Wakefield & Cavity based Monitors:

Fermilab BPM Development Plans

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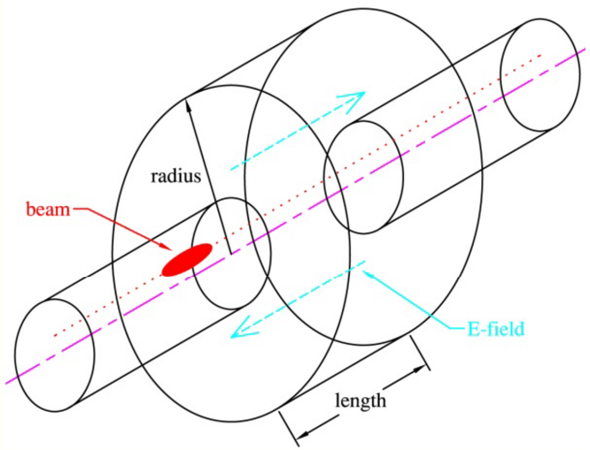
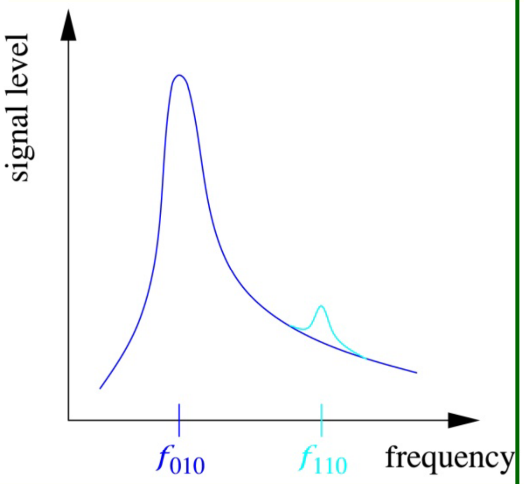
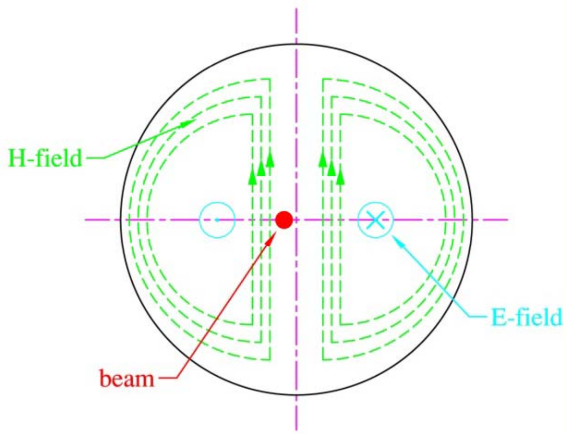
Agenda

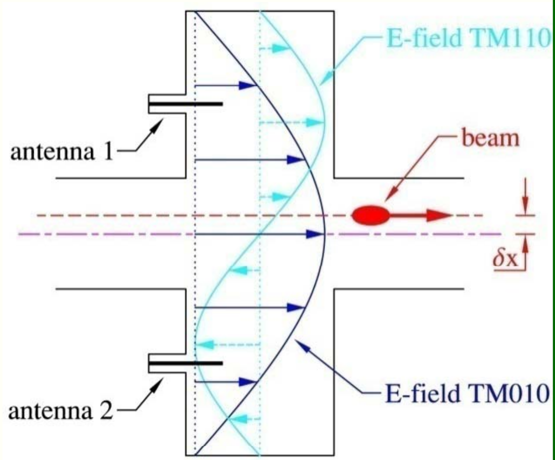
- Introduction
- Examples of CM-free, high-resolution cavity BPMs
- Cold ILC cavity BPM R&D
- Cold cavity BPM ideas for NML
- Conclusions

Cavity BPM Principle



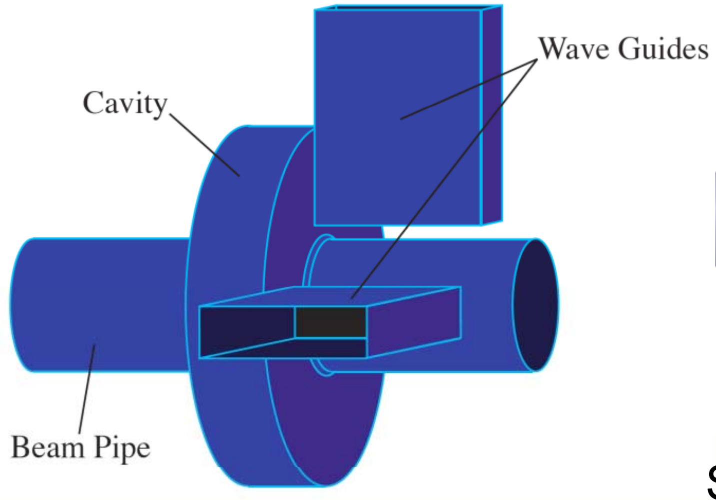


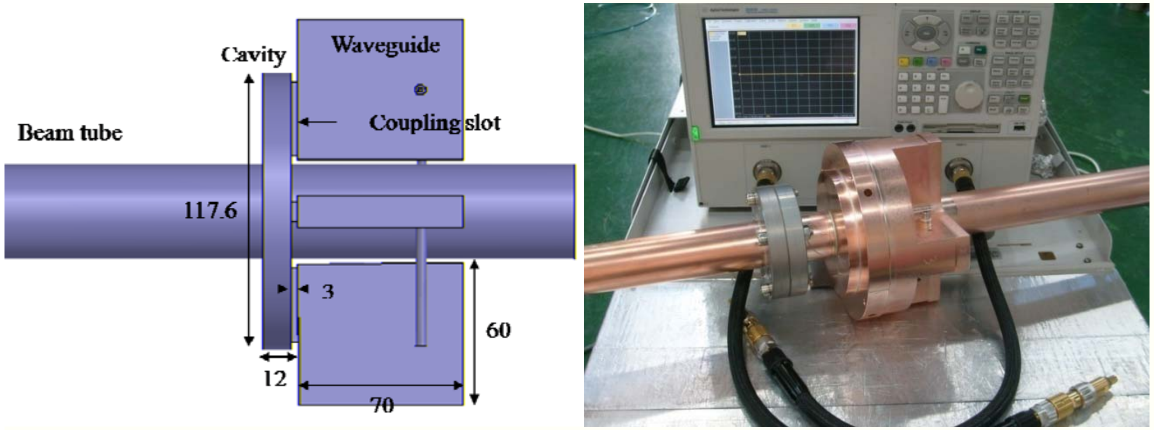




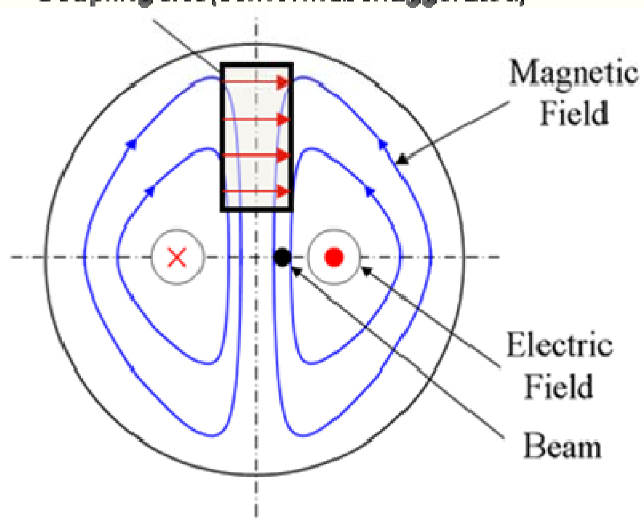
- "Pillbox" cavity BPM
  - Eigenmodes:
    $$f_{mnp} = \frac{1}{2\pi\sqrt{\mu_0\varepsilon_0}}\sqrt{\left(\frac{j_{mn}}{R}\right)^2+\left(\frac{p\pi}{l}\right)^2}$$
  - Beam couples to
    $$E_z = C J_1\left(\frac{j_{11} r}{R}\right)\cos\theta\, e^{i\omega t}$$
    dipole (TM_{110}) and monopole (TM_{010}) modes
  - Common mode (TM_{010}) suppression by frequency discrimination
  - Orthogonal dipole mode polarization (xy cross talk)
  - Transient (single bunch) response (Q_L)
  - Normalization and phase reference

CM-"free" Cavity BPM





S-Band cavity BPM for ATF2 (KNU-LAPP-RHUL-KEK)



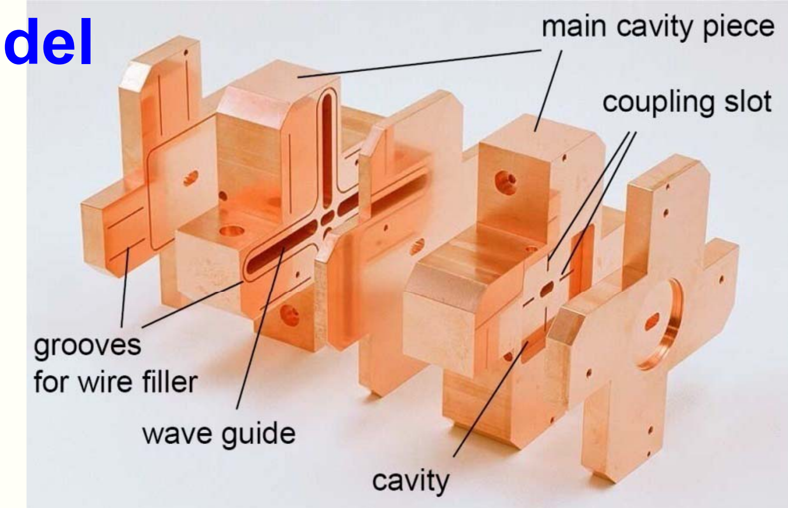
- **Waveguide TE_{01}-mode HP-filter**

$$f_{010} < \quad f_{10} = \frac{1}{2a\sqrt{\varepsilon\mu}} \quad < f_{110}$$

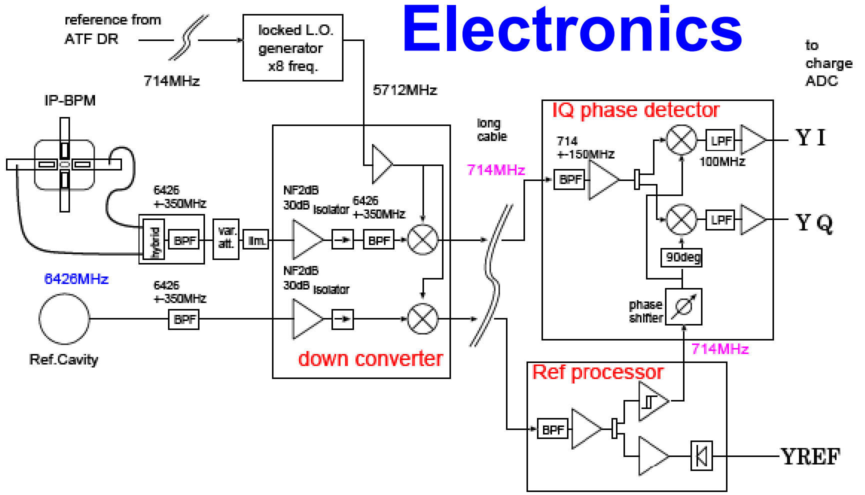
  between cavity and coaxial output port
- **Finite *Q* of TM_{010} still pollutes the TM_{110} dipole mode!**

Example: KEK C-Band IP-BPM

Model



Electronics



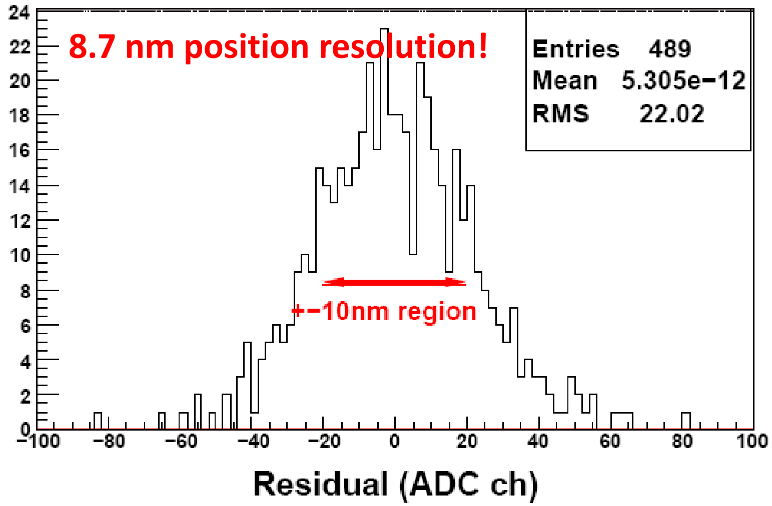
Characteristics

- Narrow gap to be insensitive to the beam angle.
- Small aperture (beam tube) to keep the sensitivity.
- Separation of x and y signal. (Rectangular cavity)
- Double stage homodyne down converter.

Design parameters

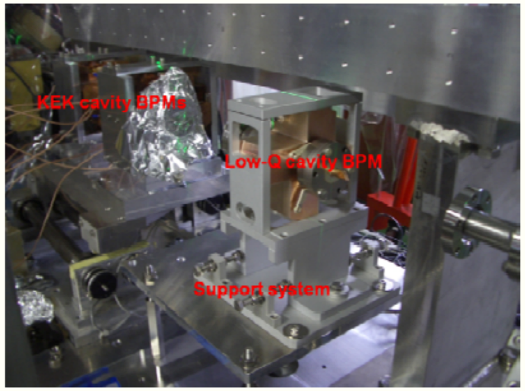
Port	f (GHz)	β	Q_0	Q_{ext}
X	5.712	1.4	5300	3901
Y	6.426	2	4900	2442

Results

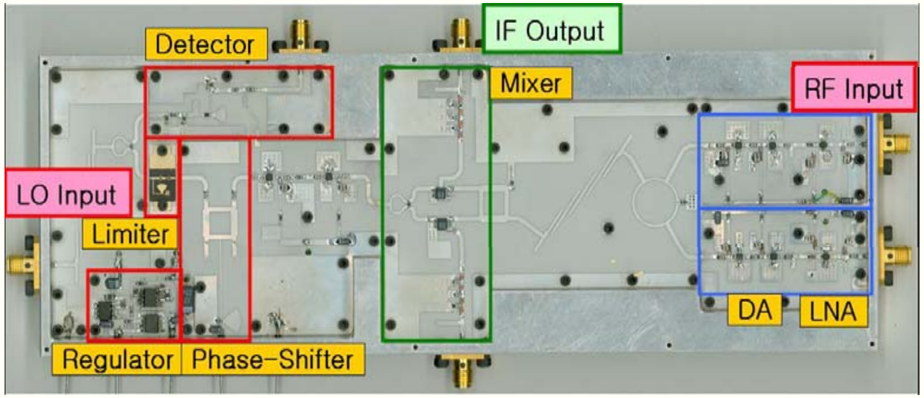


Example: KNU-KEK Low-Q BPM

Model



Electronics



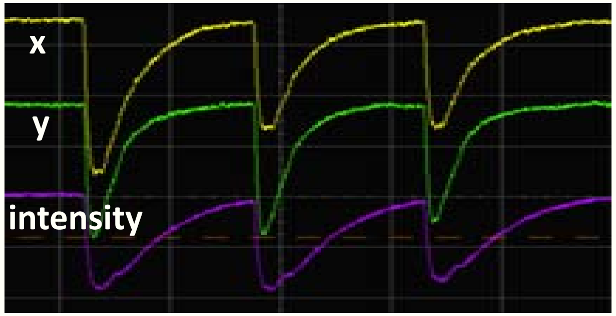
Characteristics

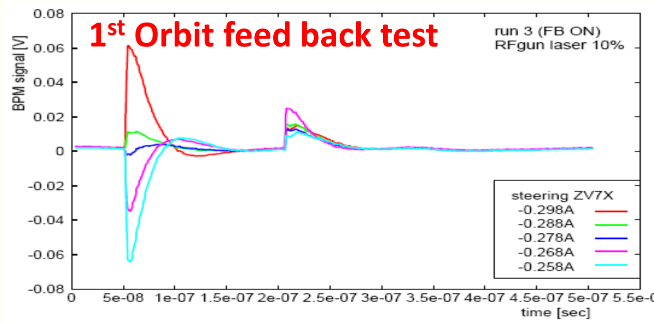
- Sam basic idea as the KEK IP-BPM.
- Short decay time, 20 ns for x and y signals.
- Short decay time (30 ns) for the reference signal.
- Single stage homodyne down-converter.
- LO-signal from reference cavity.

Design parameters

Port	f (GHz)	β	Q_0	Q_{ext}
X	5.712	8	5900	730
Y	6.426	9	6020	670
Reference	6.426	0.0117	1170	100250

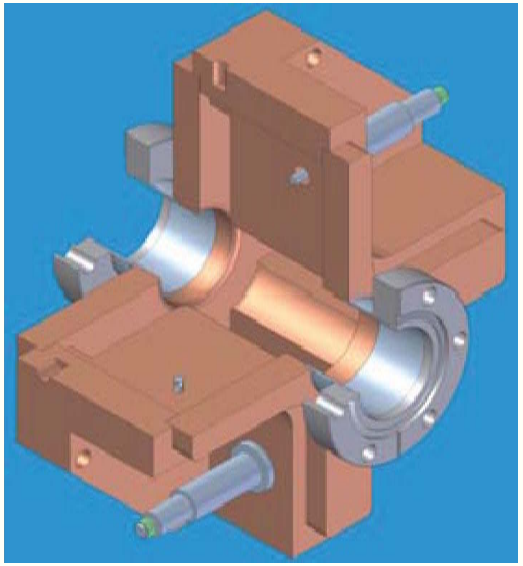
Results

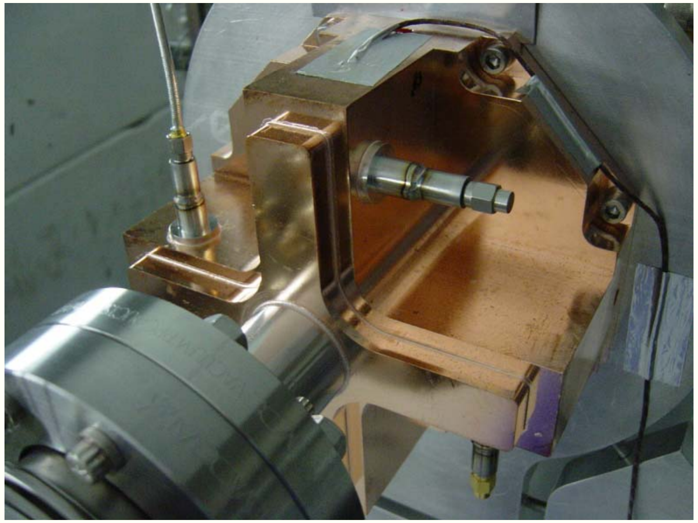


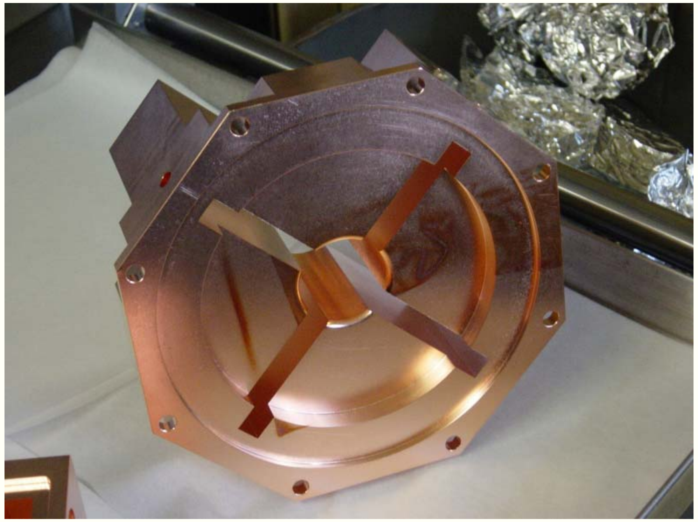


ILC Cryomodule Cavity BPM

- **SLAC approach:**
  - S-Band design with reduced aperture (35 mm)
  - Waveguide is open towards the beam pipe for better cleaning
  - Successful beam measurements at SLAC-ESA, ~0.8 μm resolution
  - No cryogenic tests or installation
  - Reference signal from a dedicated cavity or source





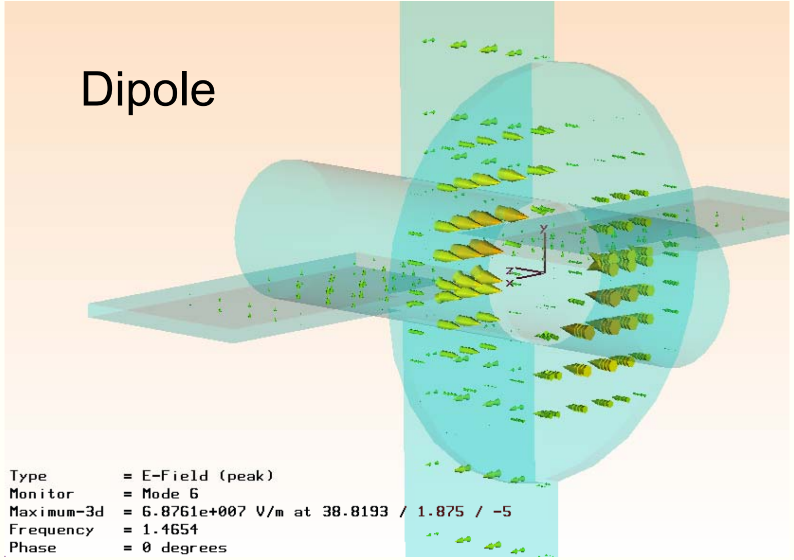


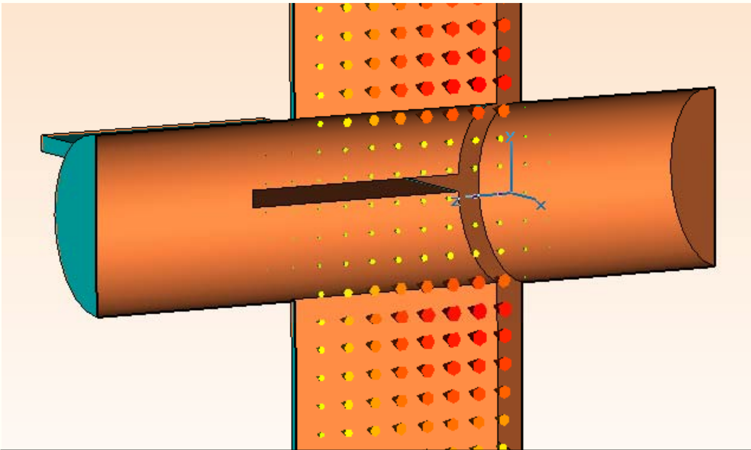
Cold BPM for an ILC Cryomodule

- ILC beam parameters, e.g.
  - Macro pulse length t_{pulse} = 800 µs
  - Bunch-to-bunch spacing $\Delta t_b \approx 370$ ns
  - Nominal bunch charge = 3.2 nC
- Beam dynamic requirements
  - < 1 µm resolution, single bunch (emittance preservation, beam jitter sources)
  - Absolute accuracy < 200 µm
  - Sufficient dynamic range (intensity & position)
- Cryomodule quad/BPM package
  - Limited real estate, 78 mm beam pipe diameter!
  - Operation at cryogenic temperatures (2-10 K)
  - Clean-room class 100 and UHV certification

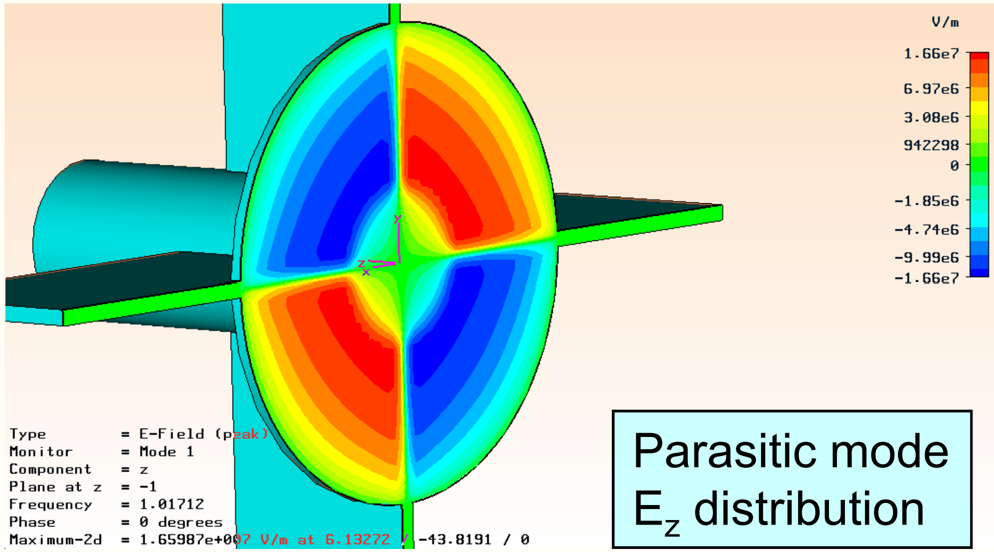
SLAC BPM Scaled to L-Band

Mode	Frequency
1	1.017 – Parasitic E_{11}-like
2	1.023 – Parasitic E_{21}-like
3	1.121 – Monopole E_{01}
4	1.198 - Waveguide
5	1.465 - Dipole E_{11}
6	1.627





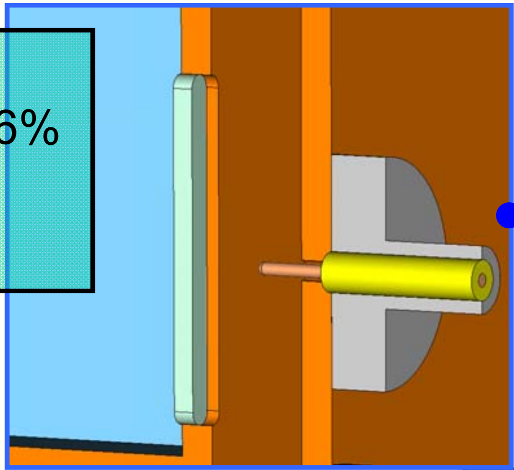
Parasitic mode. Coupling through horizontal slots is clearly seen

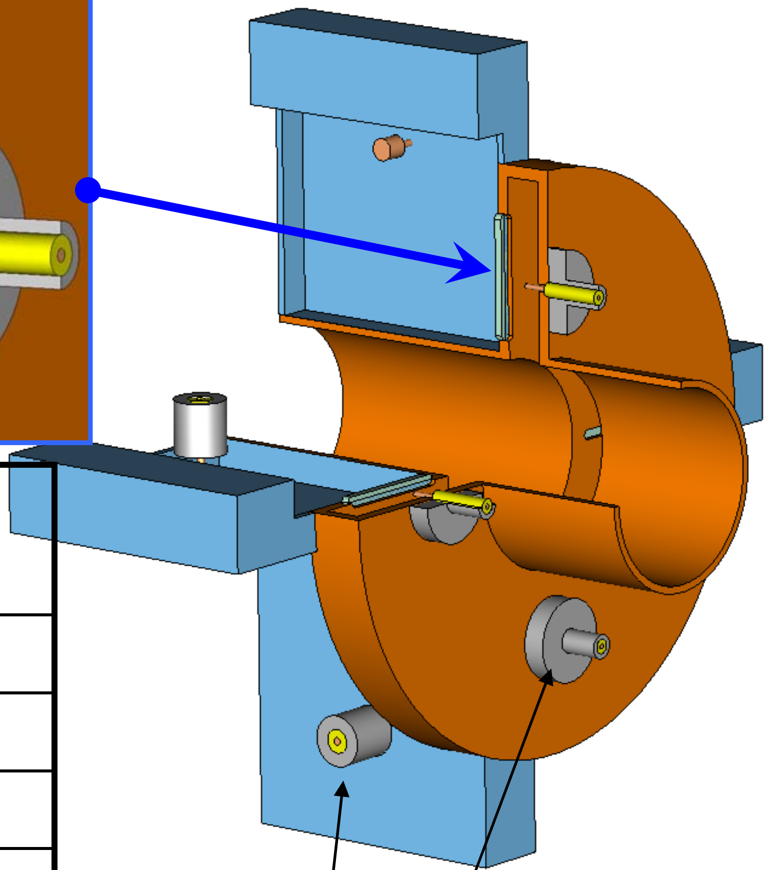


Parasitic mode E_z distribution

Fermilab L-Band Design

Window –
Ceramic brick of alumina 96%
$\varepsilon_r = 9.4$
Size: 51x4x3 mm

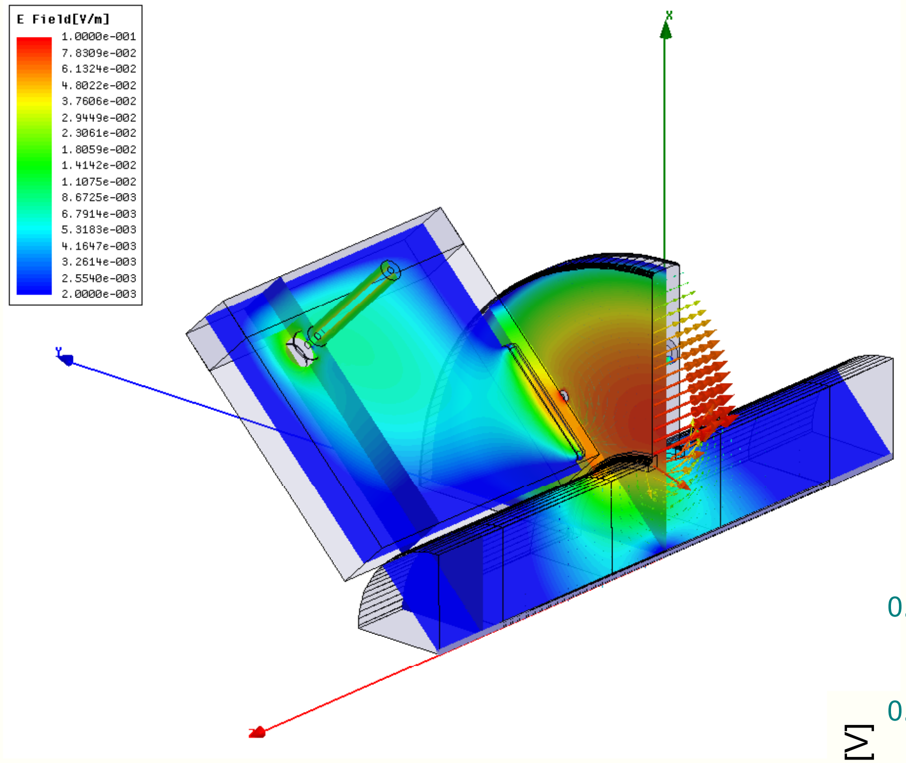




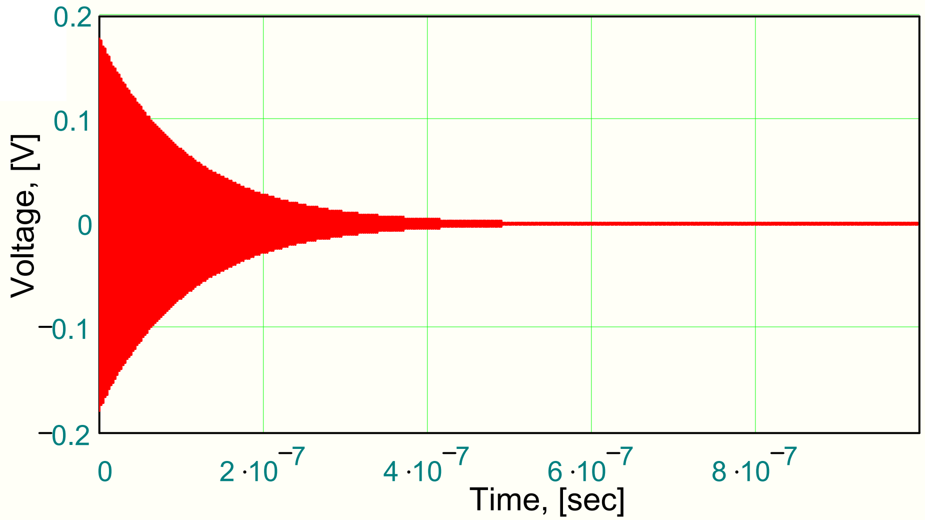
Frequency, GHz, dipole **monopole**	**1.468** **1.125**
Loaded Q (both monopole and dipole**)**	**~ 600**
Beam pipe radius, mm	**39**
Cell radius, mm	**113**
Cell gap, mm	**15**
Waveguide, mm	**122x110x25**
Coupling slot, mm	**51x4x3**

N type receptacles, 50 Ohm

HFSS Simulations: Dipole Mode

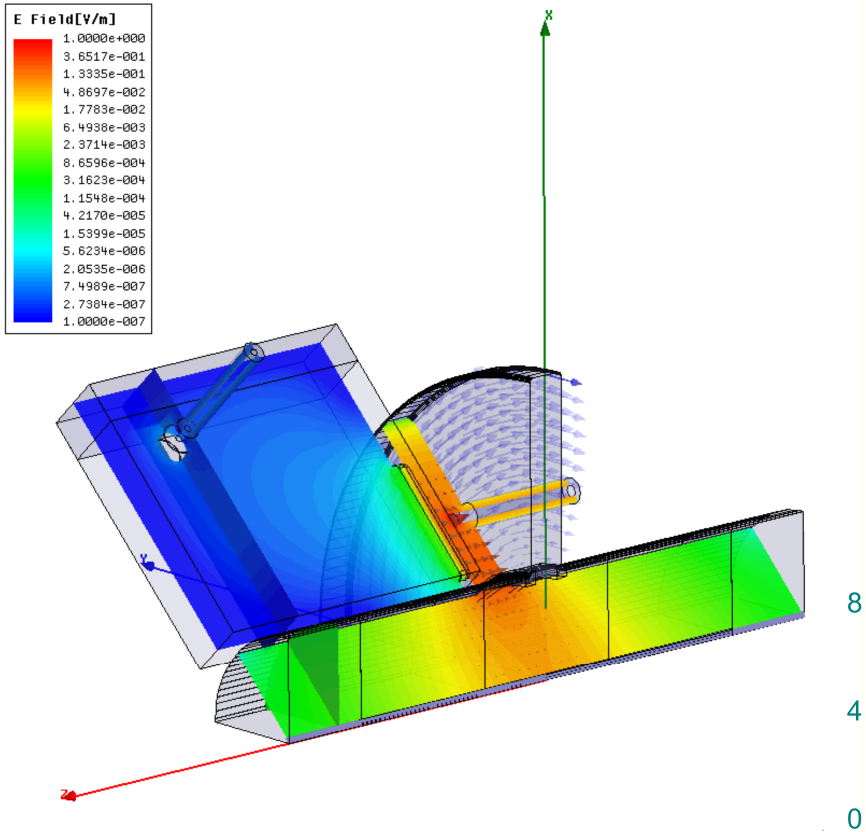


Frequency, [GHz]	1.480
Q, External Q, Surface (Cu) Q, Ceramic(AL_2O_3)	500 22000 5600
Test charge, [coulomb] (X=0, Y=1mm)	1E-9
Stored energy, [joule]	5.9.0E-11
Output Voltage at T=0*, [V]	0.24

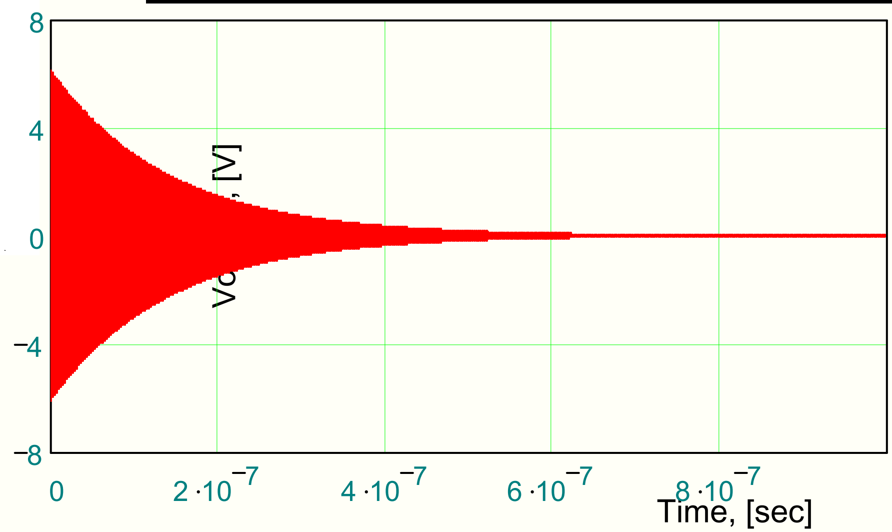


* Normalized to 50 Ohm,
The total signal combines with two ports

Simulations: Monopole Mode

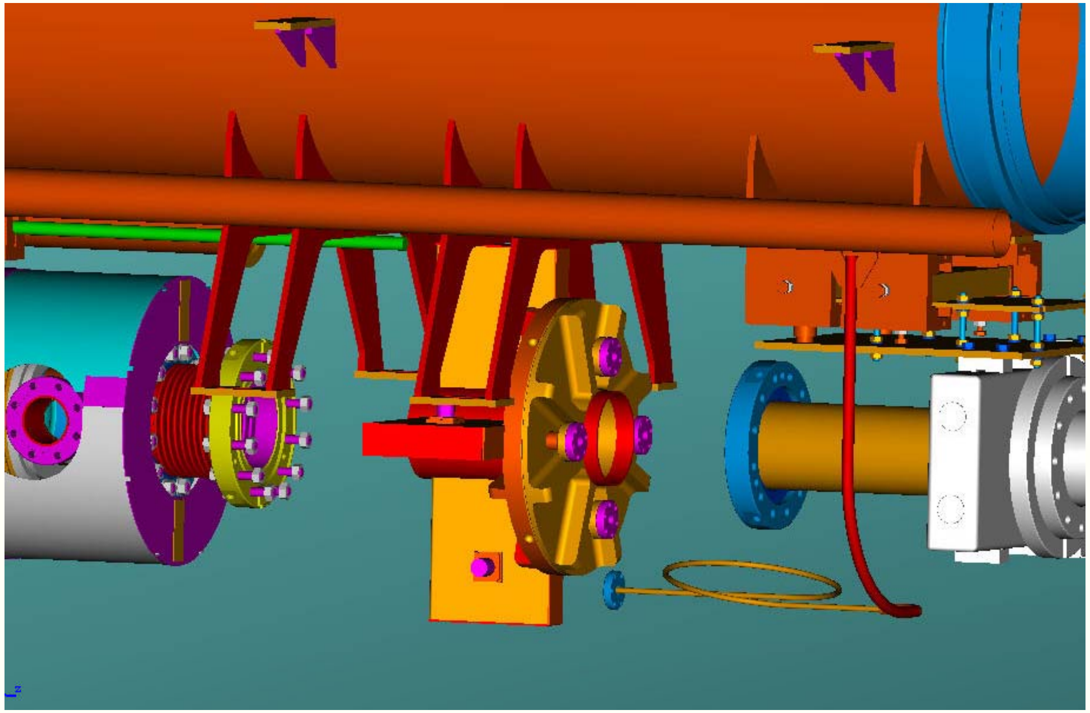


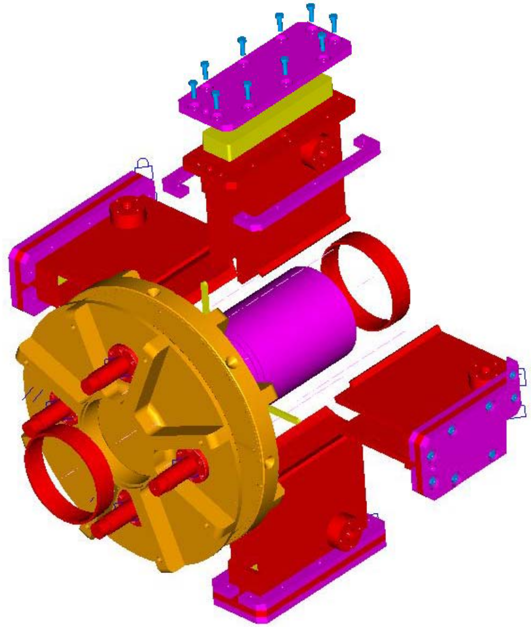
Frequency, [GHz]	1.120
Q, External Q, Surface (Cu) Q, Ceramic(AL_2O_3)	550 19500 7.9E6
Test charge, [coulomb] (X=0, Y=1mm)	1E-9
Stored energy, [joule]	6.1E-8
Output Voltage at T=0*, [V]	6.1
Coupling with TM_{11} port, Output Voltage at T=0*, [V]	5.6E-5

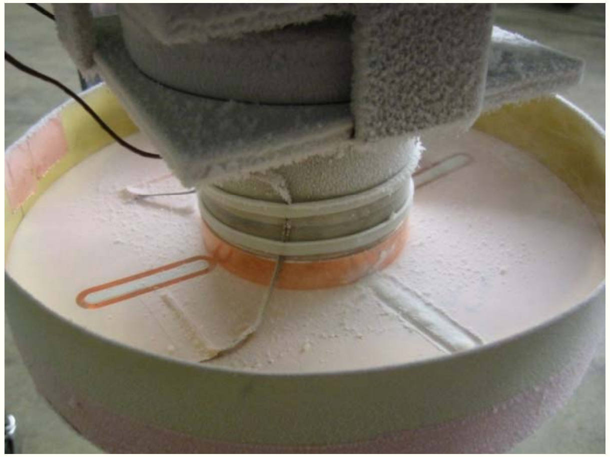


* Normalized to 50 Ohm,
The total signal combines with four ports

Cold L-Band ILC BPM R&D

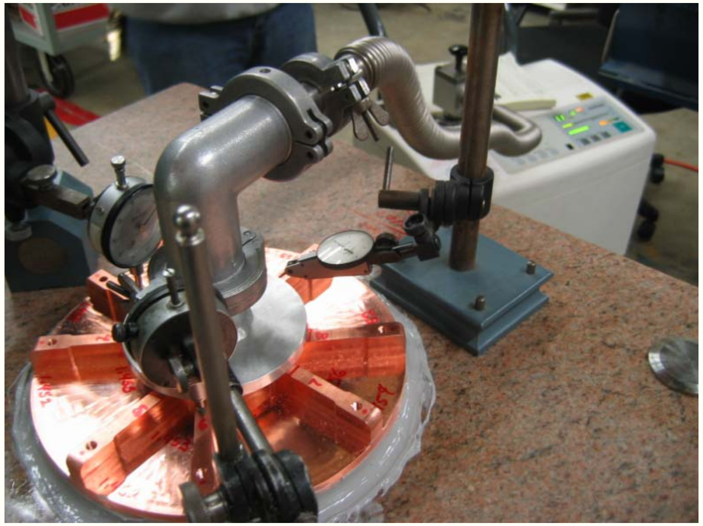


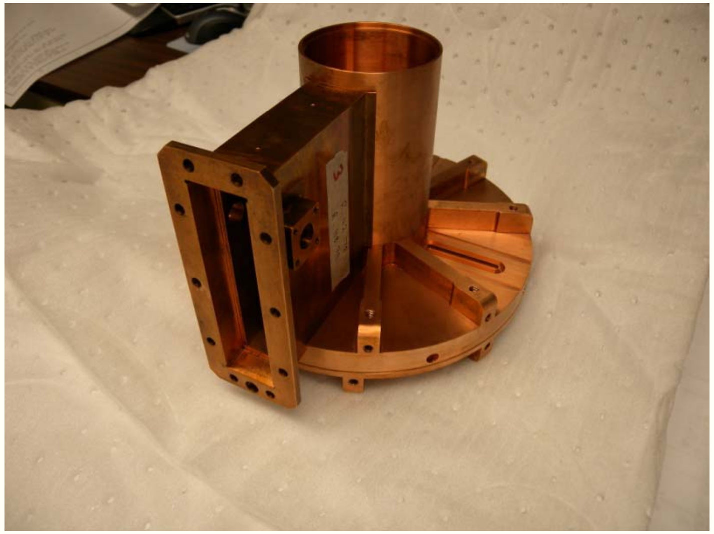




- **Status:**
  - **EM simulations & construction finalized**
  - **Brazing and low temperature UHV tests**
  - **All parts manufactured, ready for brazing**
  - **Prototype has “warm” dimensions**

Cold ILC L-Band Cavity BPM

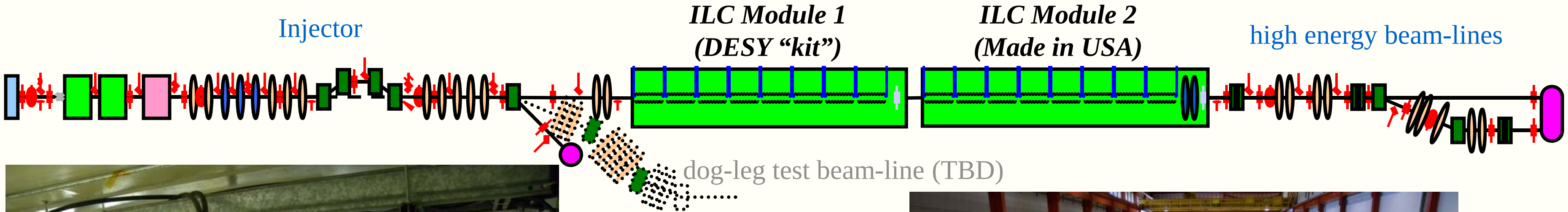


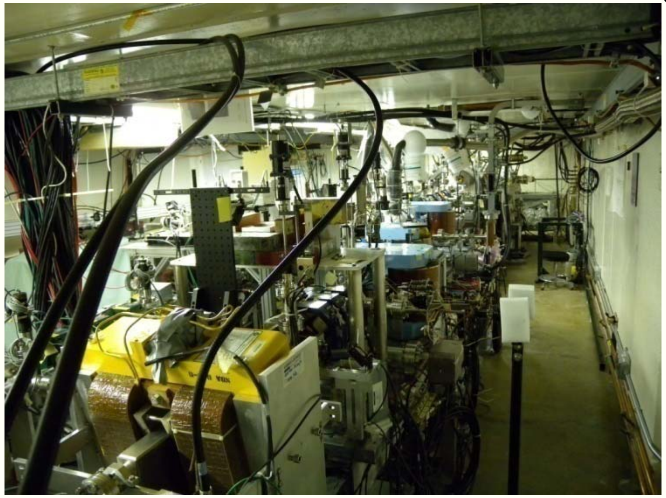


ILC Cavity BPM Summary

- Cold L-Band cavity BPM, fits in an ILC cryostat, 78 mm aperture.
- Waveguide-loaded pillbox with slot coupling.
- Dimensioning for f_{010} and f_{110} symmetric to f_{RF},
  f_{RF} = 1.3 GHz, f_{010} = 1.125 GHz, f_{110} = 1.468 GHz.
- $(R_{sh}/Q)_{110} \approx 14\ \Omega$ (1 mm beam displ.), providing < 1 µm resolution.
- Dipole- and monopole ports, no reference cavity for intensity signal normalization and signal phase (sign).
- $Q_{load} \approx 600$ (~10 % cross-talk at 300 ns bunch-to-bunch spacing).
- Minimization of the X-Y cross-talk (dimple tuning).
- Simple (cleanable) mechanics.
- Many EM-simulations (HFFS, MWS) analyzing dimensions and tolerances (see *A. Lunin, et.al*, DIPAC 2007).
- Successful tests of the ceramic slot windows, i.e. four thermal cycles 300 K -> 77 K -> 300 K
- Next Steps:
  - Warm prototype finalization (brazing), RF measurements, tuning, beam tests at the A0-Photoinjector.

SCRF Test Accelerator ("NML")



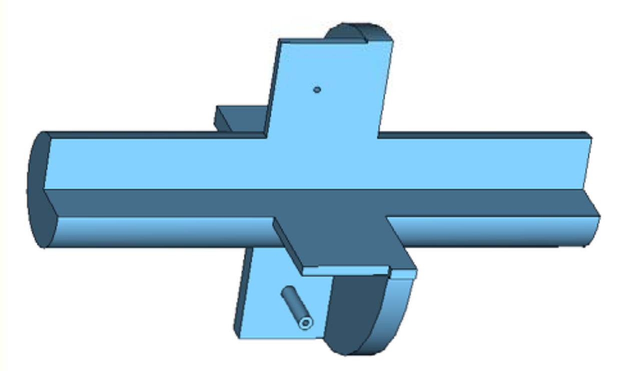


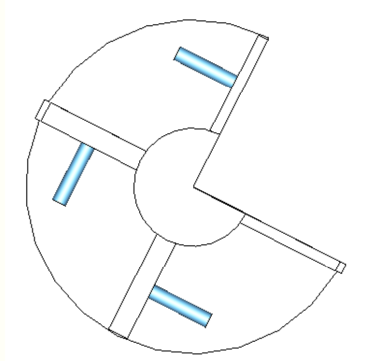
A0-Photoinjector

NML SCRF
Test Accelerator

- **ILC & Project X *like* e-beam operations, ~400 MeV, 1 ms beam pulse, 5 Hz repetition-rate**
  - **ILC: single bunch (bunch-by-bunch), $\Delta t_b \approx 370$ ns, 3.2 nC**
  - **Project X: multi-bunch, $f_b = 1300 / 325$ MHz, ~11 / 44 pC**

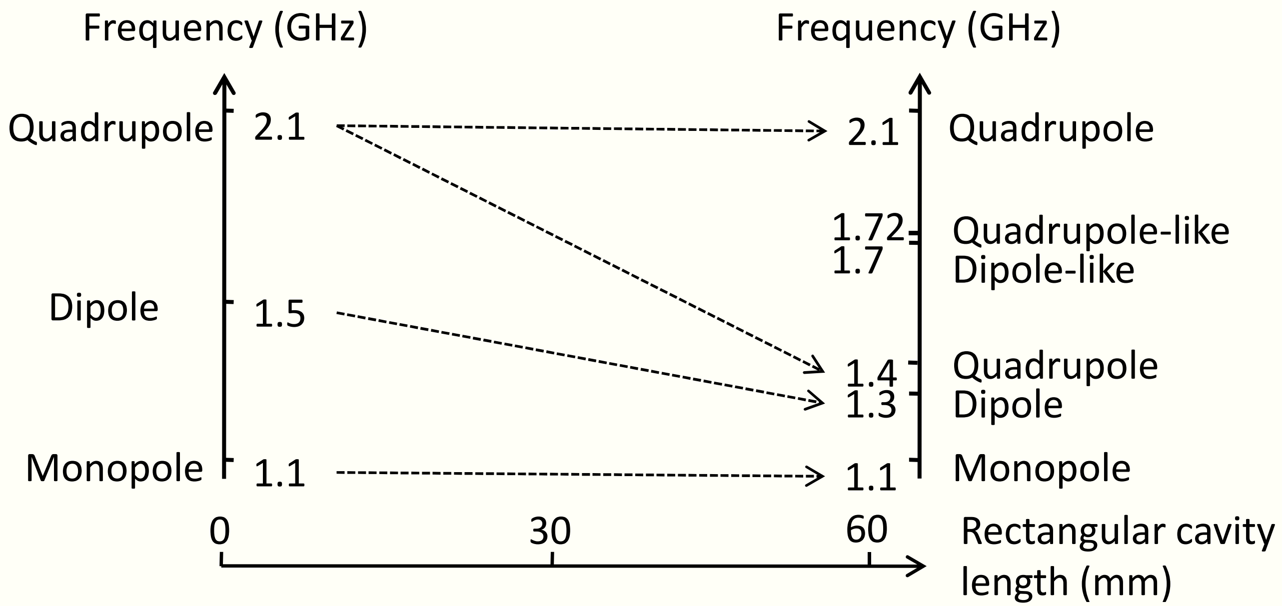
1.3 GHz Cavity BPM Design





- **All previous requirements apply:**
  - **Cryogenics, dimensions, resolution, etc.**
  - **f_{110} = 1.3 GHz, to operate with Project X (multi-bunch) and ILC (single bunch) like beams**
- **Cavity diameter ~230 mm (to fit into the cryomodule), aperture: 78 mm.**
- **Rectangular cavities (waveguides) for CM suppression.**
- **Intensity and phase reference signals from HOM coupler (2^{nd} monopole mode pass-band TM_{020} ~2.6 GHz)**

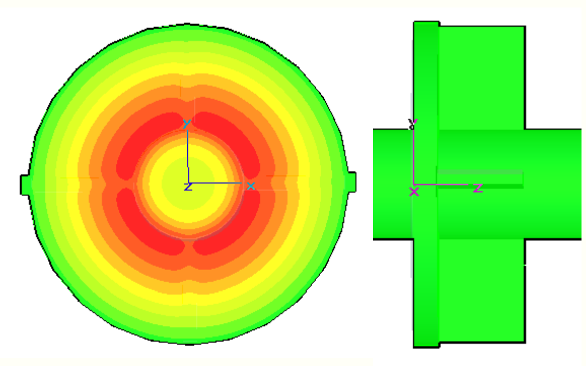
Eigenmode Characterization



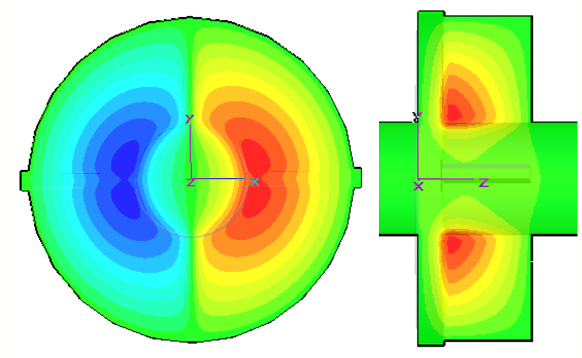
- **Rectangular cavities, open to the beam pipe (for cleaning) generate additional unwanted modes.**
- **Dipole mode leakage to the beam pipe causes a higher sensitivity to a beam trajectory angle or BPM tilt**

$$(R/Q)_{angle} = (R/Q)_{position} \times (\frac{1}{x} \frac{L}{2\sqrt{2}} \sin(\frac{\omega L}{4c}))^2 x'^2$$

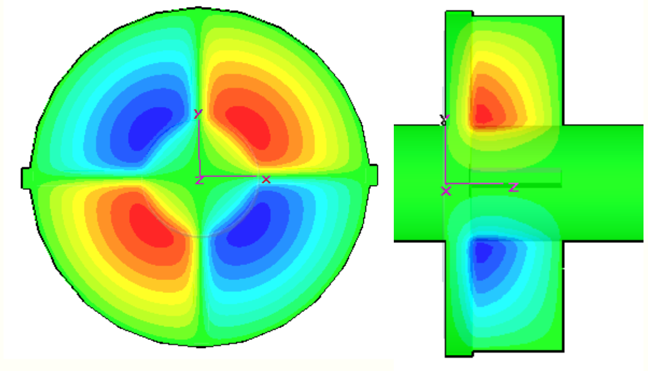
Eigenmodes of coupled Cavities



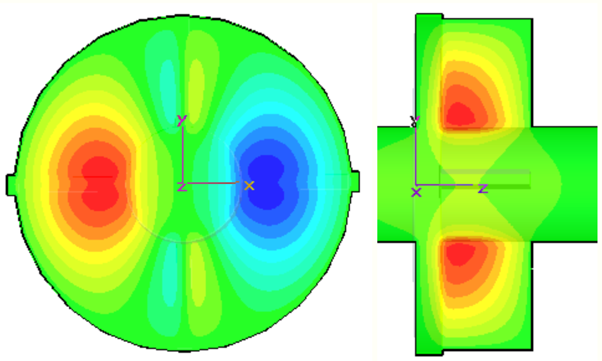
Monopole mode
1.1 GHz



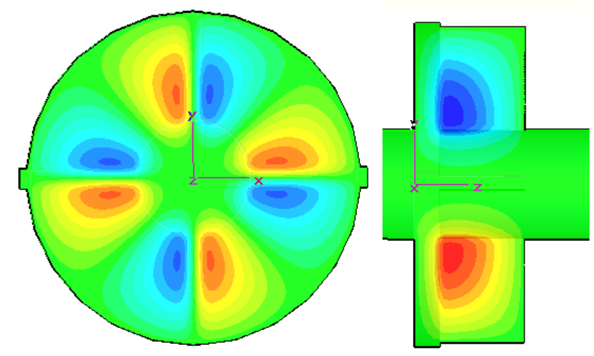
Dipole mode
1.3 GHz



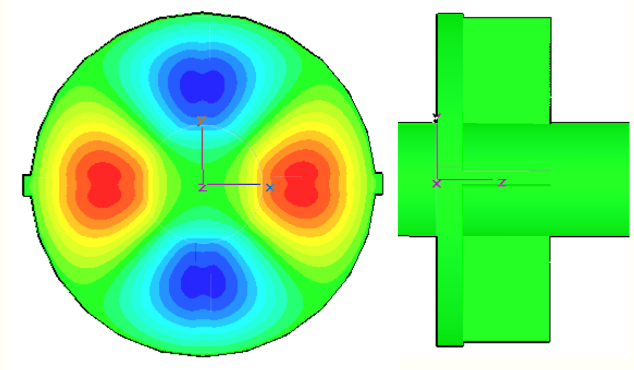
Quadrupole mode
1.4 GHz



Dipole-like
1.70 GHz

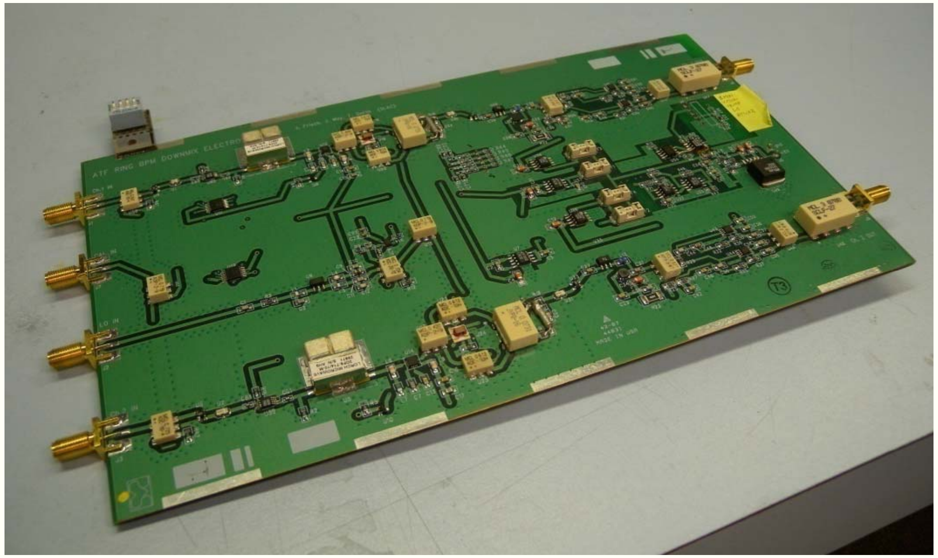


Quadrupole-like
1.72 GHz



Quadrupole mode
2.07 GHz

Read-out Electronics



- Analog down-mixer(s) (single or dual stage, IF ≈ 30-50 MHz)
- Digitizer & FPGA-based down-converter, digital signal processing in base-band.

Conclusions

- **Resonant BPMs with waveguide-based CM suppression achieved <10 nm resolution (C-Band, Q_{load} ≈ 3000).**
- **A cold L-Band cavity BPM prototype with 78 mm aperture, Q_{load} ≈ 600, resolution < 1 µm, is in fabrication.**
- **A cold 1.3 GHz cavity BPM for operation at the NML test accelerator is in an early design stage.**

- **A personal remark to the CLIC BPM requirements:**
  - **Large quantities require an as simple as possible approach!**
  - **A cavity BPM solution is in reach, when relaxing on the time resolution (i.e. averaging over the entire macropulse).**
  - **Read-out and calibration electronics need to be pushed towards digital signal processing to reduce costs and simplify DAQ.**