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Cold Cavity BPM R&D for the ILC

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Abstract. A cold L-Band cavity BPM for installation in a SCRF cryomodule is currently under development at Fermilab. The BPM has to meet the ILC BPM specifications, i.e. < 1 µm single bunch, single pass resolution, going along with sufficient accuracy and reproducibility. Real estate limitations and the superconductive RF environment require some special considerations for this design.

INTRODUCTION

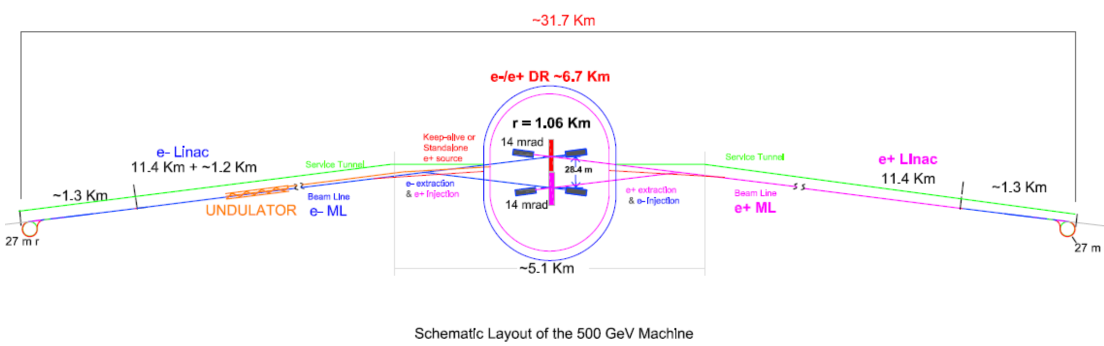

FIGURE 1. Layout of the International Linear Collider (ILC).

A 500 GeV center-of-mass (CM) International Linear Collider (ILC) is currently under study as the next large particle accelerator for high energy physics (HEP) to test "Mother Nature's" laws. Hearts of the machine are two ~ 10 km long superconducting RF main linacs, providing the required beam energy (see Fig. 1).

A crucial point is beam transport through the main linacs, i.e. preserving its low-emittance, in order to achieve the luminosity goal. Table 1 gives an overview of the ILC beam parameters, showing a vertical emittance of ~ 0.04 mm mrad, which is equivalent to a 5 nm (!) vertical beam size at the IP. Particle tracking studies of the main linac lattice, using different orbit correction methods, pointed to the need of a high resolution beam orbit measurement. In order to preserve the emittance, and therefore the luminosity, to a > 90 % level, the resolution requirement of the beam position monitors (BPM) is well below 5 µm. For diagnostics purposes, i.e. to find

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TABLE 1. ILC beam parameters (nominal).		
beam energy	=	2 x 250 GeV
luminosity L	=	2 x 10^{34}
rep. frequency f_{rep}	=	5 Hz
macro pulse length t_{pulse}	=	800 µs
bunch spacing $\Delta\ t_b$	=	369 ns
bunch charge	=	3.2 nC
bunch length σ_z	=	300 µm
vert. emittance $\gamma\ \varepsilon_y^*$	=	0.04 mm mrad
RMS energy spread	=	0.1 %
β_x^* (IP)	=	21 mm
B_y^* (IP)	=	0.4 mm
hor. beamsize (IP) σ_x	=	500 nm
vert. beamsize (IP) σ_y	=	5 nm

sources of beam jitter, fluctuations and other problems, we have to be able to detect beam displacements in the order of a fraction of the nominal transverse beam size. Therefore a single bunch (bunch-by-bunch, measurement time < 369 ns) resolution < 1 µm is required for the main linac BPMs.

"COLD" BEAM POSITION MONITORS FOR THE ILC

Table 2 shows an overview of the major beam instrumentation systems needed in the different ILC accelerator areas. The beam position monitors (BPM) are the most complex, while also most important distributed beam instrumentation system in the ILC accelerator complex. About 600, of a total of ~ 4000 BPMs, are located inside every 3rd cryomodule, flanged to a superconducting quadrupole magnet package; these "cold" BPMs are used in the Main Linac (ML) and in the Ring-To-Main-Linac (RTML) areas. Along the ~ 10 km Main Linac the BPMs are almost the only beam instrumentation, therefore they are a key component to diagnose problems and errors.

The requirements for the cold BPMs are very specific, also because of their neighborhood to the superconducting 1.3 GHz RF cavities:

- A real estate of ~ 170 mm length and 78 mm circular beam pipe aperture is given.
- The BPM has to operate in a cryogenic environment (~ 4 K).
- A cleanroom class 100 certification is required, because of the nearby superconducting cavities.
- The BPM has to operate in ultra-high vacuum (UHV).
- A single bunch (bunch-by-bunch, i.e. < 350 ns measurement time) resolution of < 1 µm is required to preserve the vertical emittance along the Main Linacs. This high resolution will also enable the use of the BPMs for troubleshooting and diagnostics e.g. spot sources of beam jitter.

INSTRUMENT requirements (e.g. resolution)	ILC ACCLELRATOR AREA					
	e^--source	**e^+-source**	**DR**	**RTML**	**ML**	**BDS**
Button/stripline BPM 10…30 µm ($e^{-/+}$-source) <0.5 µm averaged (DR)	69	400	2x747			
Cavity BPM (warm) < 0.1…0.5 µm (C, S-Band) 1…5 µm (L-Band)		109 (C)		2x649 (C) 2x27 (L)		42 (L) 14 (S) 262 (C)
Cavity BPM (cold) ~0.5…2 µm (L-Band)				2x28	2x280	
Laserwire ~ 10 % of tr. beam size (0.05…0.5 µm)	8	20	2x1	2x12	2x3	8
DMC dE~0.01% / s_z~100 µm (< 1 µm)	3	4		2x2		2 (cold)
Beam phase monitor 0.01^0(BC)…0.1^0@1.3GHz	4	2		2x3		
Wirescanner	12	8				
Beam current monitors 0.5…1 % of bunch charge	7	11	2x1	2x2	2x3	10
Optical monitors	6	17	2x2	2x8		11
BLM (PMT/IC) < 0.01 % of total beam int.	60/2	400/20	2x40/4	2x25/2	2x325/10	100/10
Feedback systems	5	10	2x2	2x1	2x10	12

Table 2: Counts of beam instrumentation system installations in the ILC accelerator complex, along with some basic requirements (DR: Damping Rings, RTML: Ring-To-Main-Linac areas, ML: Main Linacs, BDS: Beam Delivery System).

- The absolute alignment error between electrical center of the BPM and magnetic center of the corresponding quadrupole should be < 200 µm.

Related issues to the cold BPM pickup are the cold RF feedthroughs, the RF cabling inside the cryostat and the read-out system for the pickup signals.

A "COLD" CM-FREE CAVITY BPM FOR THE ILC

There are basically two possible ways to approach the cold BPM requirements of the ILC:

- A dedicated, high resolution BPM based on a common mode (CM) free dipole mode cavity BPM pickup (baseline design).
- The use of a simple, button-style BPM pickups of low or moderate single bunch resolution in combination with a signal processing scheme of a beam excited dipole mode on the higher-order mode (HOM) couplers, offering a high resolution BPM measurement (alternative design).

Other ongoing cold BPM developments include a modified re-entrant coaxial cavity BPM (CEA-Saclay), as well as a CM-free S-Band dipole mode cavity BPM with reduced aperture (~ 35 mm) (SLAC).

Cavity BPM Principle

A cylindrical "pillbox" having conductive (metal) wall dimensions of radius *R* and length *l* resonates at eigenfrequencies:

$$f_{mnp} = \frac{1}{2\pi\sqrt{\mu_0\varepsilon_0}}\sqrt{\left(\frac{j_{mn}}{R}\right)^2 + \left(\frac{p\pi}{l}\right)^2}$$

This resonator can be utilized as passive, beam driven cavity BPM by assembling it into the vacuum beam pipe. A subset of these eigenmodes is excited by the beam, for use as BPM the lowest transverse-magnetic dipole mode TM_{110} is of interest. Its

$$E_z = C J_1\left(\frac{j_{11} r}{R}\right)\cos\phi\, e^{i\omega t}$$

field component couples to the beam, with almost linear dependence to the beams displacement r, and beam intensity (hidden in the constant *C*).

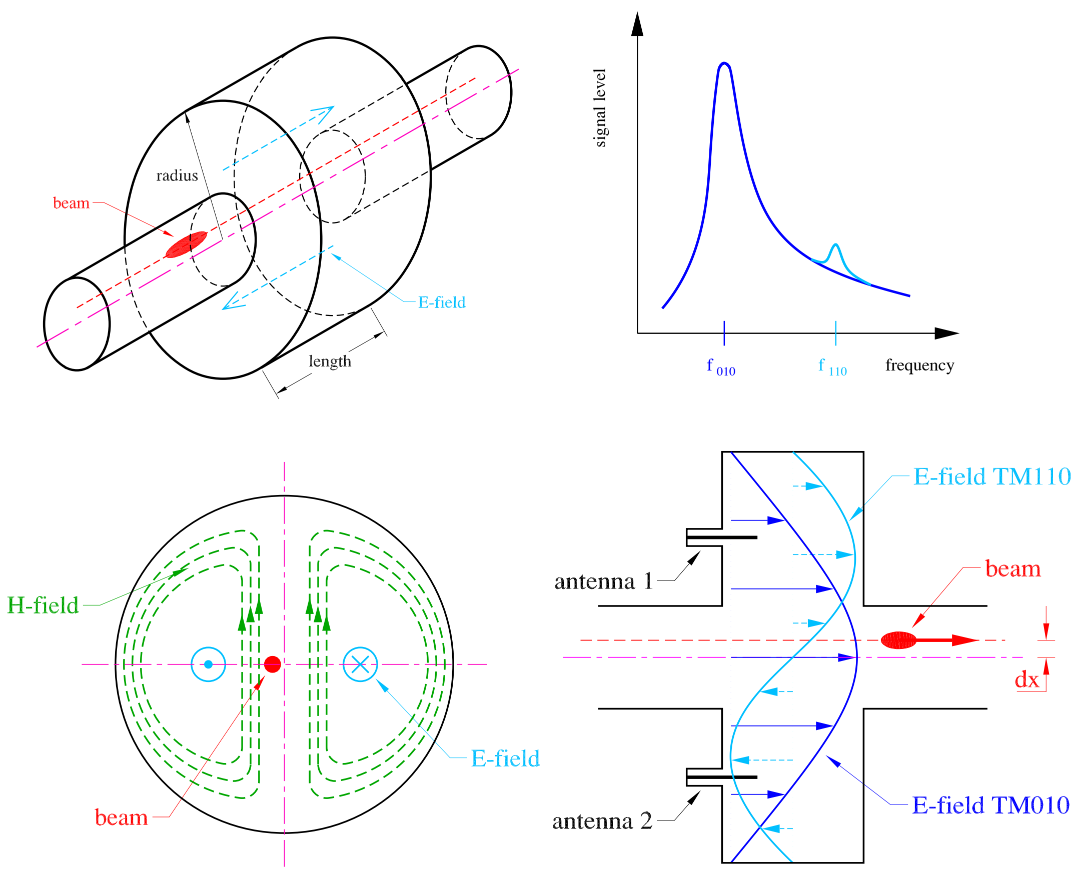


FIGURE 2. Principle of a "pillbox" cavity BPM.

As Fig. 2 illustrates, the TM_{110} dipole mode vanishes as the beam moves exactly through the center of the cavity pickup (r = 0). A set of capacitive coupling pin-antennas can be used to sense this dipole mode displacement signal of frequency f_{110}. Compared to broadband BPM pickups, e.g. button- or stripline style, the strength of the beam excited eigenmode is due to the cavity shape. For a simple cylindrical cavity BPM the corresponding R_{sh}/Q (shunt impedance over Q-value) typically has much higher values, compared to the transfer impedance of a broadband BPM, i.e. has higher beam displacement sensitivity and therefore a much greater potential to work as a high resolution BPM.

Unfortunately this simple, basic pillbox cavity BPM setup has several issues, which have to be addressed for a practical implementation:

- **Common modes:** Fig. 2 further illustrates that monopole modes (in BPM applications often called "common" modes, as they are independent from the beam displacement, thus always present) are also excited by the beam – here shown the fundamental TM_{010} eigenmode. The finite Q-value generates an unwanted contribution of this fundamental, high level TM_{010} monopole mode at f_{110} of the dipole mode. As the ILC BPMs have to time resolve every passing bunch, the Q-value of the resonator has to be chosen in a way that the stored energy doesn't last longer than the bunch-to-bunch time interval (~ 350 ns). In practice this requires rather low Q-values (500…1000), thus would result in a high monopole mode contamination at the dipole mode frequency (Fig. 2 upper-right plot).
- **Cross talk:** In an ideal cylindrical cavity the *polarization axes* of the dipole and other higher modes are undefined. Fig. 2 shows the vertical polarized part of the TM_{110} dipole mode, thus functioning as horizontal BPM. Every dipole mode has two polarization axes, which in practice align to small imperfections of the circular cross-section, or to the feedthrough pin-antennas, etc. In case of larger asymmetries the frequencies of the two polarizations may be not exactly the same. To act as a usable BPM both polarization axes of the cavity BPM have to be aligned to the horizontal/vertical plane within the specified tolerances. Without special considerations a simple pillbox cavity BPM may have somehow undefined polarization axes, which results in so-called "cross talk" effects between horizontal and vertical planes.
- **Transient response:** As already mentioned, the loaded Q-value has to be low enough to time resolve the beam position of every passing bunch, i.e. Q_l ~ 500…1000. In case of the simple pillbox cavity BPM, made out of copper or equivalent, the unloaded Q-value Q_0 usually is rather high if made out of high. As the pin-antenna loading does not lower the Q-value substantially, either very unusual dimensions have to be realized (very short gap), or a less conductive material has to be used, e.g. stainless steel. Both ways have disadvantages, particular the second:
- **Wakepotetial and heat-load:** All undamped, beam excited modes in the cavity BPM increase the wakepotential. Higher order modes may cause beam breakup and kick effects, trapped monopole and other modes mainly

contribute to an unwanted heat load in the cryomodule, which is particular high when using lossy conductors as cavity walls.

Beside these issues the cavity BPM located in the cryomodule has to fulfill special cleanroom and vacuum requirements. Both, magnitude and phase, of the dipole mode signal have to be processed, the magnitude represents the unnormalized beam displacement, the phase gives the sign. To perform a calibrated beam position measurement the dipole mode signal furthermore has to be normalized to the beam current (or bunch charge).

The Common-mode Free Cavity BPM

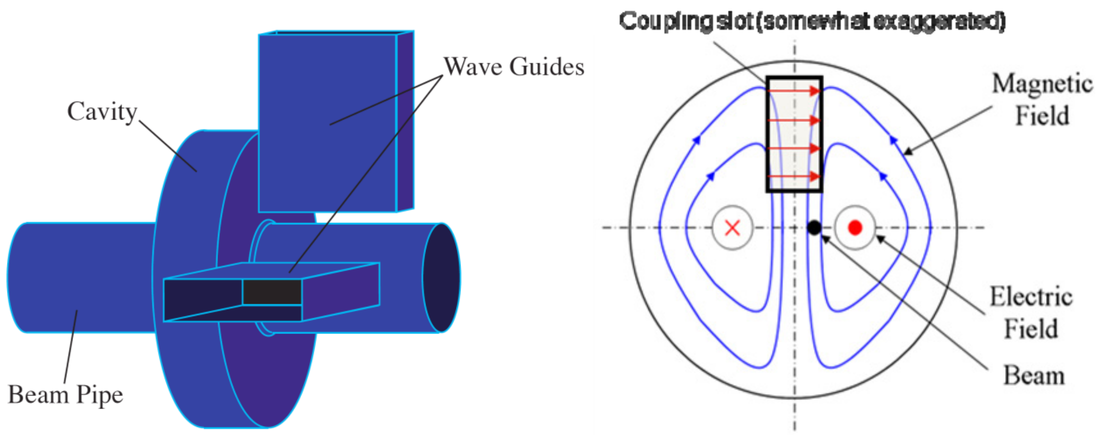


FIGURE 3. Waveguide-loaded CM-free cavity BPM (courtesy of Sean Walston).

The total suppression of the TM_{010} common mode is the key to realize the full resolution potential of a cavity BPM. This can be realized by arranging a set of two or four rectangular waveguides, coupled to the cavity (see Fig. 3). The waveguide acts as a very effective high-pass filter between the cavity and the coaxial output port, utilizing a TE_{10} waveguide-mode cutoff frequency:

$$f_{10} = \frac{1}{2a\sqrt{\varepsilon\mu}}$$

Dimensioning the longer side a of the waveguide's cross-section such that its TE_{10} cutoff frequency is well between the f_{010} monopole mode and the f_{110} dipole mode frequencies of the cavity, will almost vanish the monopole mode contribution at the dipole mode frequency. The coupling slots for the waveguides in the cavity also help to align the polarization axes horizontally and vertically.

CM-free cavity BPM's with various coupling schemas between cavity and waveguides, waveguide arrangements and geometries have been tested at various laboratories. Most impressive results have been demonstrated at the nanoBPM collaboration. By using a set of 3 CM-free C-Band cavity BPMs in a hexapod spaceframe at the KEK Advanced Test Facility (ATF), a resolution < 20 nm could be achieved!

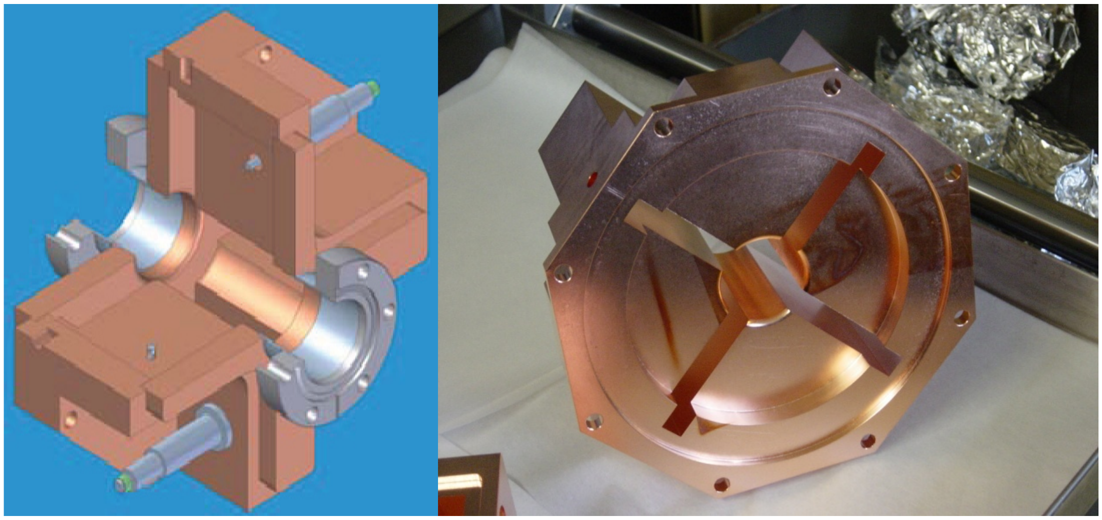
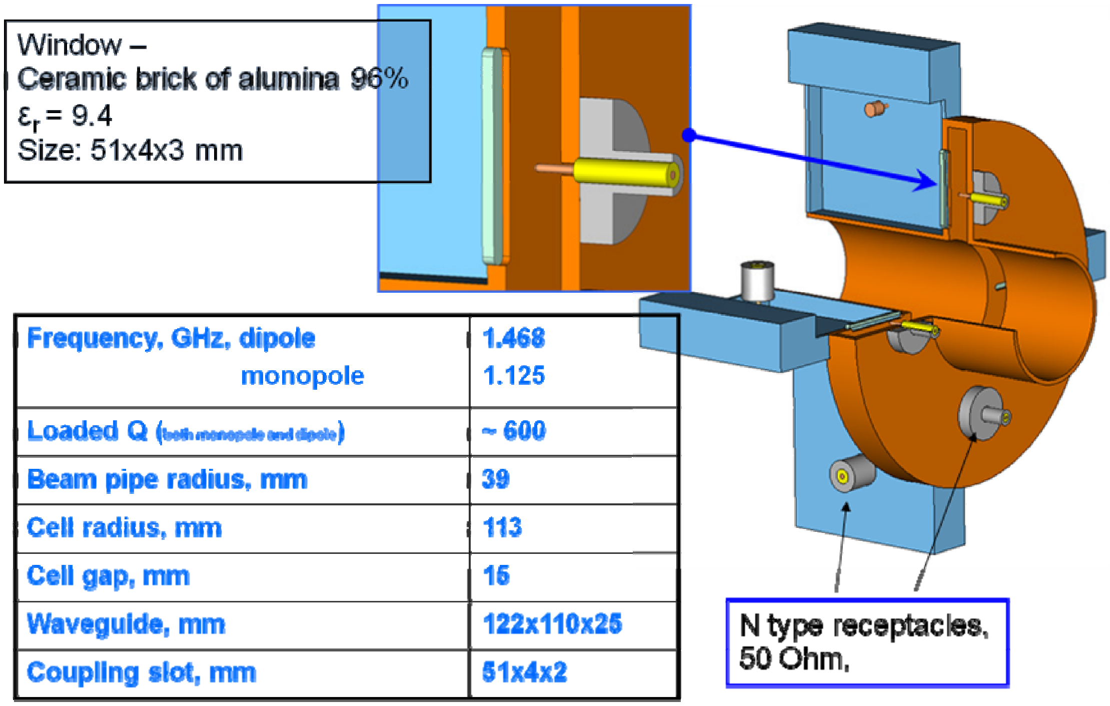


FIGURE 4. CM-free S-Band cavity BPM (courtesy of Zenhai Li).

For the practical realization of a cold cavity BPM in a superconducting RF environment, the additional waveguides appear to be a major problem for the cleaning procedure. Fig. 4 shows a prototype S-Band cavity BPM, addressing this problem by opening the waveguides towards the beam pipe to improve the accessibility for the cleaning procedure. A set of three S-Band cavity BPM's where tested with beam at the SLAC Endstation A (ESA), demonstrating a single bunch resolution < 1 µm. However, a detailed EM analysis shows a strong quadrupole-like parasitic mode below the TM_{010} frequency under certain beam conditions.

Cold L-Band Cavity BPM Development



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	51x4x2

FIGURE 5. Cold L-Band cavity BPM development.

A cold L-Band cavity BPM (Fig. 5), currently at Fermilab under development, tries to address most of the mentioned problems:

- CM-free design using narrow waveguides to couple out the dipole mode signals.
- A ceramic filled slot-window utilizes a Q_l ~ 600, and also addresses the cleaning issues.
- Pin-antennas used to couple to the monopole mode signals, used for normalization and phase information. A non-matched signal combiner in combination with transmission-lines realizes an in-phase loading at the monopole mode frequency, while not loading at the anti-phase dipole mode frequency.
- The monopole mode frequency f_{010} and the dipole mode frequency f_{110} are chosen symmetrically to the accelerator frequency f_{RF}, which is foreseen to act as precise, jitter-free LO frequency reference.
- Tuning dimples at the cavity rim allow minimizing the horizontal/vertical cross-talk.

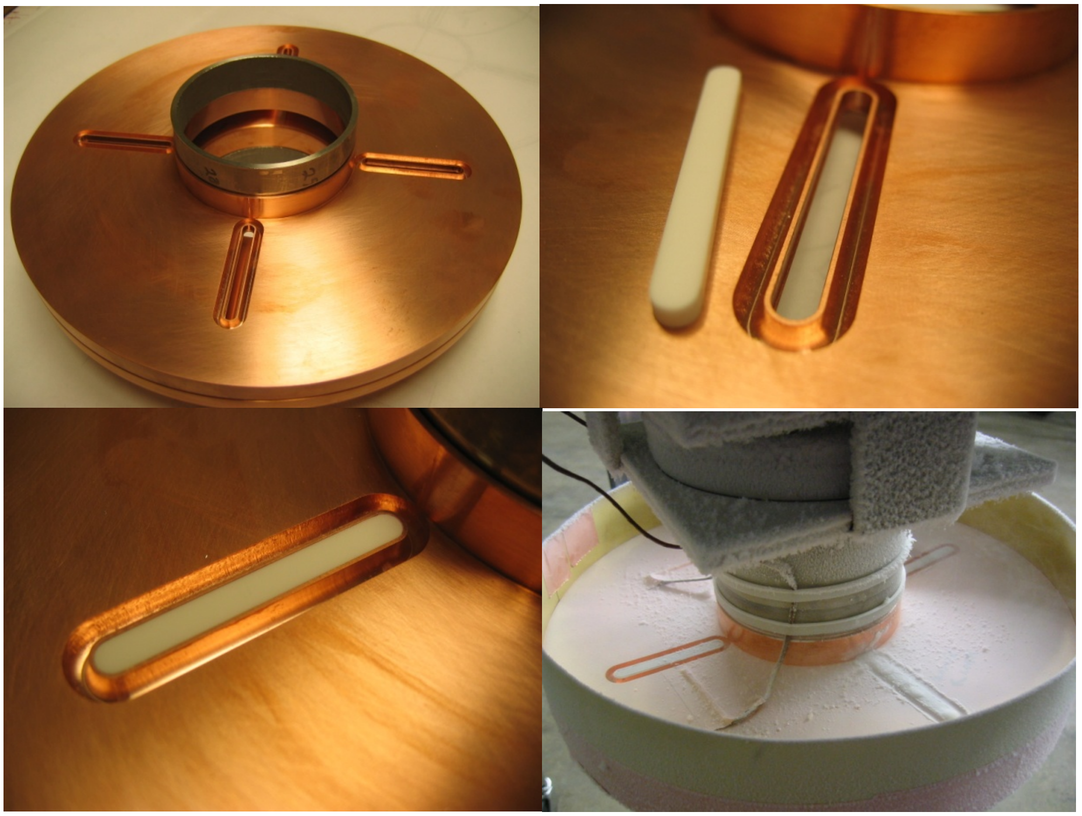


FIGURE 6. Brazing test and temperature cycling.

An experimental setup was used to study the brazing of the ceramic into the slot window, and testing the vacuum certification after several 77 K temperature cycles (Fig. 6). Even though only one of four windows survived all temperature cycles, we could acquired important information and experience with these experiments to further improve and optimize construction details.

From the EM simulations a computed dipole mode shunt impedance $(R_{sh}/Q)_{110} \sim 14$ Ω (for 1 mm beam displacement) promises a sub-micrometer single bunch resolution.

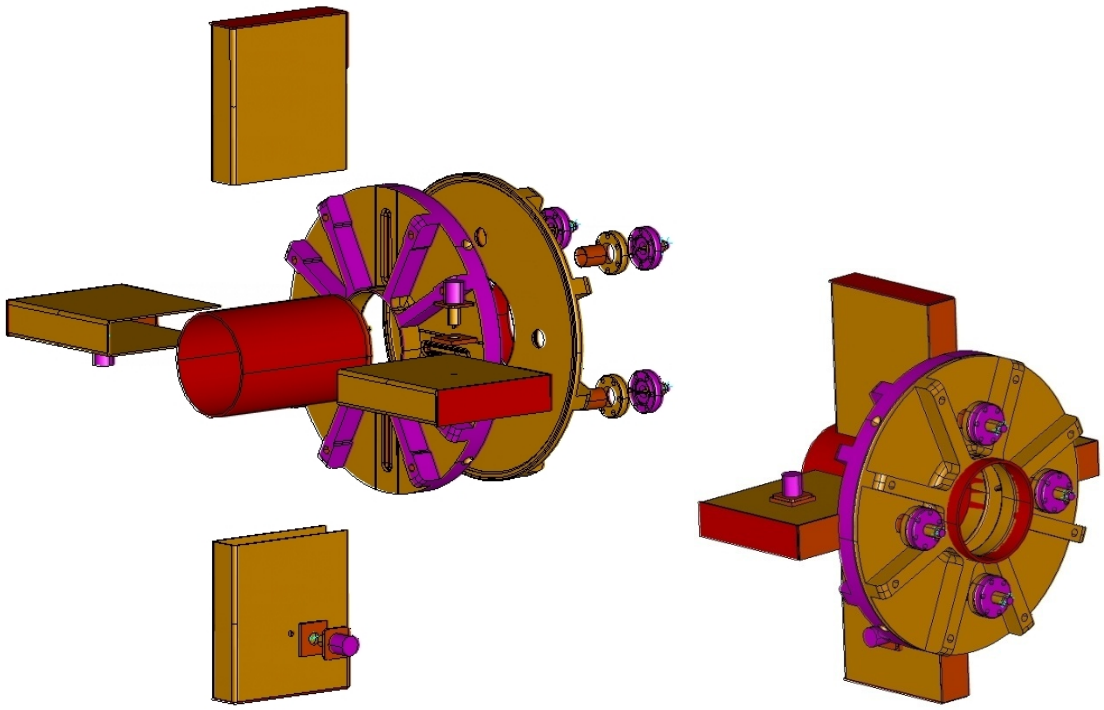


FIGURE 7. Cold L-Band cavity BPM assembly.

Fig. 7 shows a 3D view of the cold L-Band cavity BPM assembly at the current construction status. Most parts will be manufactured using OFHC copper. To reduce the deformation due to the atmospheric pressure a "rip" structure will be used to mechanically strengthen the cavity disks. UHV N-type RF feedthroughs with pin-antennas, mounted under 90^0 on the cavity disk, are used to couple to the monopole mode signals. Higher order mode signals are suppressed with filters in the read-out system. Standard N-type feedthroughs are used on the waveguide as waveguide-to-coaxial transition for the dipole mode signals. Several brazing processes at different temperatures are needed to assemble the complete unit. Next steps in the development are:

- A vacuum experiment to study the eigen-frequency shift due to the deformation of the cavity disks.
- A complete prototype assembly has to be manufactured and undergo a complete test series, including vacuum tests and temperature cycles.
- A network-analyzer based RF characterization and calibration has to be performed.
- The final prototype BPM has to undergo several cleaning procedures to meet the cleanroom class 100 specification.

Finally the goal is the installation of a prototype cavity BPM in a cryomodule, to be used at the NML linac test facility, currently under construction at Fermilab.