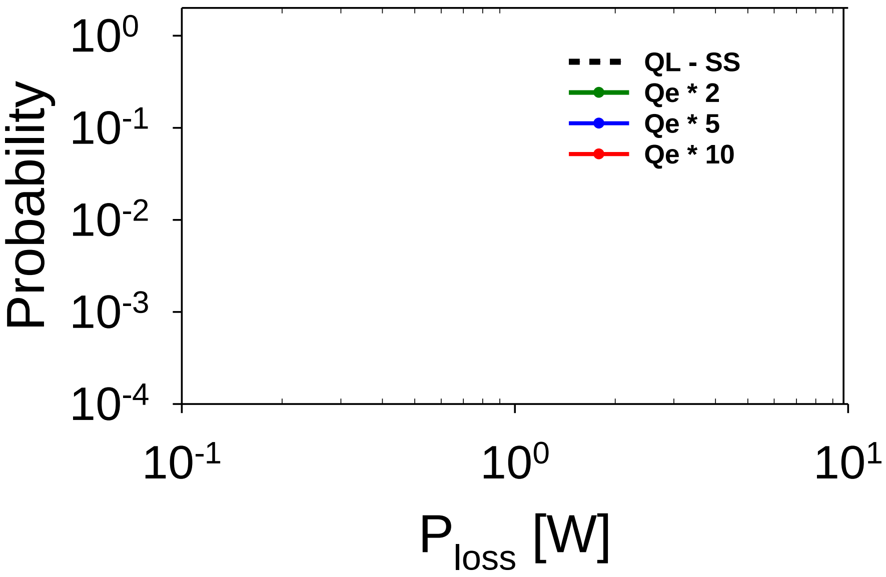
SS Beam Pipe (250 mm)

Perfect E-wall

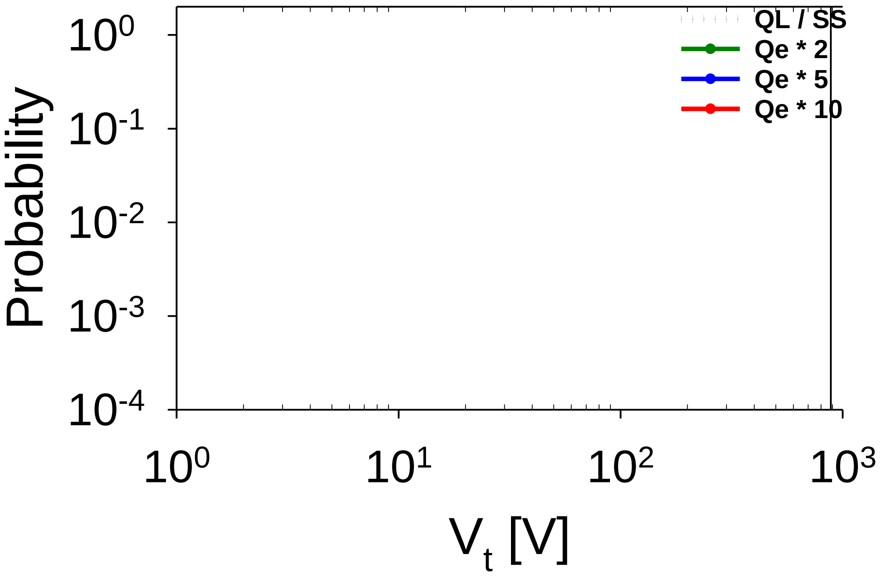
Perfect E-wall

Trapped HOM
NO Radiation

HOM Power, P_{HOM}

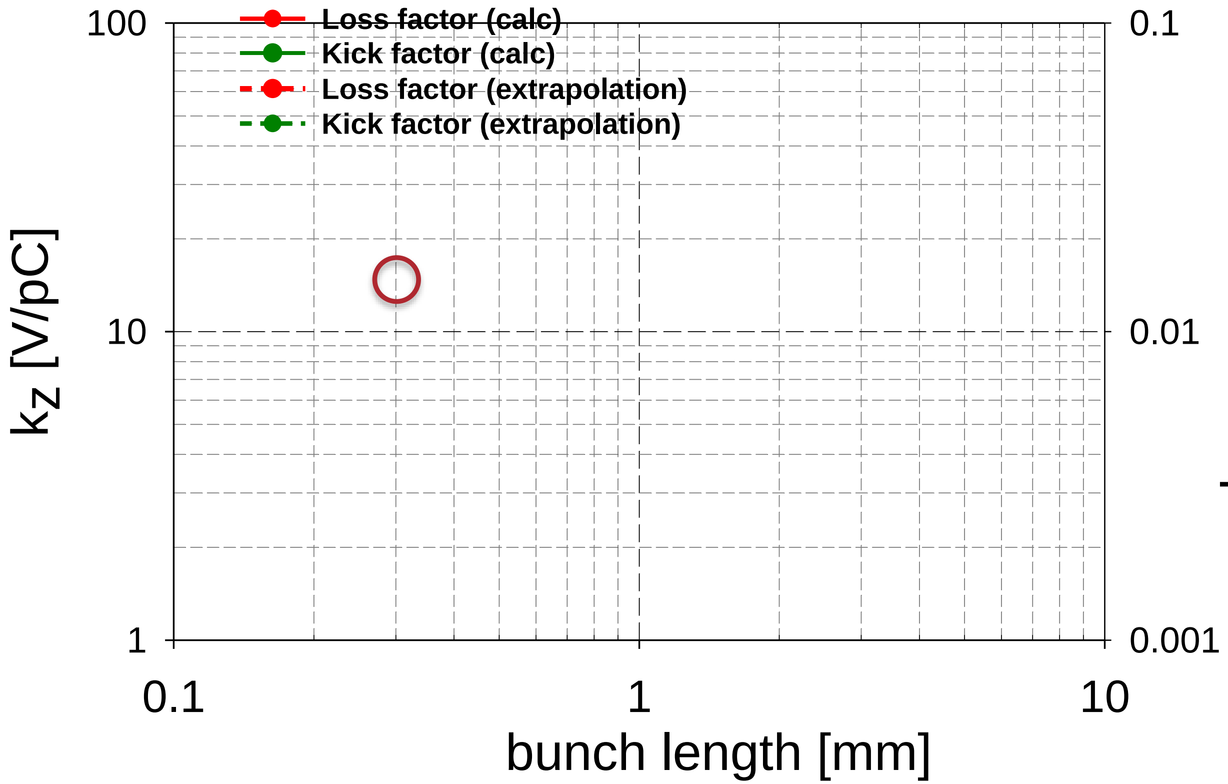


HOM Kick Voltage, VT_{HOM}

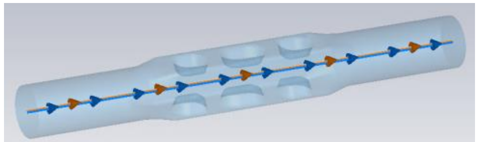


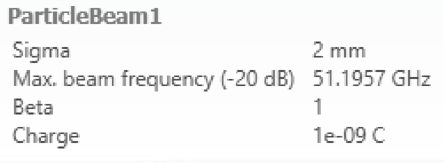
- **With 99% probability: $P_{HOM} < 1.2$ W and $VT_{HOM} < 100$ V**
- **E-wall (full reflection) – worst-case and overestimated scenario**

QMiR Incoherent HOM Excitation



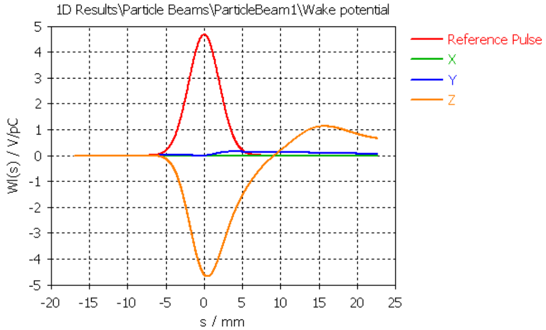
CST Particle Studio Simulation





ParticleBeam1

Sigma	2 mm
Max. beam frequency (-20 dB)	51.1957 GHz
Beta	1
Charge	1e-09 C



Estimated Loss and Kick factors: $k_z <= 15$ V/pC, $k_x <= 0.02$ V/pC/mm

Radiated wakefield power: $P = k_z q_0^2 N_b * f_{rep} \approx 1$ W

Crab Cavity HOM Impedance Limits

Resonant HOM Excitation ($V_{HOM} = k_0 x_0 I_p\, r_\perp$) can cause:

$$\left(\frac{r_\perp}{Q}\right) \equiv \frac{\left|\int_{-\infty}^{\infty}\left(\frac{\partial E_z(x,0,z)}{\partial x}\right)_{x=0} e^{i\omega z/c} dz\right|^2}{W k_0^2 \omega_0} \equiv \frac{U_{kick}^2}{W\omega_0} \quad [\Omega]$$

a) Crabbing voltage distortion

- HOM kick voltage should be less than the crabbing voltage (*V*$_0$)

$$V_{HOM}\sigma_z k_0 \ll V_0\, \sigma_z \omega_{RF}/c \quad \text{or} \quad r_\perp \ll \frac{V_0\, \sigma_z \omega_{RF}/c}{k_0^2 x_0 I_p}$$

b) Beam emittance dilution

- HOM kick should be less than the transverse momentum spread

$$V_{HOM}\sigma_z k_0 \ll \frac{\sigma_{p_\perp} c}{e} = \frac{p_\parallel c}{e}\sqrt{\frac{\varepsilon}{\gamma\beta}} \quad \text{or} \quad r_\perp \ll \frac{E}{k_0^2 x_0 \sigma_z I_p}\sqrt{\frac{\varepsilon}{\gamma\beta}}$$

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·GHz^2

- Vertical Shunt Impedance Limit

$r_y f_{HOM}^2 \ll$ 0.7 GΩ·GHz^2

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

$$V_{kick} \ll V_0\, \sigma_z \omega_{RF}/c \quad \text{or} \quad k_\perp \ll \frac{V_0\, \sigma_z \omega_{RF}/c}{q x_0}$$

b) Beam emittance dilution

- Transverse kick should not increase the bunch emittance

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

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

Horizontal Kick Factor Limit	k_x **<< 1.60 V/pC/mm**
Vertical Kick Factor Limit	k_y **<< 0.12 V/pC/mm**

QMiR Cavity for ILC HOM & Wake Summary

Operation mode $\left(\frac{r_\perp}{Q}\right) = 225\ \Omega$

HOM/SOM

Maximal dipole *horizontal* SOM $\left(\frac{r_\perp}{Q}\right)_x = 2.5\ \Omega$ (120 Ω/m)

$(r_\perp)_x \approx 0.7$ MΩ/m << 49 MΩ/m (spec #24)

Maximal dipole *vertical* HOM $\left(\frac{r_\perp}{Q}\right)_y = 0.05\ \Omega$ (3.6 Ω/m)

$(r_\perp)_y \approx 0.02$ MΩ/m << 62 MΩ/m (spec #24)

Wakefields

Incoherent losses $k_z \approx 15$ V/pC $P_{rad} \approx k_z\, q^2 n_b f_{rep} = 1\ W$

Horizontal kick factor* k_x = 20 V/pC/m << 1.6E3 (spec #41)

Vertical kick factor* k_y = <1 V/pC/m << 120 (spec #42)

- **QMiR cavity meets the ILC/CC requirements on SOM/HOM impedance and kick factors**

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:

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

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

Beam OFF:	$P_{min} \approx 740$ W
Optimal Coupling:	$Q_L \approx 1.3 \times 10^6$
Beam ON & Microphonics:	$P_{max} \approx 1500$ W

- **3 kW Solid State RF amplifier will be sufficient at 100% overhead**

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:

$$V_{kick} = \frac{\omega_0^2}{\omega^2-\omega_0^2-i\frac{\omega\omega_0}{Q}} k_0 x_0 I_p \left(\frac{r_\perp}{Q}\right)$$

  - If the cavity detune (Δf) is much larger than the bandwidth:

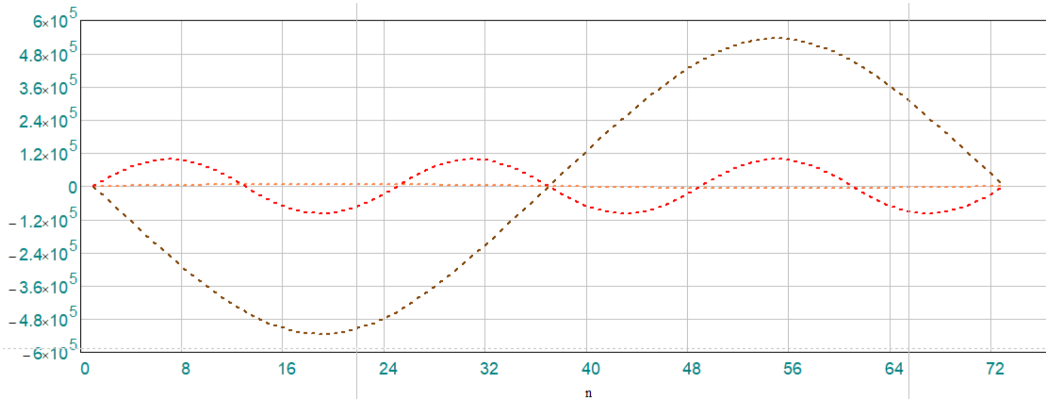
$$V_{kick} \approx \frac{1}{2m} k_0 x_0 I_p \left(\frac{r_\perp}{Q}\right) Q_L\,, \quad \text{where } m \equiv \frac{|\Delta\omega|}{\omega_0} Q_L$$

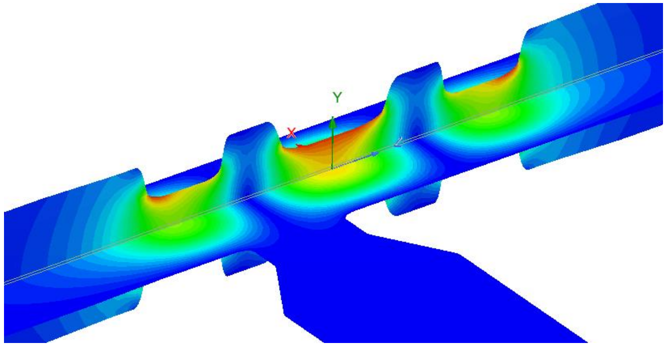
  - Required detuning:

$$m \gg \frac{\omega_0 x_0 I_p \left(\frac{r_\perp}{Q}\right) Q_L}{cE\sqrt{\frac{\varepsilon}{\gamma\beta}}} \approx \mathbf{8}\,, \quad \text{or } \Delta f >> 16 \text{ kHz}$$

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

QMiR Multipole Components Calculation





$$a_n = \frac{in}{\omega\pi r^n}\int_0^{2\pi} \sin(n\varphi) \int_{-\infty}^{\infty} (E_z(r,z,\varphi))_{r=r_0} e^{ikz} dz d\varphi \,,$$

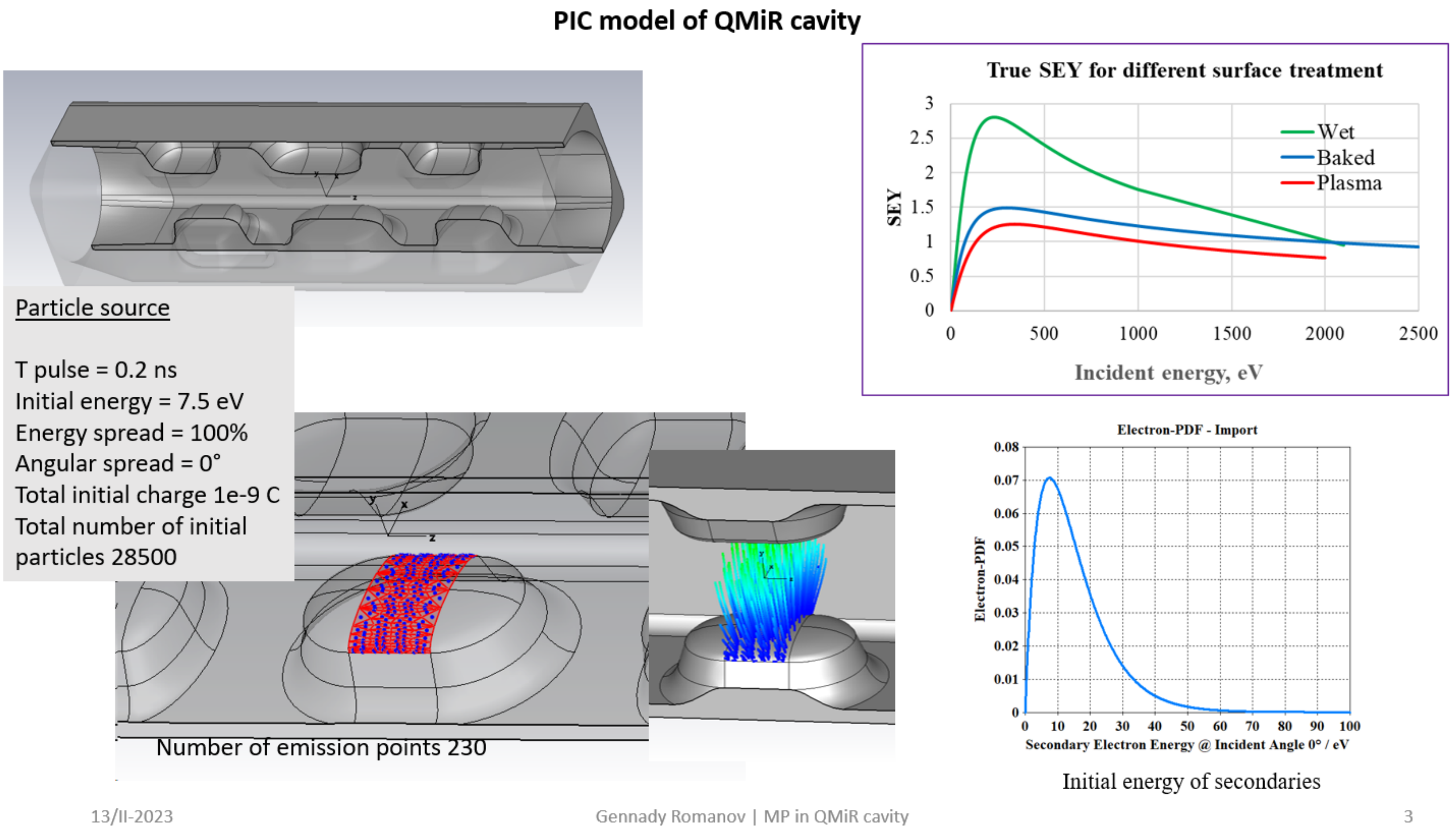
$$b_n = \frac{in}{\omega\pi r^n}\int_0^{2\pi} \cos(n\varphi) \int_{-\infty}^{\infty} (E_z(r,z,\varphi))_{r=r_0} e^{ikz} dz d\varphi \,.$$

REF: J. Barranco Garcia et al., Phys. Rev. Accel. Beams 19, 101003 (2016)

Multipole Coefficients					
Normal			Skew		
$\lvert b_1 \rvert$, Tm	$\lvert b_2 \rvert$, Tm/m	$\lvert b_3 \rvert$, Tm/m^2	$\lvert a_1 \rvert$, Tm	$\lvert a_2 \rvert$, Tm/m	$\lvert a_3 \rvert$, Tm/m^2
4.3×10^{-5}	6.2×10^{-3}	4.1	1.4×10^{-4}	7.9	12.9

- **Multipoles can be further reduced by flattening the electrodes**

QMiR Multipactor Analysis (by G. Romanov)



PIC model of QMiR cavity

Particle source

T pulse = 0.2 ns
Initial energy = 7.5 eV
Energy spread = 100%
Angular spread = 0°
Total initial charge 1e-9 C
Total number of initial particles 28500

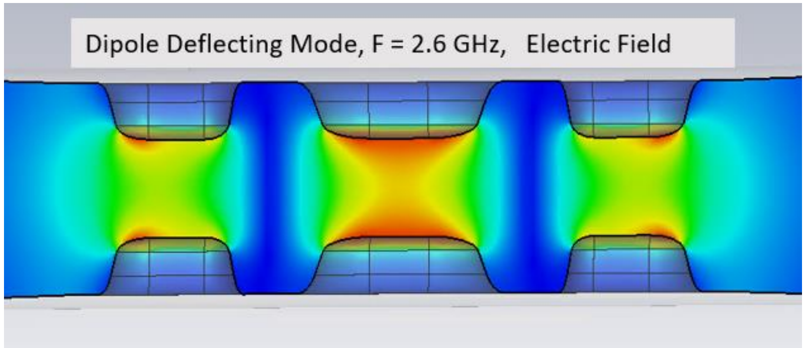
Number of emission points 230

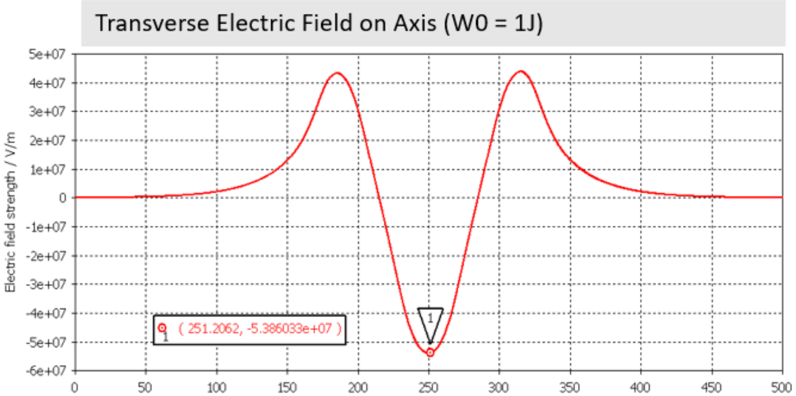
Initial energy of secondaries

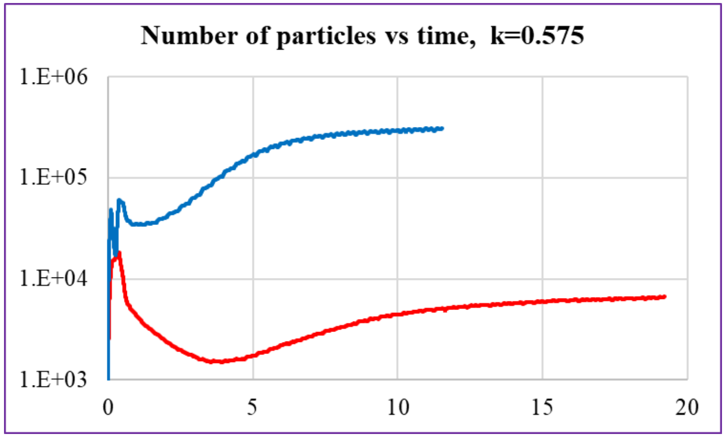
13/II-2023 Gennady Romanov | MP in QMiR cavity 3

- Probabilistic MP simulation in CST Studio
- Compared ILC design (2.6 GHz) and ANL (2.8 GHz) of QMiR
- QMiR for ANL/SPX was tested in VTS, NO problem with MP

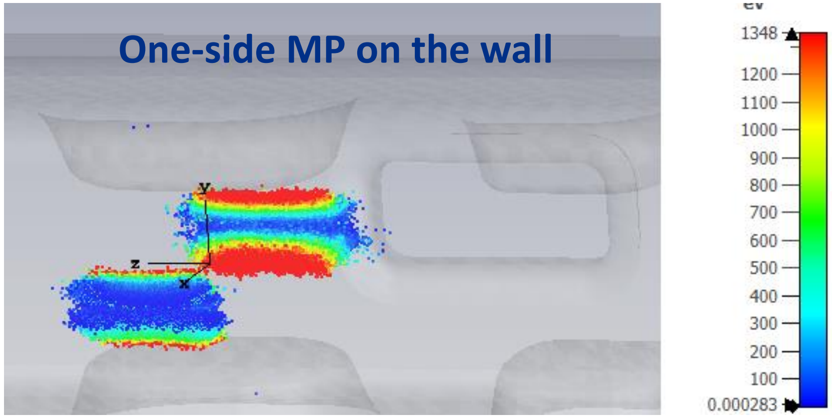
QMiR Multipactor Analysis (by G. Romanov)







Multipactor at field level k = $E_y/E_{y\_max} = 0.56$



$$\boldsymbol{Nominal\ Kick}:\ \mathbf{0.92}\ \boldsymbol{MV}$$

Stored Energy: $W_0 = 0.24$ J

Max Electric Field: $E_Y = 26$ MV/m

Max electric field E_{y_max} is a reference field level parameter

QMiR Multipactor Analysis (by G. Romanov)

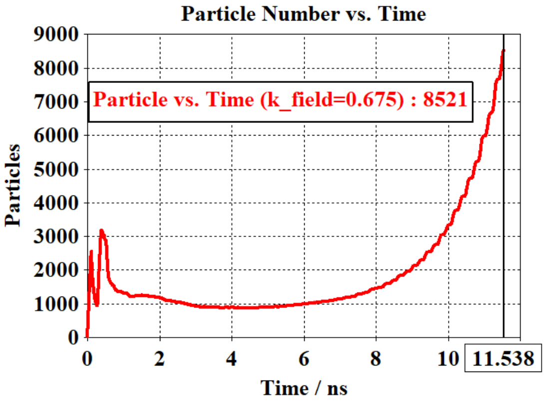
Comparison of the MP in QMiR cavities

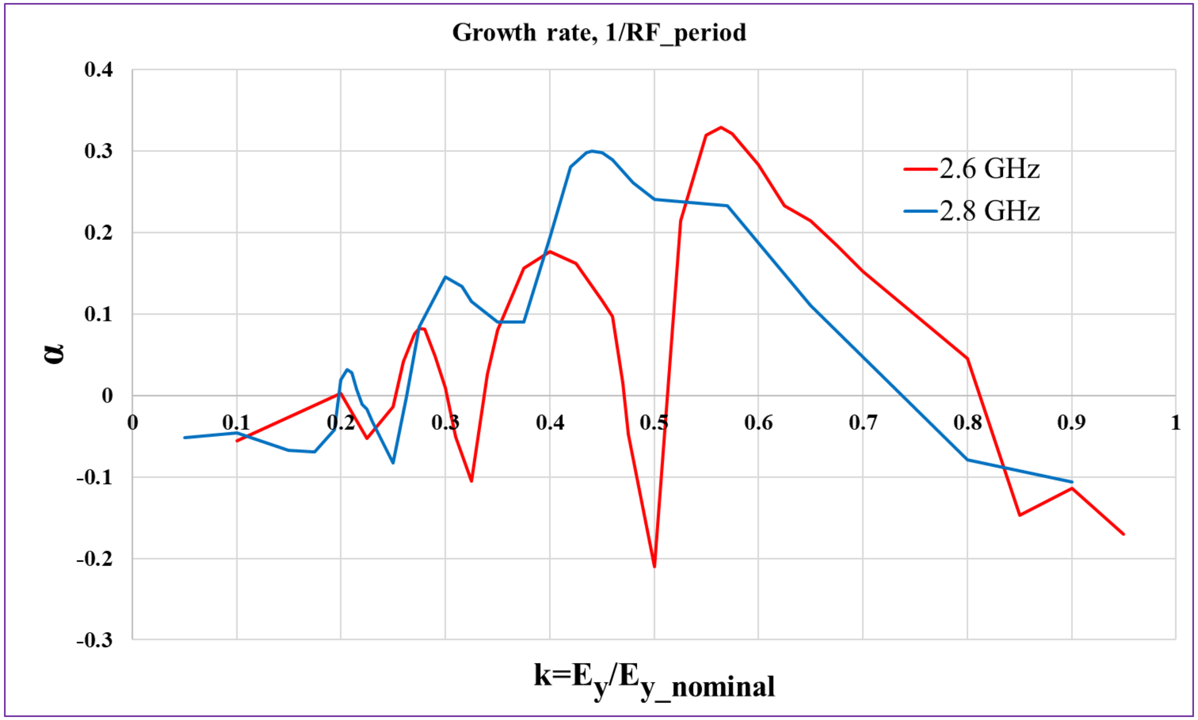
Time of simulations 30 RF periods

SEY for baked niobium

Initial number of particles at the end of injection is 3000

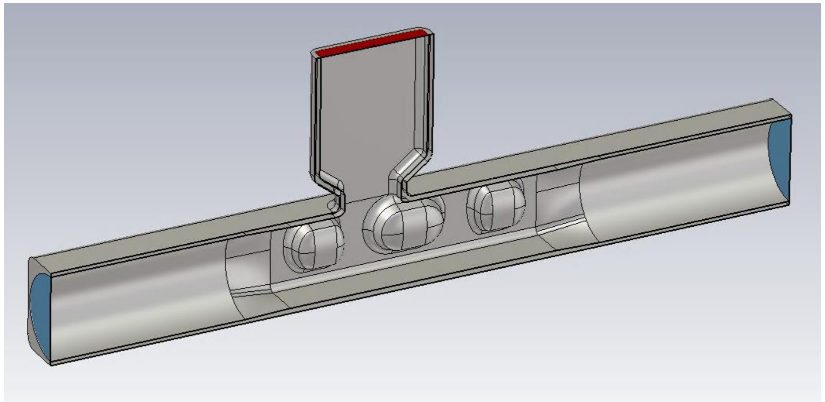
No MP activity above k=1

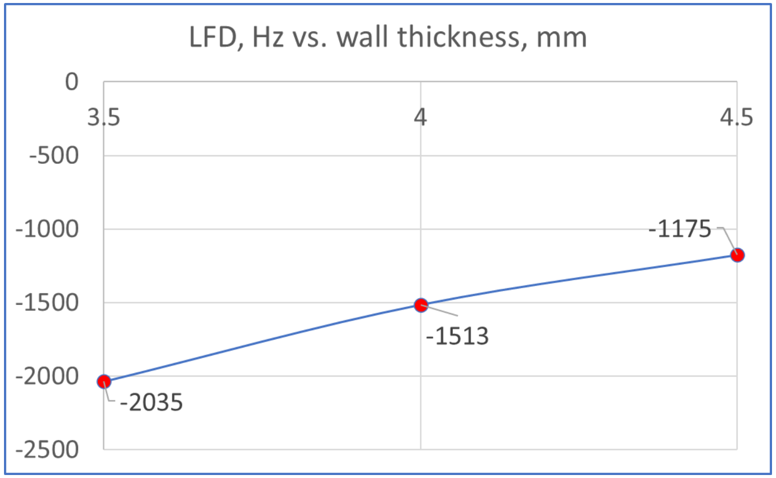


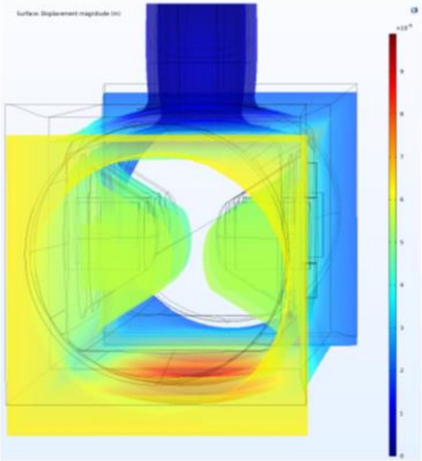


- **Both QMiR designs exhibit the same MP behavior**
- **The ILC QMiR shows signs of MP at ~0.6 of the nominal gradient**
- **NO MP when operating with nominal gradient**

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

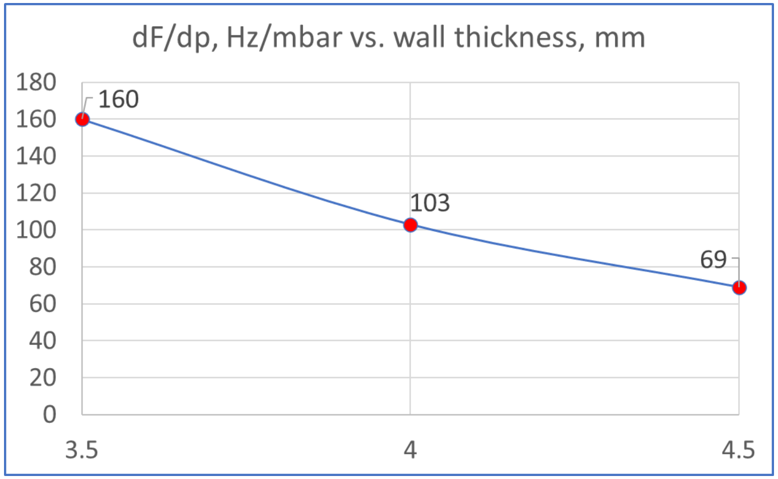






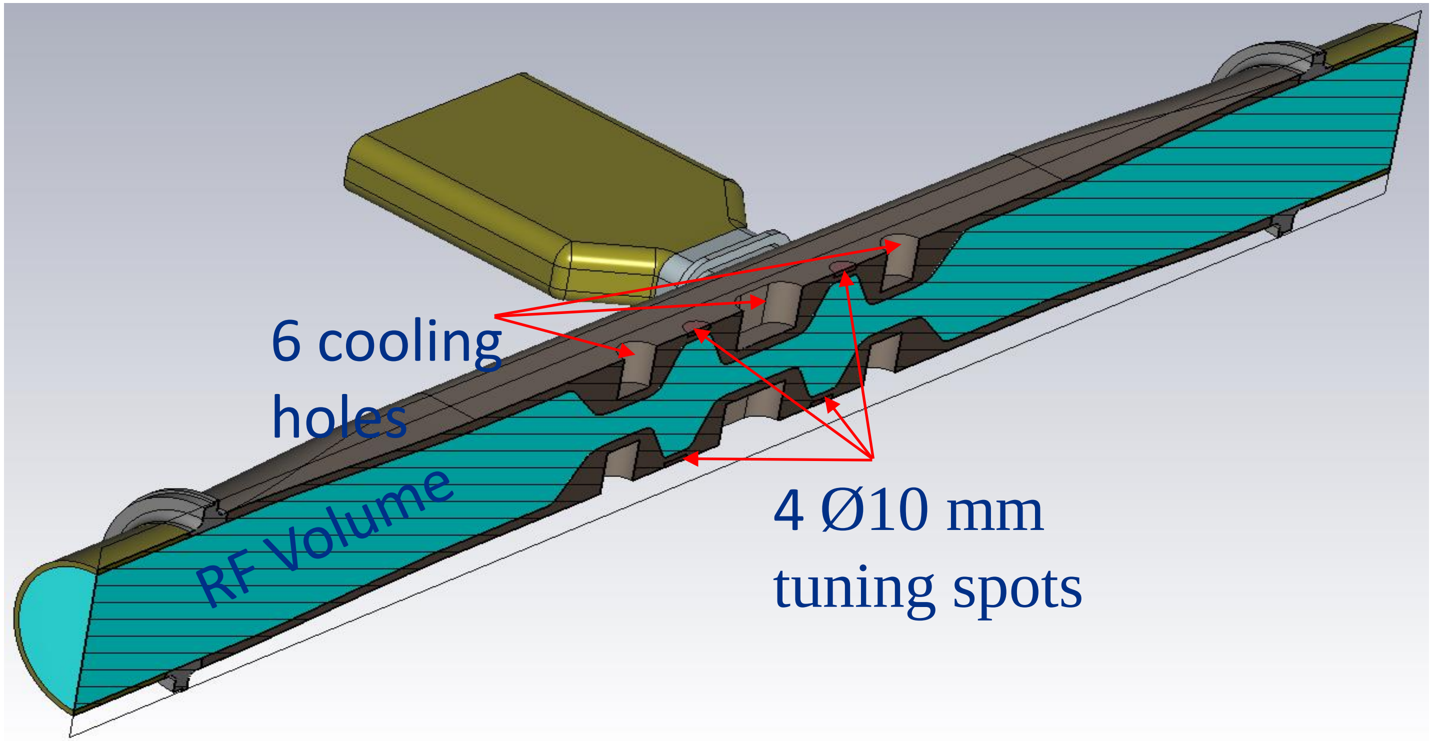
Deformation due to LFD

LFD < 1.5 kHz
dF/dP < 150 Hz/mbar



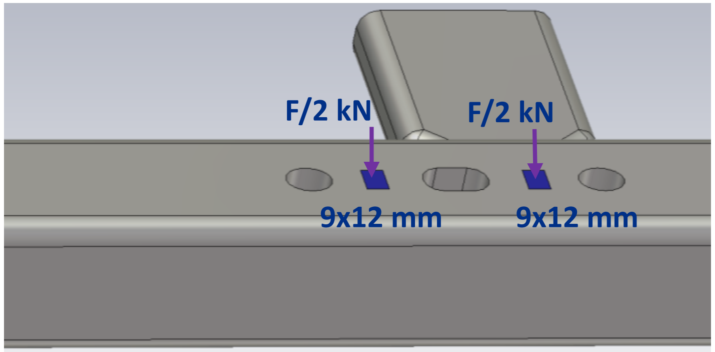
- **QMiR LFD and dF/dP are less than the cavity bandwidth (few kHz)**
- **LFD can be further reduced by adding rigid elements**

Mechanical Analysis of Frequency Tuning (by I. Gonin)

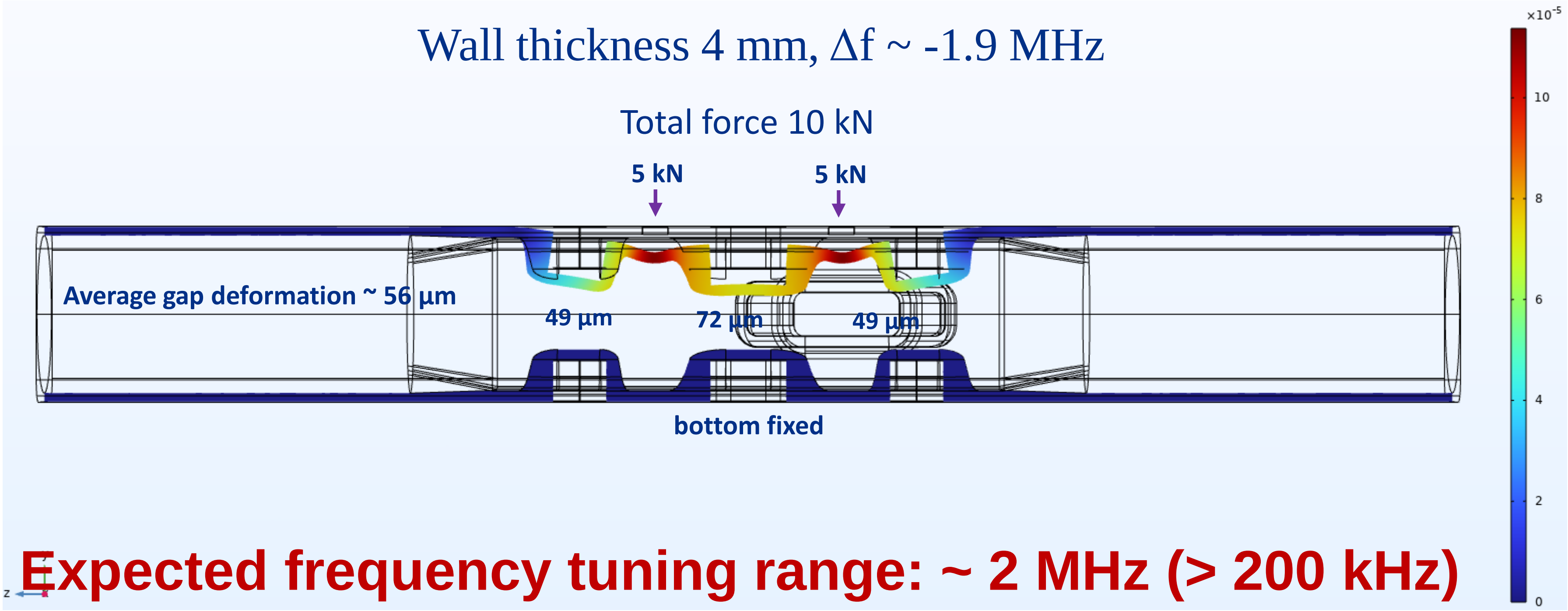


- **Introduced six hollow cooling channels**
- **Frequency tuner will require four contact area**

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



Wall thickness 4 mm, Δf ~ -1.9 MHz

Total force 10 kN

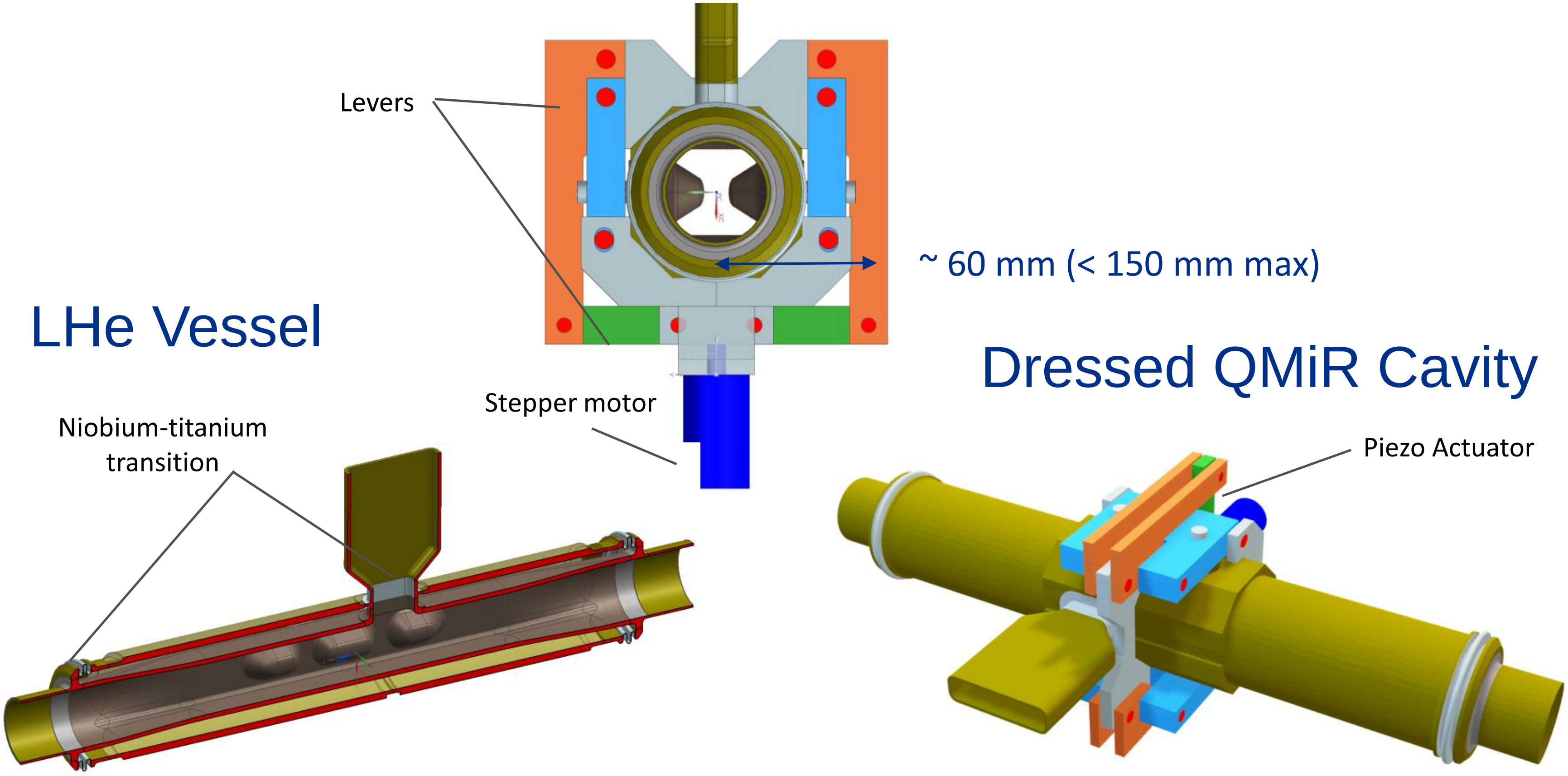
Average gap deformation ~ 56 µm

bottom fixed

Expected frequency tuning range: ~ 2 MHz (> 200 kHz)

QMiR Cavity Slow Tuner Design (by V. Polubotko)

Compact double 2-lever frequency tuner



- **Frequency tuner mechanical design concept is completed**
- **Fine tuning can be done with piezo actuators (like in LCLS-II).**
- **Tuner fits to the ILC-ML CC Envelope transverse space**

QMiR Cavity Fine Tuner Design

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

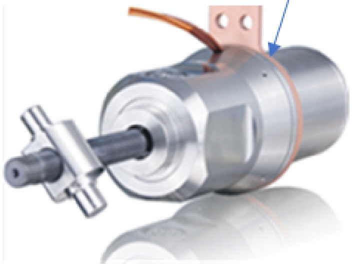
Cavity parameters:
df/dL ~45kHz/um

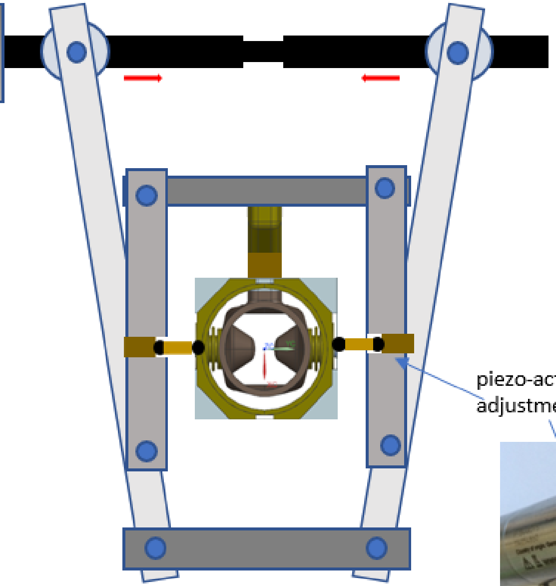
Parametrs fo the slow/coarse tuner		
Stepper	**200**	***step/360°***
Planetary Gear Box	**100**	***gear ratio***
Steps for 1mm stroke on shaft (M12X1)	**20000**	***steps***
Doubler lever ratio	**10**	
Cavity compression/stroke per 1 steps	**5**	***nm***
cavity tuning per one step	**200**	***Hz***

Slow tuner range > 1 MHz…

Titanium shaft with right and left threads

Phytron stepper motor with gear box





piezo-actuator with adjustment screw

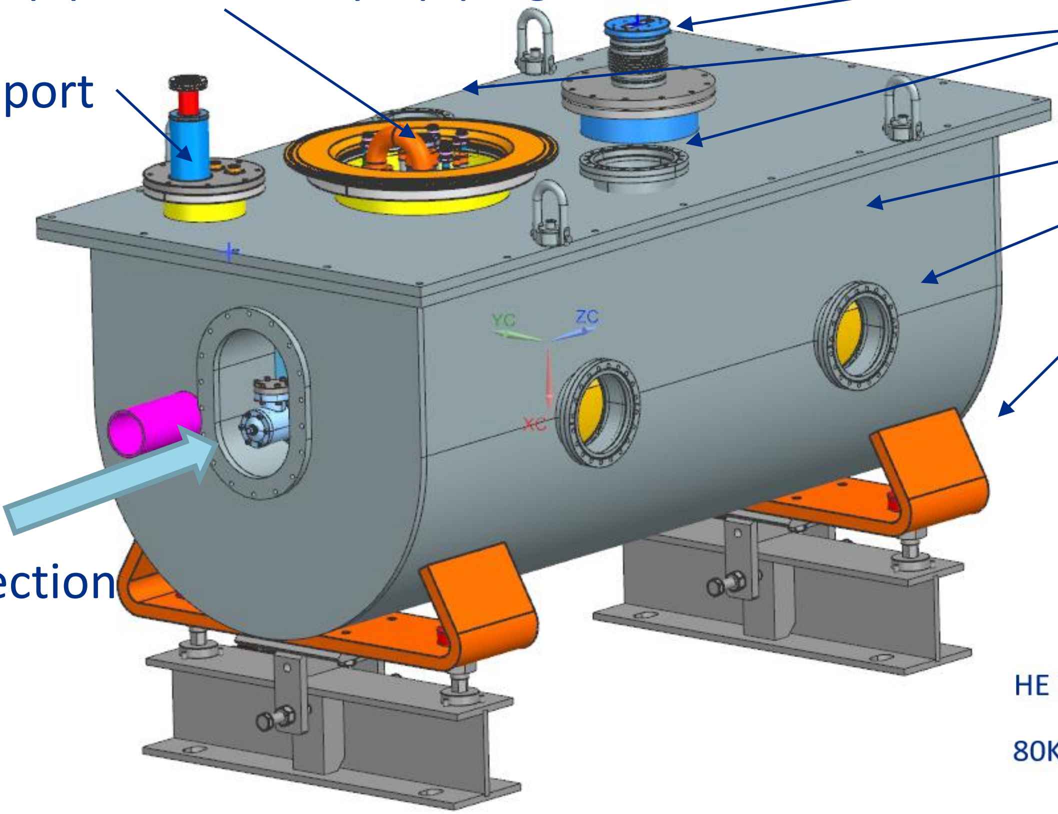
Frame with two Double lever tuner running simultaneously with one stepper motor actuator… Shaft of the stepper actuator divided on the two half … ½ shaft has left thread and second ½ shaft right thread… traveling nut will move in opposite directions ..

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)

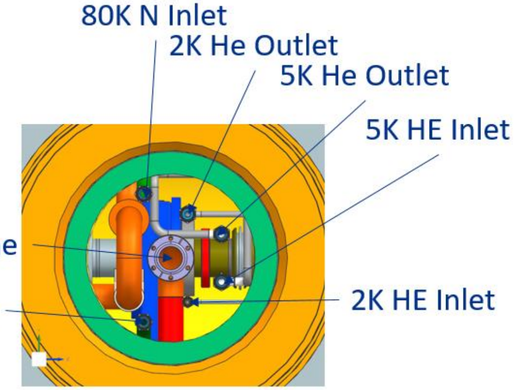
Parametrs fo the fast/fine tuner		
Piezo-stack	**10*10*5**	***mm*mm*mm***
Stroke at T=20K & V=100V	**0.5**	***um***
Cavity re-tuning at V=100V	**20**	***kHz***

Yu. Pischalnikov 12/07/21

QMiR Cryomodule Design (by Y. Orlov)



Top port*

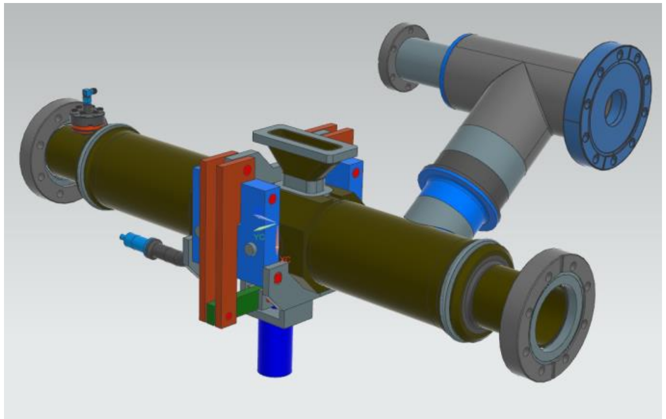


View on the Top port

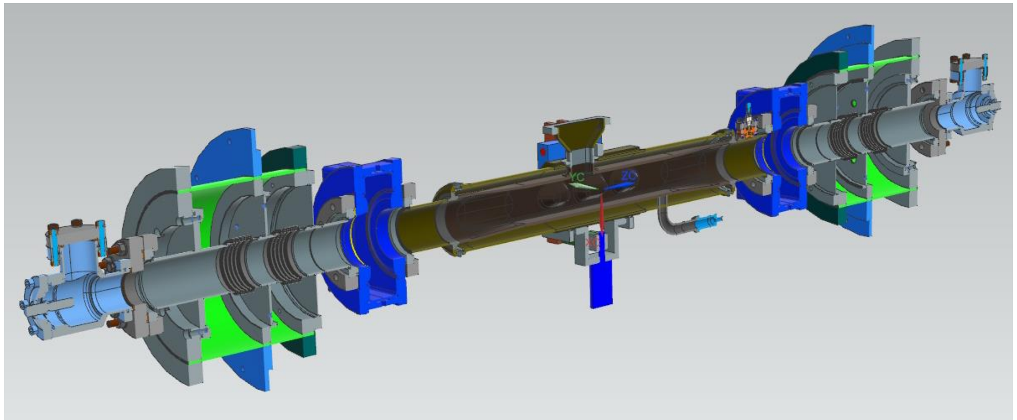
- **Design based on existing Capture Cavity CM**
  - **proven mechanical solutions, tested @FAST facility at Fermilab**
- **Cryogenic system (heat exchanger, He-lines) is similar to FAST CM**

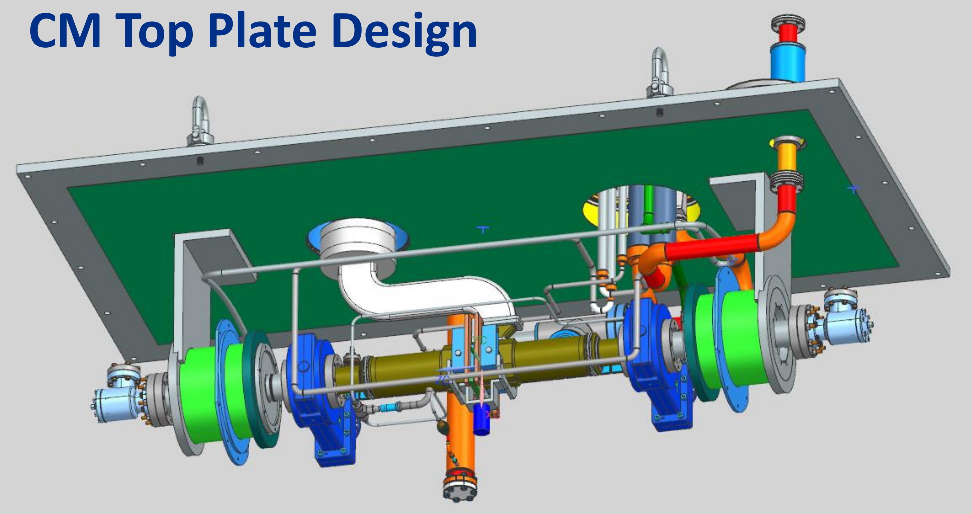
QMiR Cryomodule Design (by Y. Orlov)

Dresses Cavity with 2K Pipe



Cavity Integration with Beam Line



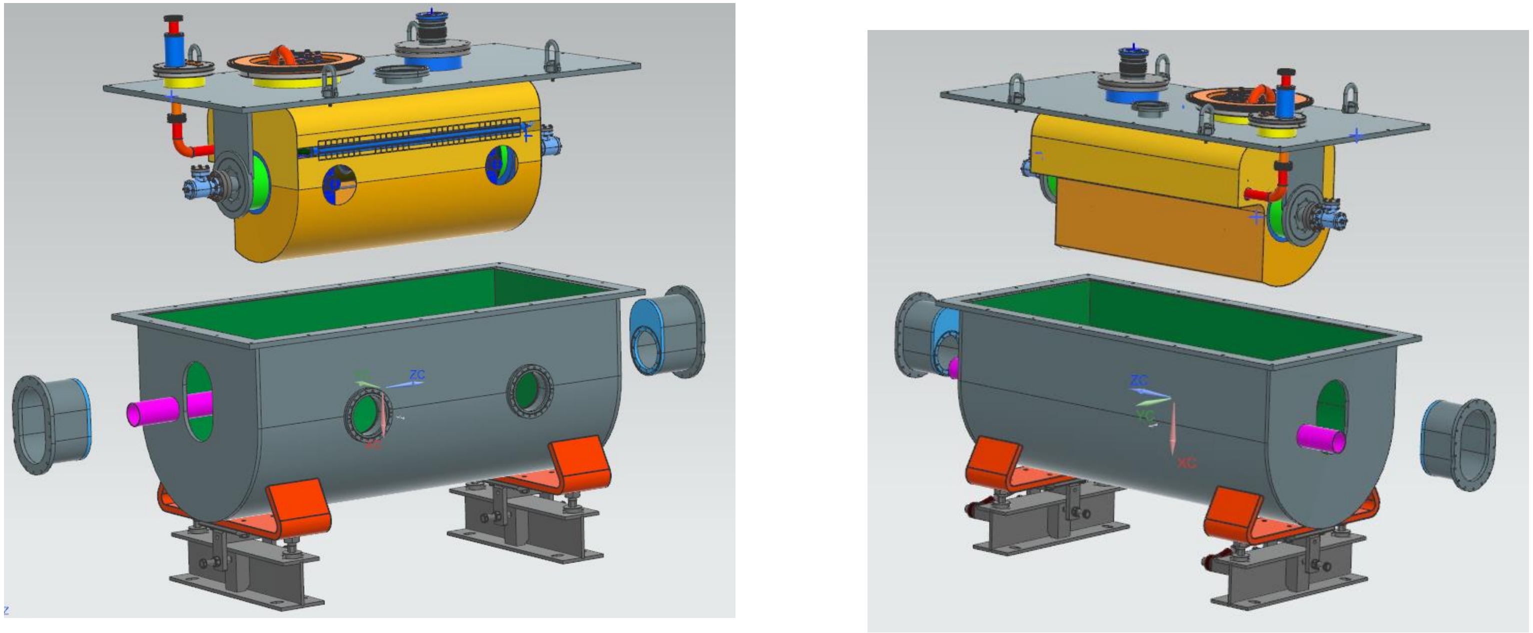


CM Top Plate Design

- **Top plate support of the cryo-string**
- **Compact design of the Input Coupler**

QMiR Cryomodule Design (by Y. Orlov)

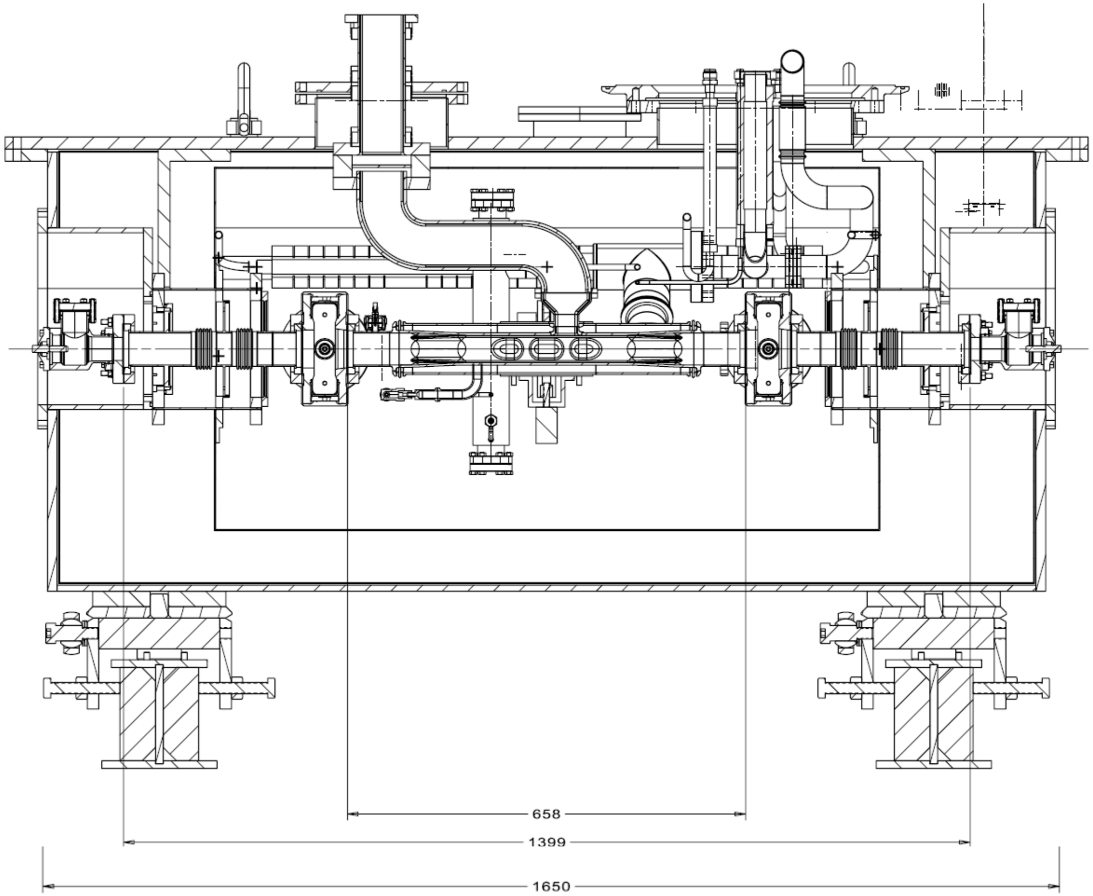
Top Assembly Scheme

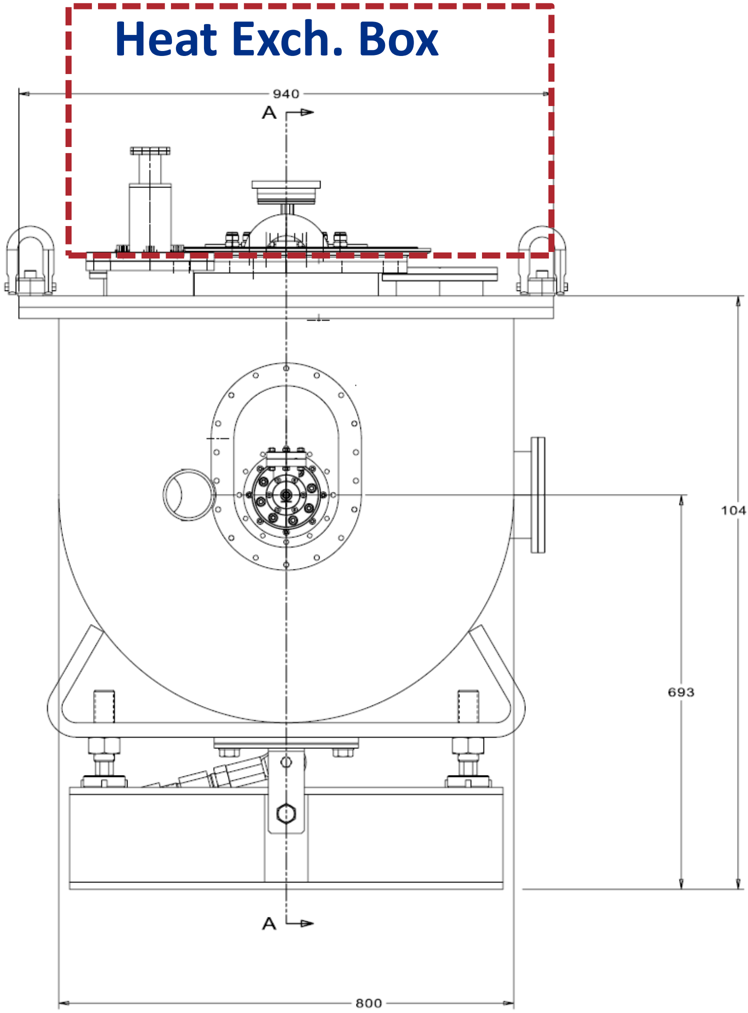


- **CM assembly sequence and procedure is developed**
- **Clean room and alignment procedures are similar to FAST/CC**

QMiR Cryomodule Design (by Y. Orlov)

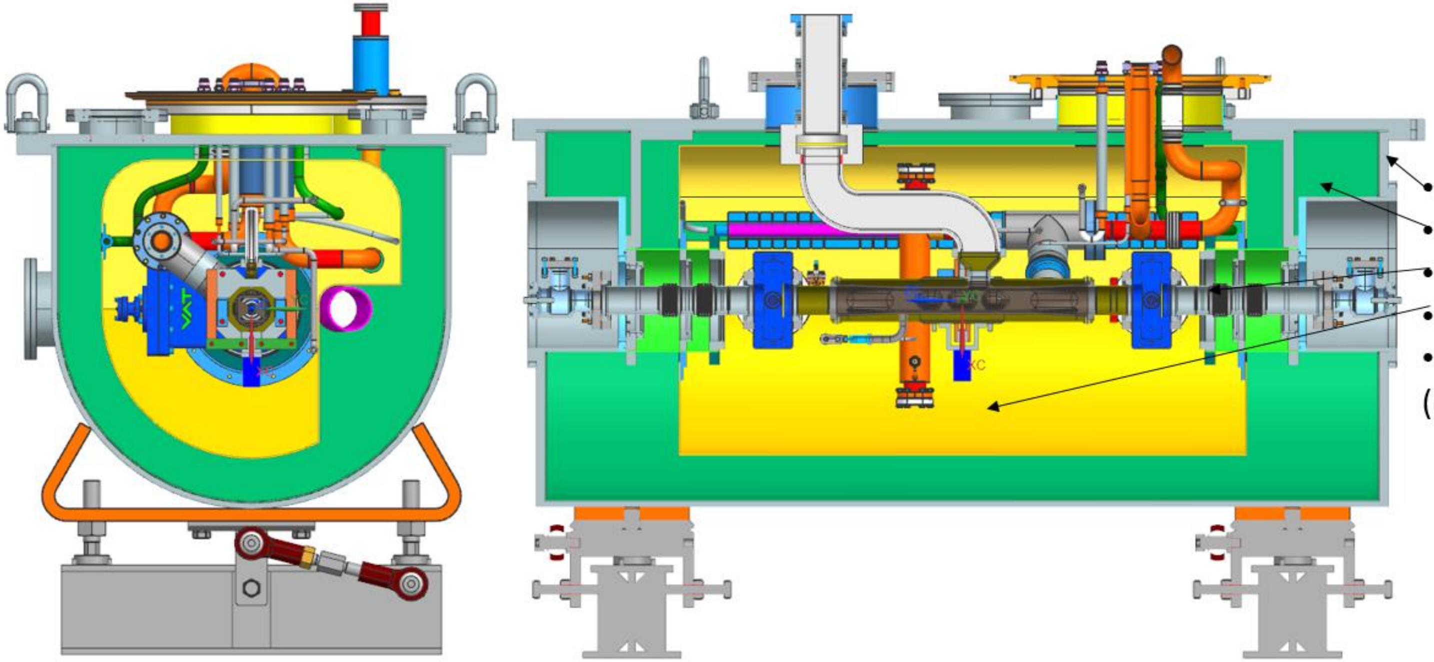
QMiR Cryomodule Drawing





- **Cryomodule space required: ~ 1650 x 1000 x 1500 mm**

QMiR Cryomodule Sectional Views (by Y. Orlov)



- Vacuum Vessel
- Magnetic shield
- Cavity String
- 50-80K Thermal shield
- No 5K Thermal Shield

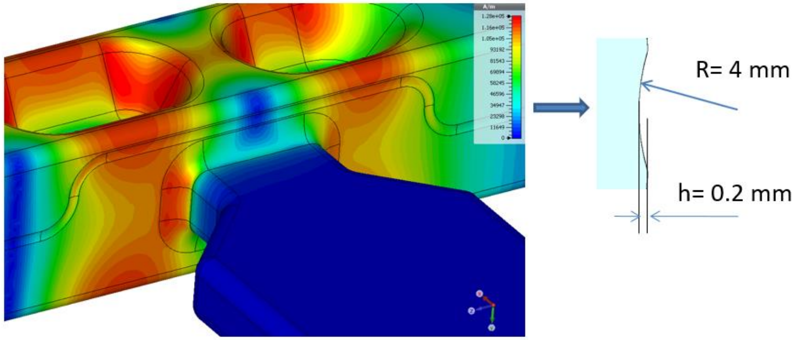
(only thermal intercepts)

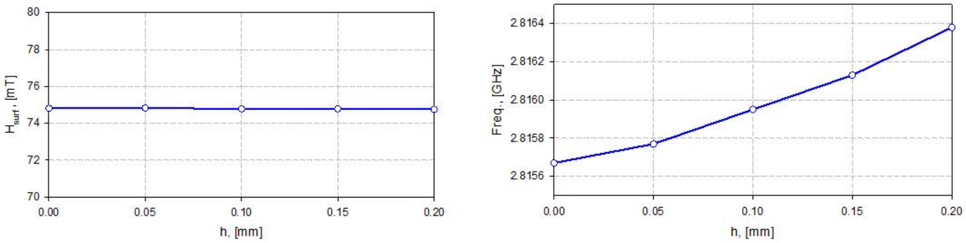
- **CM concept design is ready**
- **CM fits ILC technical requirements and environment limitations**
- **Internal alignment system and oversized backward beam pipe allow external adjustment of the cavity position (precision ± 0.1 mm)**
- **Design of the vacuum vessel and piping complies with safety codes**

QMIR Cavity Production

QMiR 2.8 GHz Bare Cavity

Minimal Effect of the Weld on H-field Enhancement



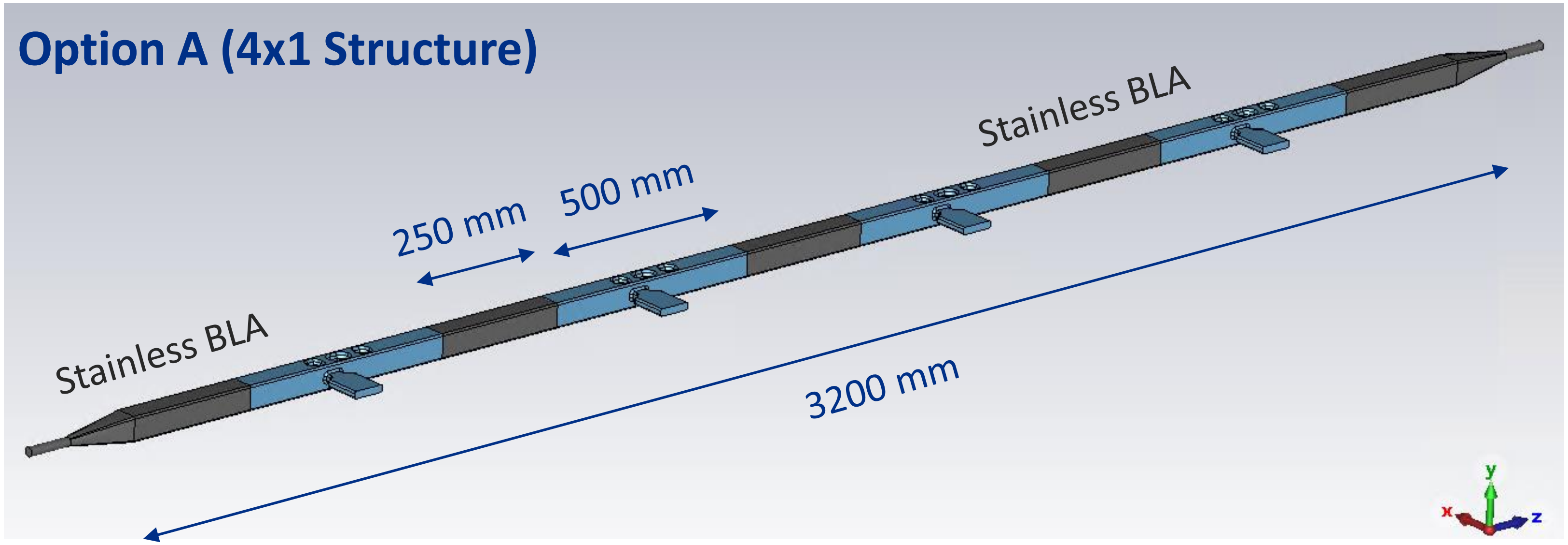


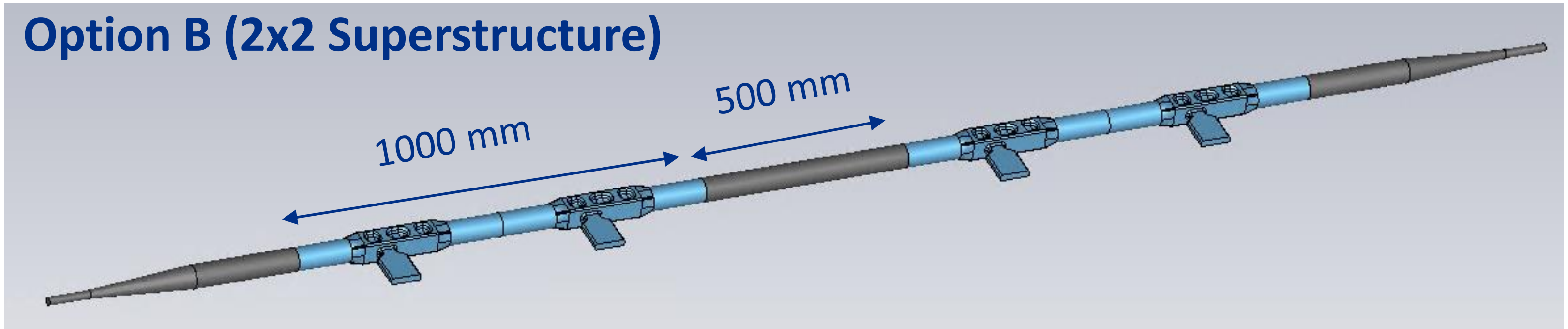
- **Cavity parts can be machined from**

  Nb Ingot of Ø 80mm x 500 mm
  about 25 kg Nb for prototype

- **Parts are milled with high precision**
- **Electron Beam (EB) welding of Nb parts is required**
- **Cavity manufacturing is similar to ANL/SPX QMiR**

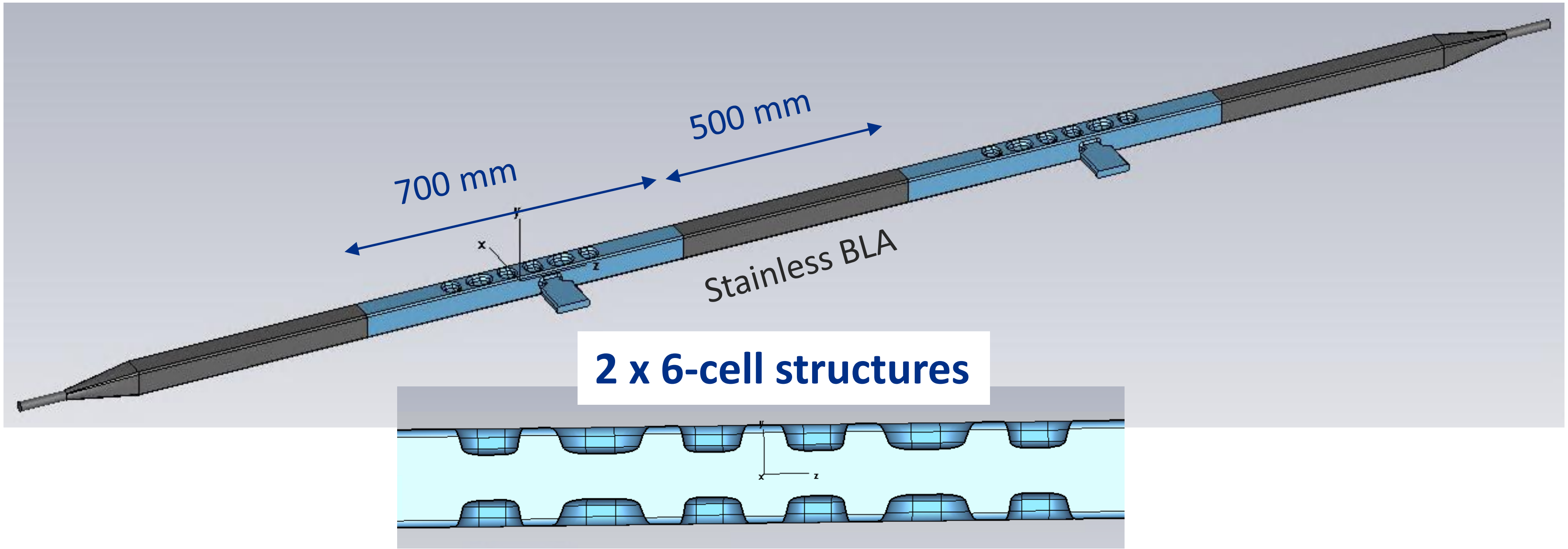
QMiR Cavity String for 1 TeV ILC





- **Two options are considered, a chain of 1x4 and 2x2 cavities**
- **Simple stainless-steel inserts to damp HOMs**
- **Total estimated HOM power for 1 TeV < 5 W**

QMiR Multicell Cavity for 1 TeV 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**

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, $E_p \approx 35$ MV/m, $B_p \approx 70$ mT, meet the ILC/CC specifications.
- 4 QMiR can provide 3.7 MV kick total for 1 TeV ILC option
- SOM/HOM damped to meet ILC requirements (with SS sections)
- NO problems with MP and thermal breakdown

☐ **Initial mechanical design of QMiR cavity and CM completed**

- LFD and dF/dP meet the requirements
- The concept of a double 2-lever frequency proposed
- Concept of the top loaded compact CM proposed (CC-CM type)

☐ **Fermilab can design, build and test the QMIR cavity and CM**

Preliminary Plans for further development of QMiR CM

❑ Cavity Production and Testing

- Validation of mechanical concepts;
- Cavity detailed mechanical design and drawings preparation;
- Cavity prototype manufacturing (two cavities, RI or Zanon);
- Cavity processing and high-gradient VTS tests (Fermilab, ANL)
- Cavity jacketing with He-vessel (Fermilab, SCIAKY, ROARK, ...)

❑ Cryomodule Production and Testing

- Coupler manufacturing (CPI, good experience with PIP-II HPCs
- Frequency tuner design, manufacturing and tests (Fermilab, good experience with ILC, LCLS II and PIP II tuners)
- Fully equipped cavity High Power tests (HTC, Fermilab)
- Cryo-vessel mechanical design and manufacturing (Fermilab)
- Cryomodule integrated High Power RF test (Fermilab)

❑ Fermilab is open for collaboration with other laboratories – KEK, ANL, JLAB, BNL, Daresbury …)

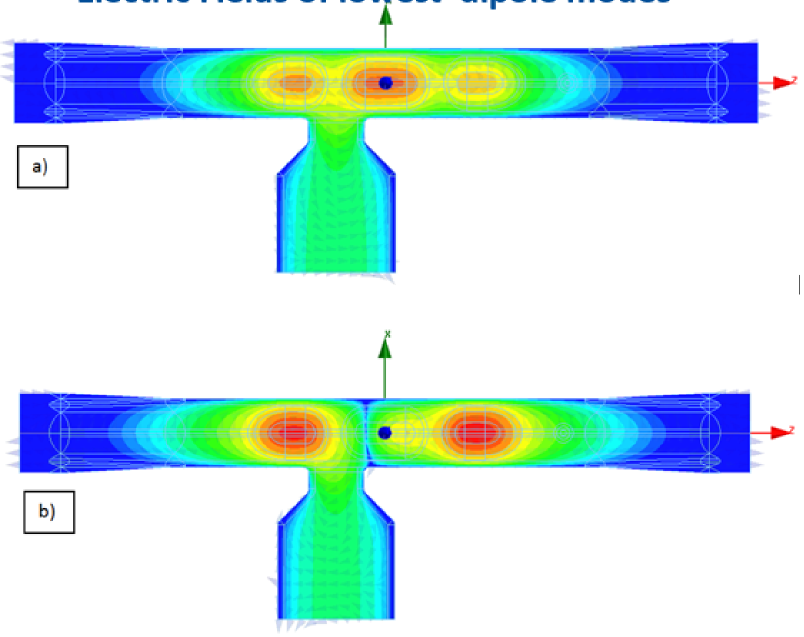
❑ QMiR is considered as a deflecting cavity for Elettra-II upgrade

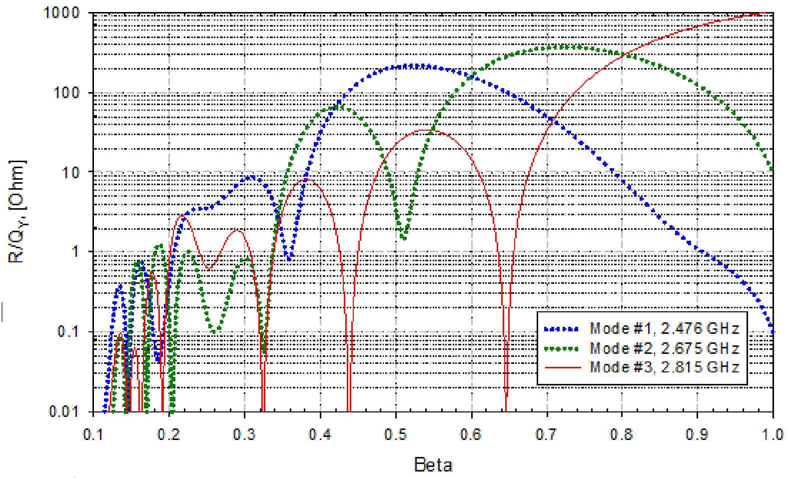
MANY THANKS

- ☐ TO KEK FOR HOSTING THE MEETING
- ☐ TO COLLEGUES FROM OTHER LABS FOR FRUITFUL DISCUSSIONS
- ☐ TO ALL FERMILAB COLLEGUES WHO MADE VALUABLE INPUTS TO THIS PRESENTATION

Same Order Mode (SOM) Damping

Electric Fields of lowest dipole modes

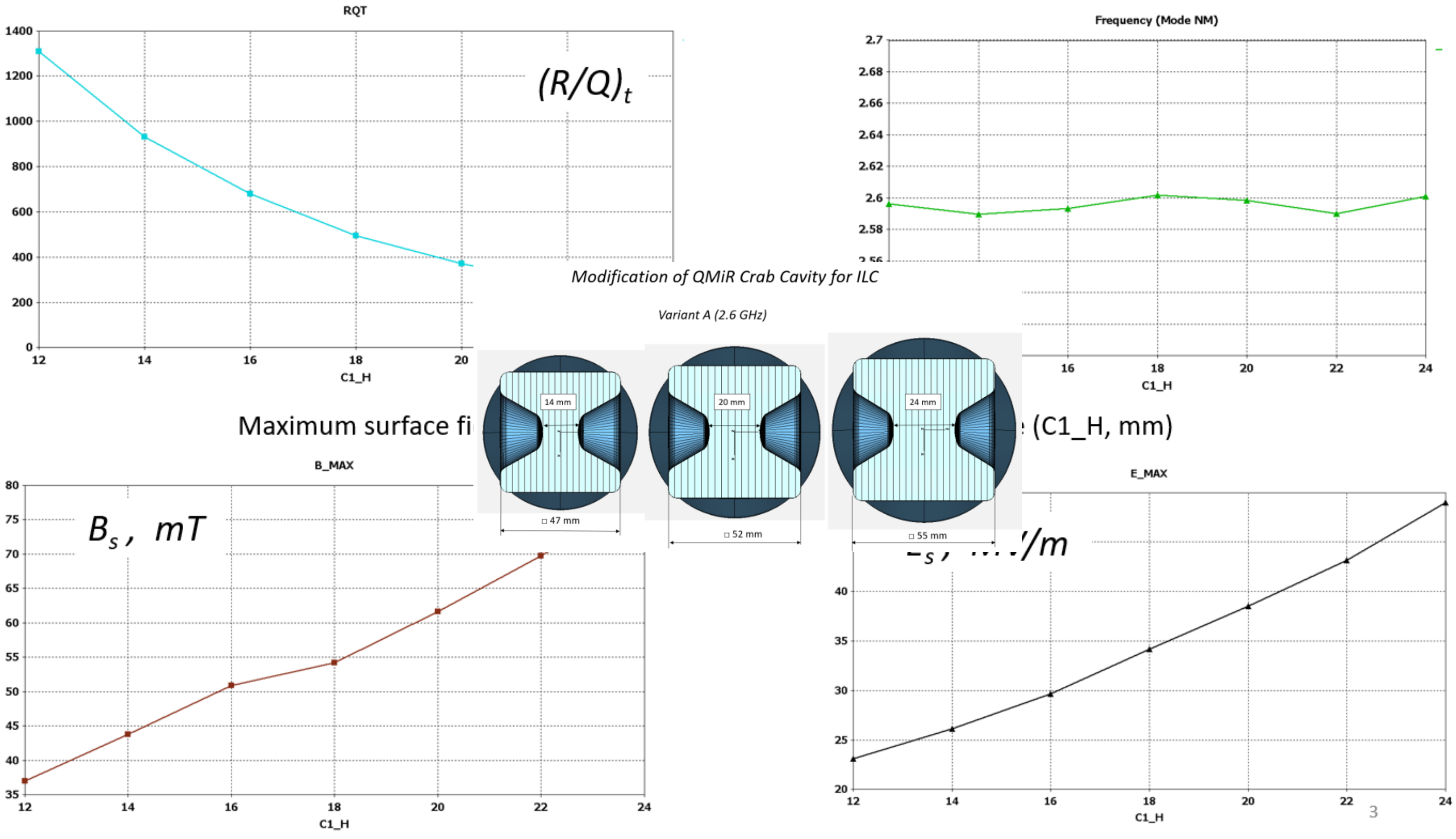




Freq., [GHz]	$(R/Q)_t$, [Ω]	Q_{ext}	R_t [MΩ/m]
2.476	0.03	2400	3e-3
2.675	5.0	6800	1.9

- 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



Modification of QMiR Crab Cavity for ILC

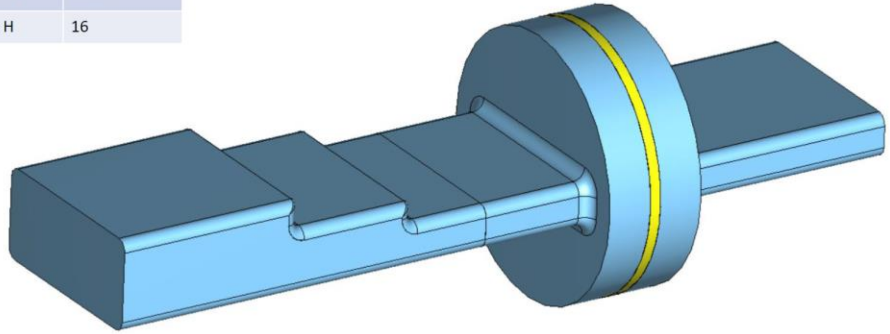
Variant A (2.6 GHz)

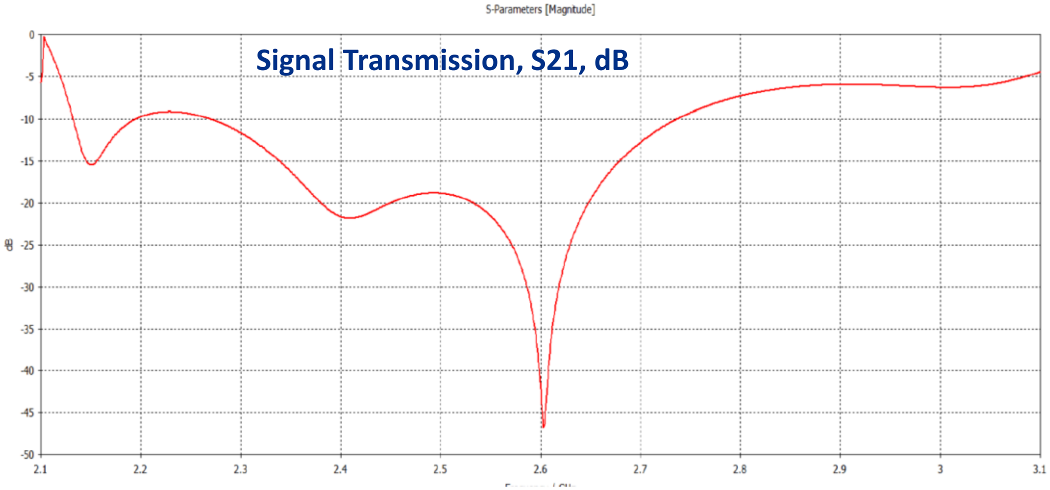
Maximum surface fi

(C1_H, mm)

Design of the Input Ceramic RF Window (by S. Kazakov)

Parameter	Value, mm
Window D	98
Window L	36.6
Ceramic T	4
Ceramic Eps	9.8
Waveguide W	72.14
Waveguide H	16




Signal Transmission, S21, dB

- **Broadband impedance matching**

Thermal Quench Analysis

A. Lunin, et. al., Physics Procedia Vol. 79, 54 –62, 2015

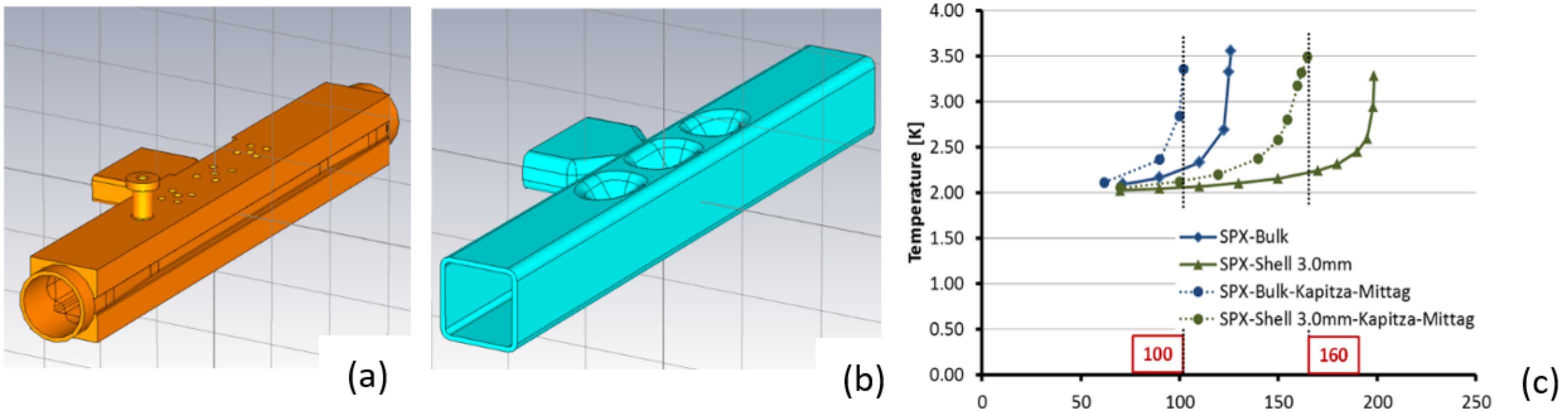
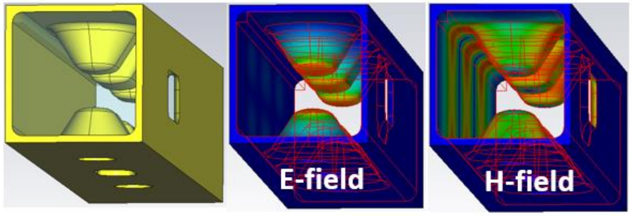
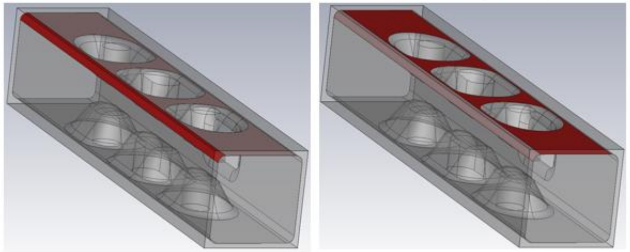


Figure 8. Thermal quench analysis of the QMiR cavity. (a) Cavity model made of bulk Niobium. (b) Cavity model made of 3 mm Niobium shell. (c) Maximum temperature vs peak magnetic field demonstrating thermal quench results for both structure.

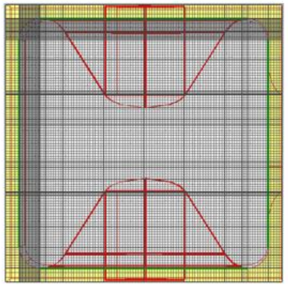
- **Bulk Nb cavity is projected to quench at >100 mT**

QMiR Multipactor Analysis (by I. Gonin)

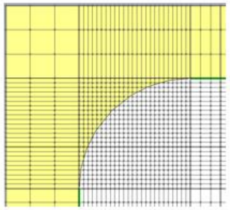




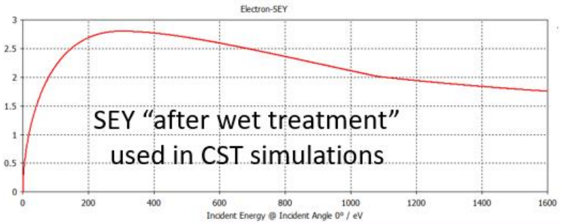
Truncated model for MP calculations
2 areas of the particles source



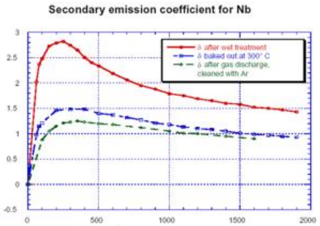
Hexahedral mesh

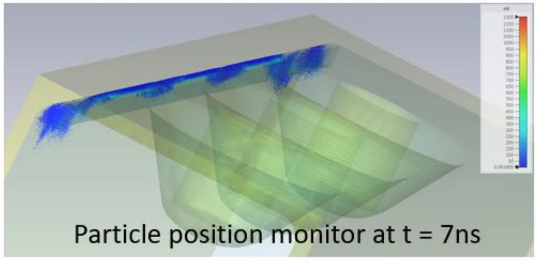


Dense mesh in
expected MP area

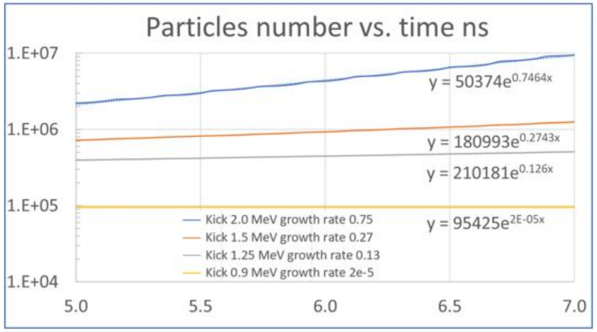


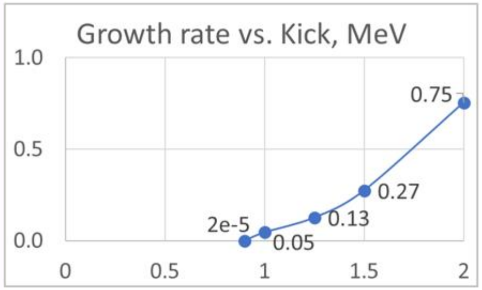
SEY "after wet treatment"
used in CST simulations





Particle position monitor at t = 7ns





Log scale of particles number growth vs. time

MP evidence for >1.5 MeV Kick Voltage

ANL QMiR Cavity Frequency Tuning

Operation	Frequency Shift [MHz]	Expected Frequency [MHz]
Body Trimming*		2958 ± 10
1st Freq. Tuning**	- 156.6 (max)	2811.4 ± 0.1
EB Welding: Weld Shrinkage Weld Bump	 ± 5.7 + 1	
Freq. check after EBW		2812.4 ± 5.7
Chemical Polishing: even NB removal +50% on electrodes	 - 4 + 2	
Freq. check after CP		2812.4
2nd Freq. Tuning***	± 9.7 (max)	2811.4 ± 0.1
Cooling Down to 2K	+ 4	2815.4

*** Assuming additional +0.125” cavity height**
**** Trimming cavity body half, df/dhc ~ -46 MHz/mm**
***** Plastic deformation of all 3 electrodes, df/dhe ~ -75 MHz/mm**

Scaling of QMiR Crab Cavity for ILC