Cryomodule BPM R&D
- Status & Outlook -

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Fermilab

Cold BPM for a Cryomodule

- **Fermilab cryomodules are developed**
  - **Based on the DESY FLASH/XFEL type 3+ cryomodule**
  - **Have integrated quad/BPM package(s)**
  - **R&D for different machine targets**
    - **ILC prototype, Project X prototype, beam tests at NML with ILC and/or Project X beam conditions**
- **Cold BPM for the cryomodule**
  - **Limited real estate, 78 mm beam pipe diameter!**
  - **Operation at cryogenic temperatures (2-10 K)**
  - **Clean-room class 100 and UHV certification**
  - **Different types of cold BPMs are proposed**
    - **Cavity BPM – for ILC / TESLA (Fermilab / SLAC / DESY)**
    - **Re-entrant BPM – XFEL (CEA-Saclay / DESY)**
    - **Button BPM – XFEL, Project X (<u>DESY</u>, Fermilab)**

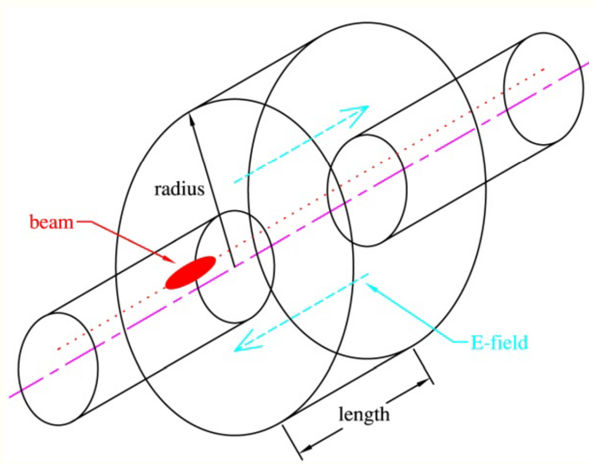
BPM Introduction

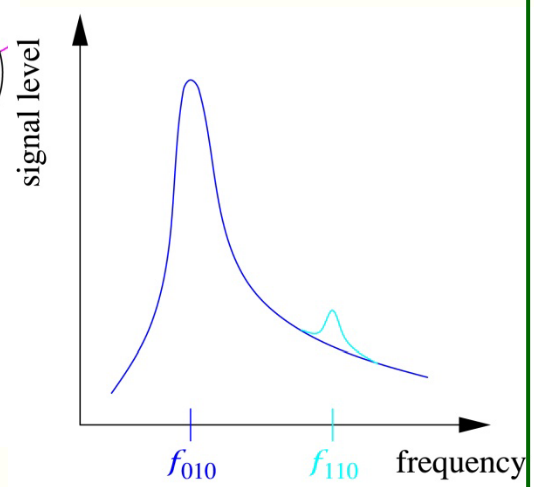
- **BPMs are used / needed for**
  - Beam position / orbit monitoring
  - Orbit correction, BBA, low-emittance optimization
  - Timing measurements, beam-RF phasing, TOF measurements
  - Machine commissioning
  - False detection, trouble-shooting, beam optics verification
- **Technical specifications for the BPM system are**
  - Driven by the machine parameters
    - Beam intensity range, bunch timing, beam / bunch dimensions, etc.
  - Defined by beam dynamic simulations, operational experience, environmental conditions, and common sense
    - Resolution, accuracy, linearity, long-term reproducibility (self calibration), dynamic range, pickup style and dimensions, etc.

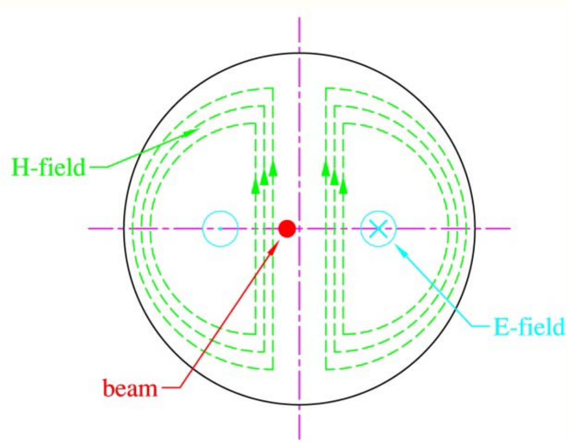
BPMs for ILC-like Beams

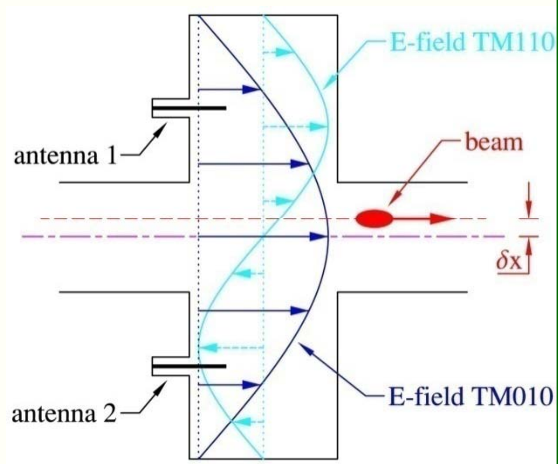
- **BPMs are the only beam diagnostic and observation devices within a string of cryomodules!**
  - No moving parts, no exotic materials.
  - No other beam instruments, e.g. toroids, wire scanners, laser-based diagnostics, screen monitors, etc.
- **ILC-like BPM requirements**
  - Single bunch detection, $t_b \approx 370$ ns
  - High resolution: ~1 µm
    (emittance preservation, sourcing beam jitter causes)
  - High linearity: few percent
  - Absolute accuracy: ~200 µm
  - Sufficient dynamic range to operate at nominal bunch intensities (3.2 nC), as well as on a low intensity pilot bunch (< 1 nC)
  - Sufficient position range: ±1 mm for high resolution measurements
  - Proposed solution:
    Common-mode free L-Band cavity BPM

Cavity BPM Principle



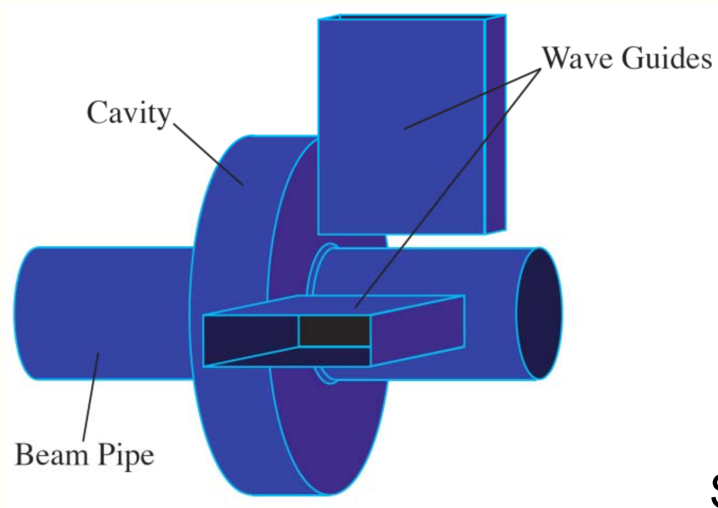


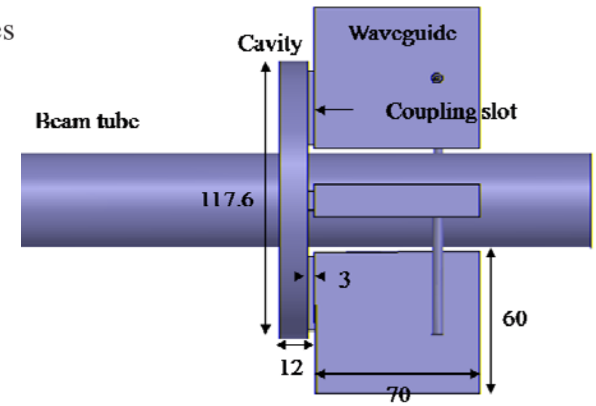


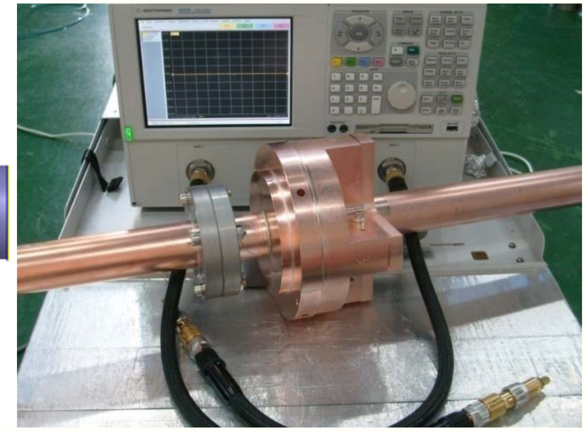


- "Pillbox" cavity BPM
  - Eigenmodes:
    $$f_{mnp} = \frac{1}{2\pi\sqrt{\mu_0 \varepsilon_0}} \sqrt{\left(\frac{j_{mn}}{R}\right)^2 + \left(\frac{p\pi}{l}\right)^2}$$
  - Beam couples to
    $$E_z = C J_1\left(\frac{j_{11} r}{R}\right) \cos\phi \, e^{i\omega t}$$
    dipole (TM_{110}) and monopole (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

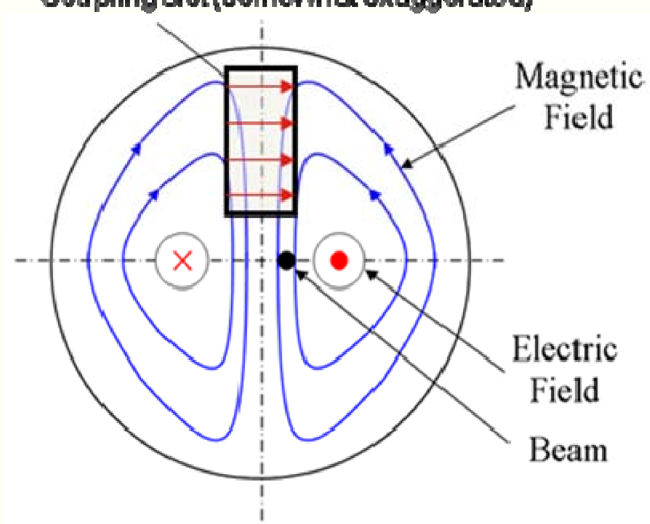






S-Band cavity BPM for ATF2 (KNU-LAPP-RHUL-KEK)

Coupling slot (somewhat exaggerated)



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

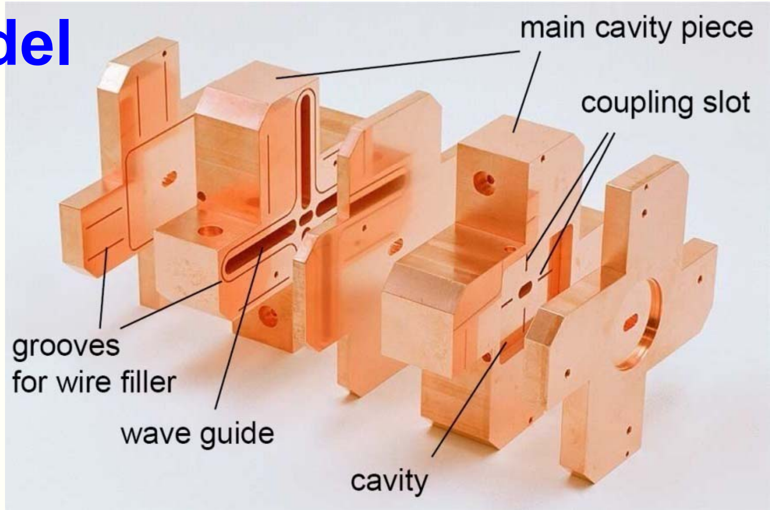
  $$f_{010} < \quad f_{10} = \frac{1}{2a\sqrt{\varepsilon\mu}} \quad < f_{110}$$

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

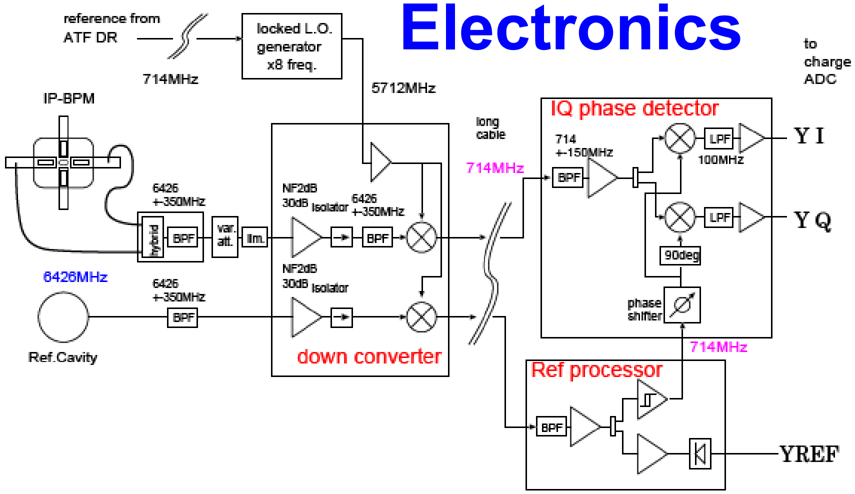
Example: KEK C-Band IP-BPM

Project X

Model



Electronics



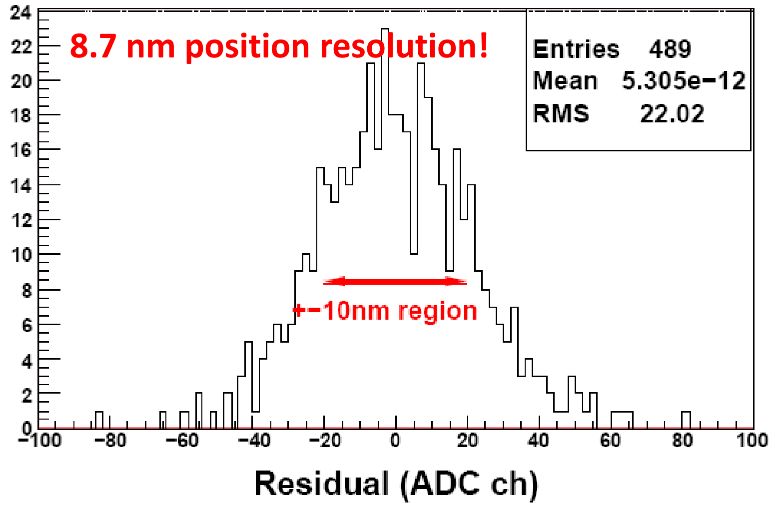
Characteristics

- **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

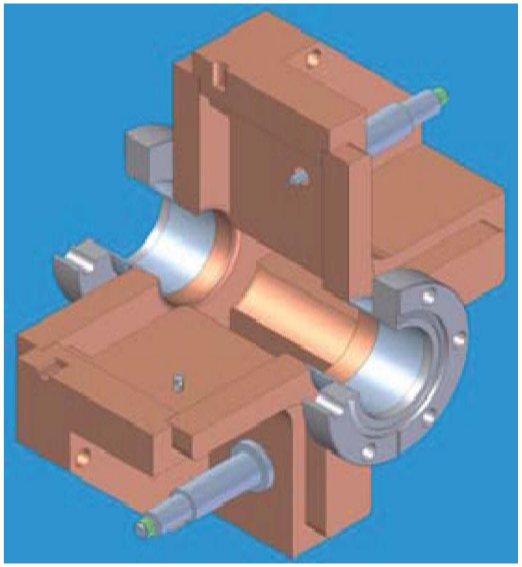
Port	f (GHz)	β	Q_0	Q_{ext}
X	5.712	1.4	5300	3901
Y	6.426	2	4900	2442

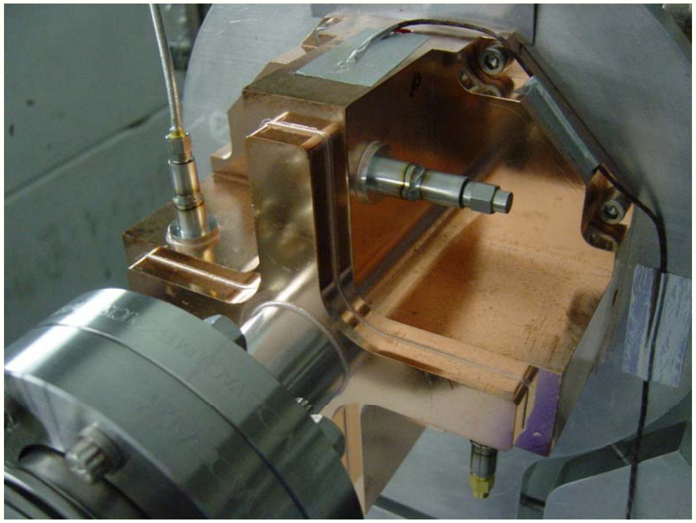
Results

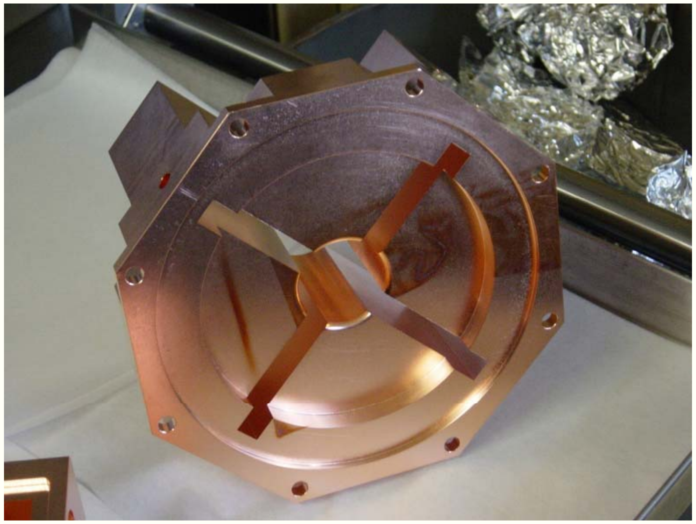


ILC Cryomodule Cavity BPM

- **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**

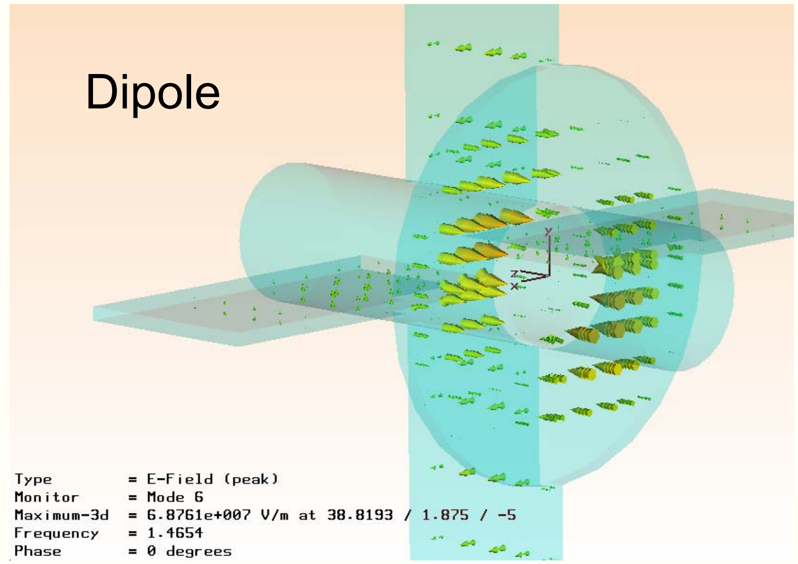


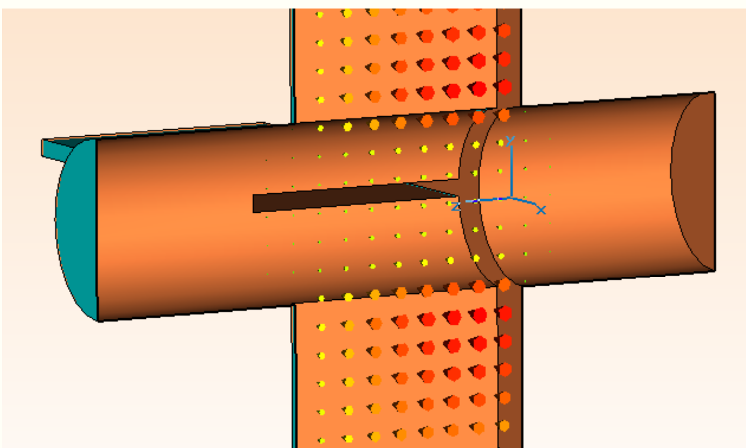




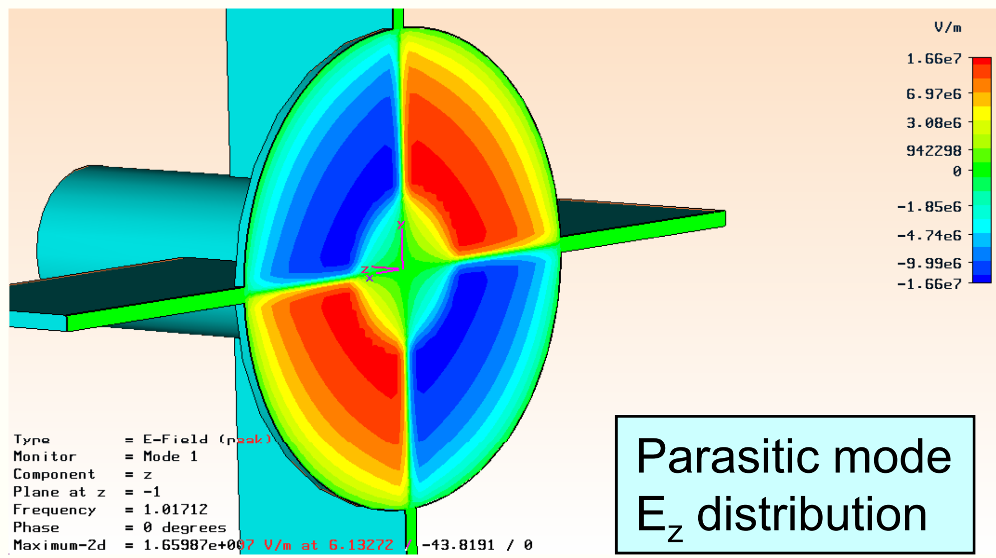
SLAC BPM Scaled to L-Band

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

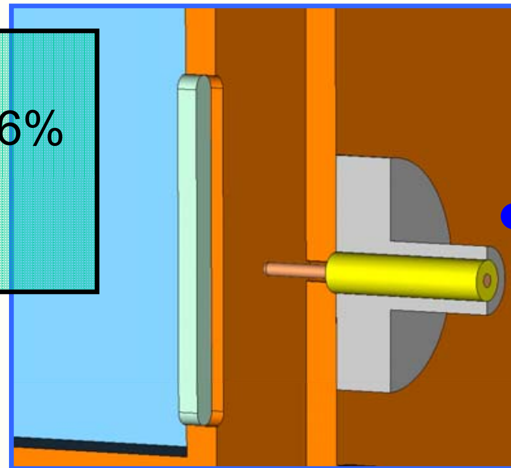


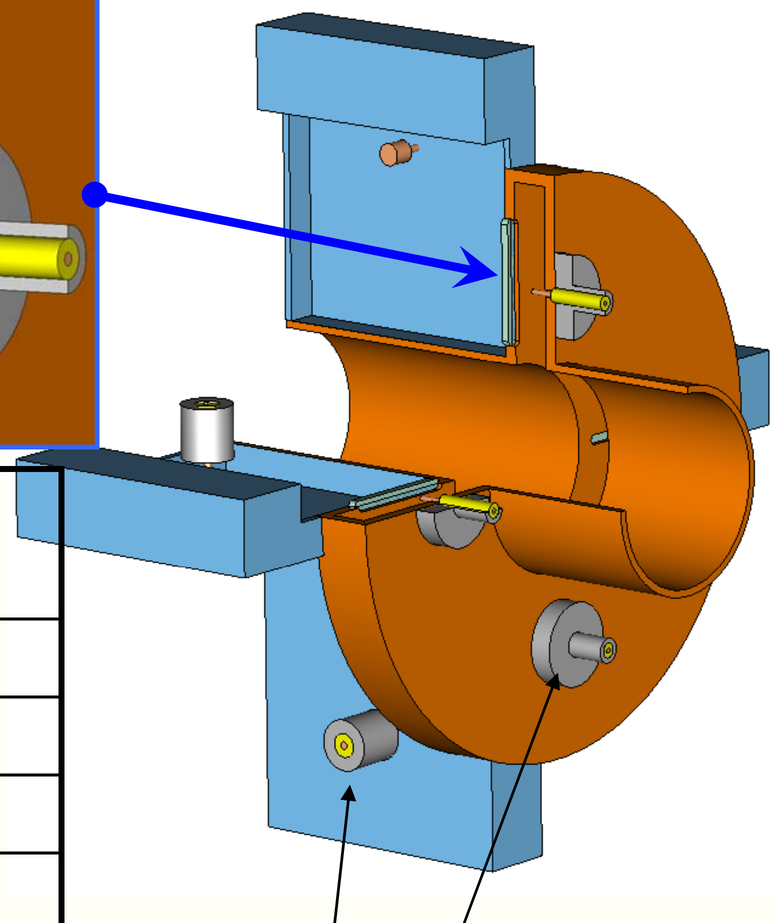
Parasitic mode E_z distribution

Fermilab L-Band Design

Project X

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

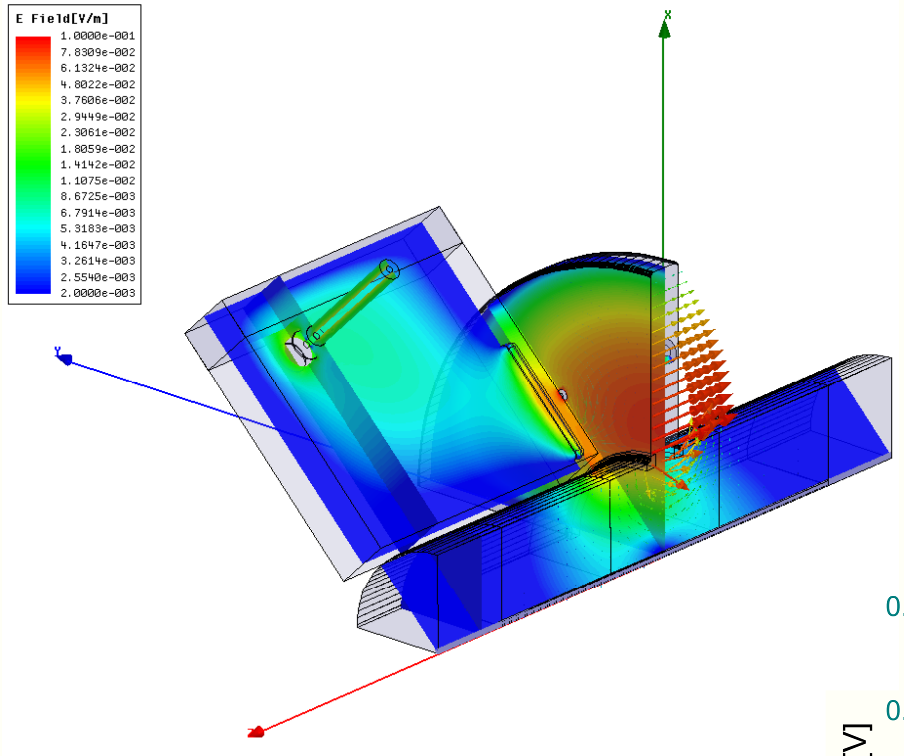




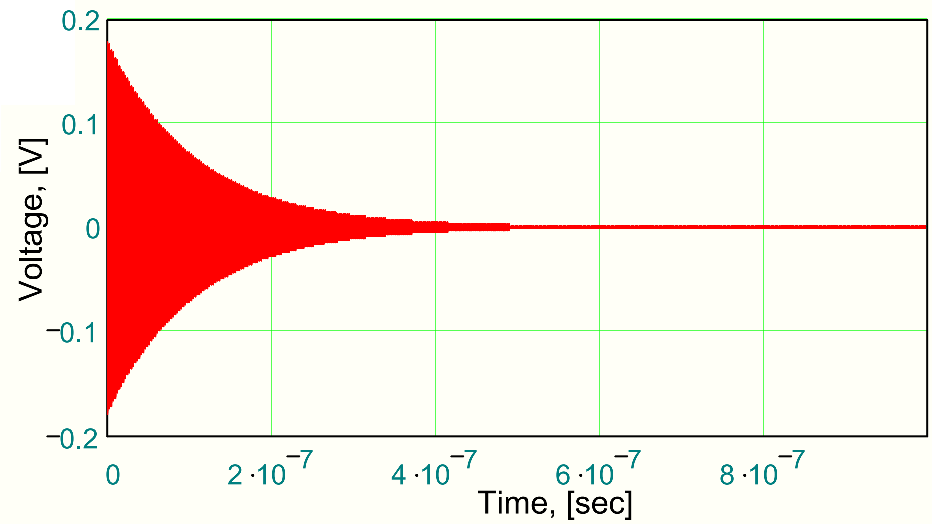
N type receptacles, 50 Ohm

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**

HFSS Simulations: Dipole Mode

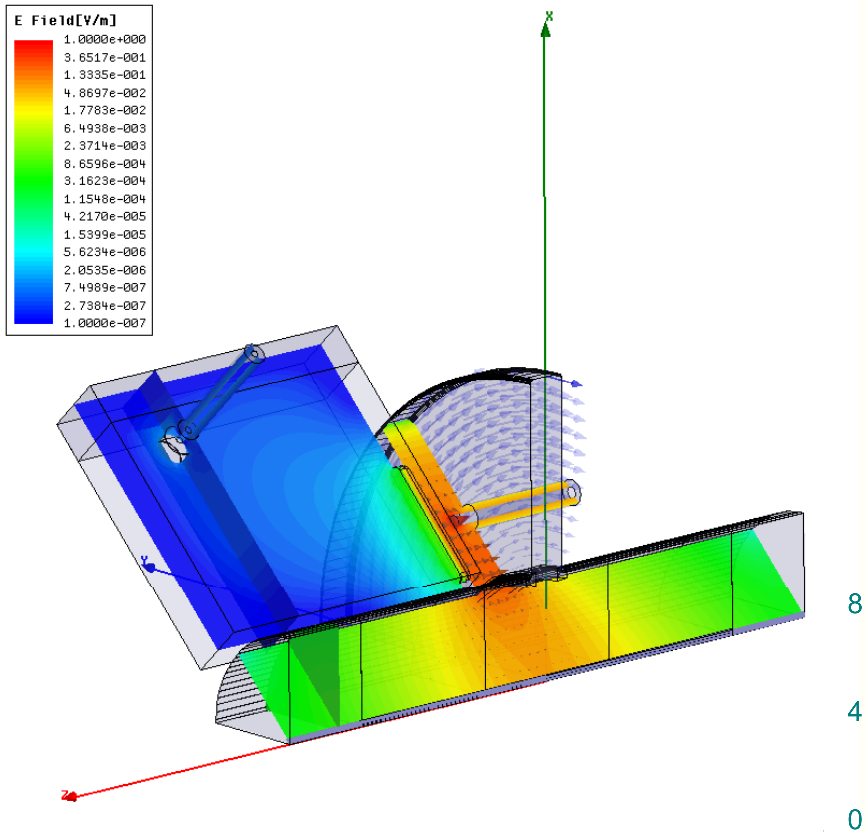


Frequency, [GHz]	1.480
Q, External Q, Surface (Cu) Q, Ceramic(AL_2O_3)	500 22000 5600
Test charge, [coulomb] (X=0, Y=1mm)	1E-9
Stored energy, [joule]	5.9.0E-11
Output Voltage at T=0*, [V]	0.24

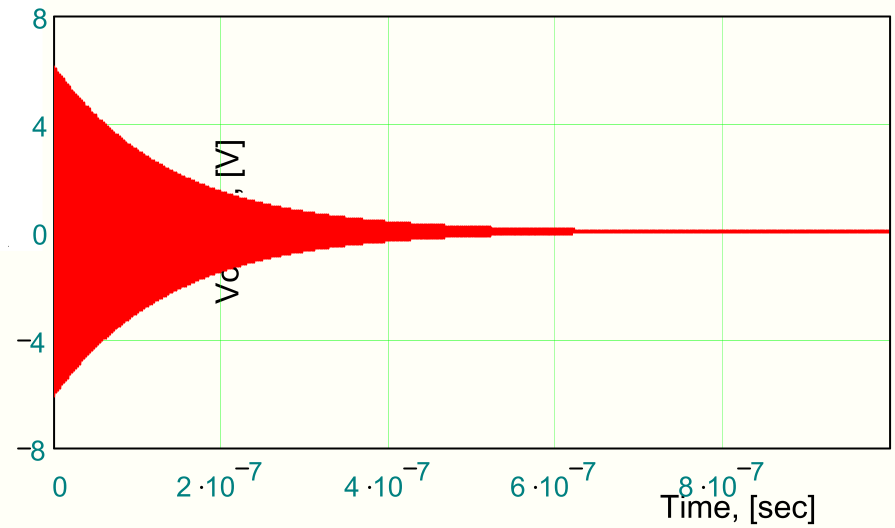


* Normalized to 50 Ohm,
The total signal combines with two ports

Simulations: Monopole Mode

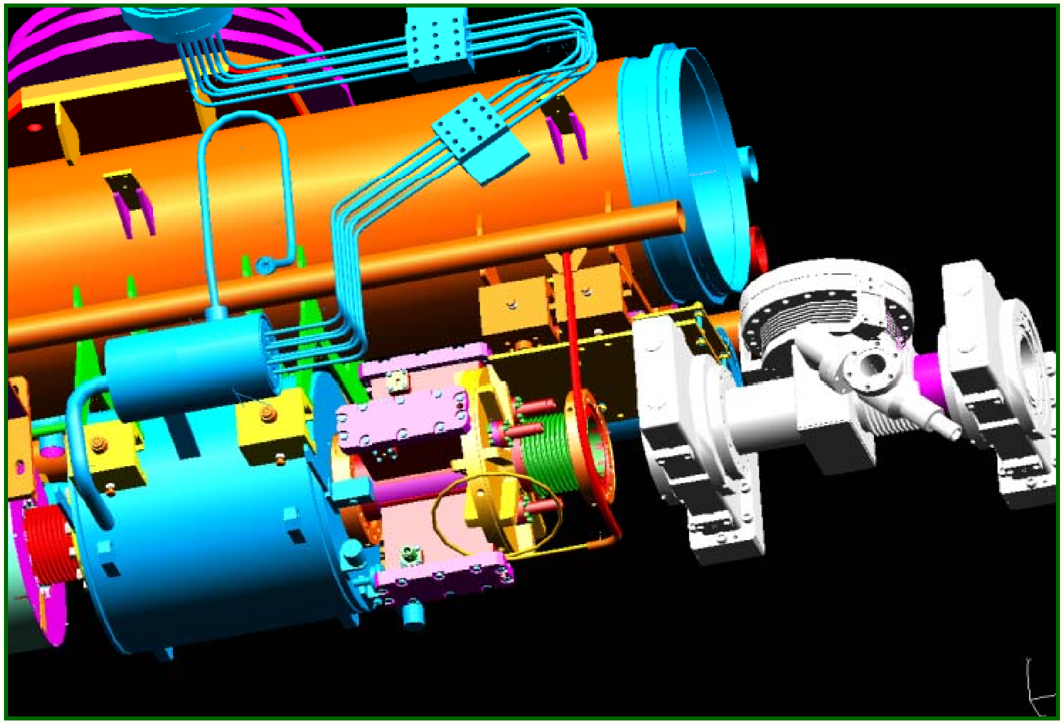


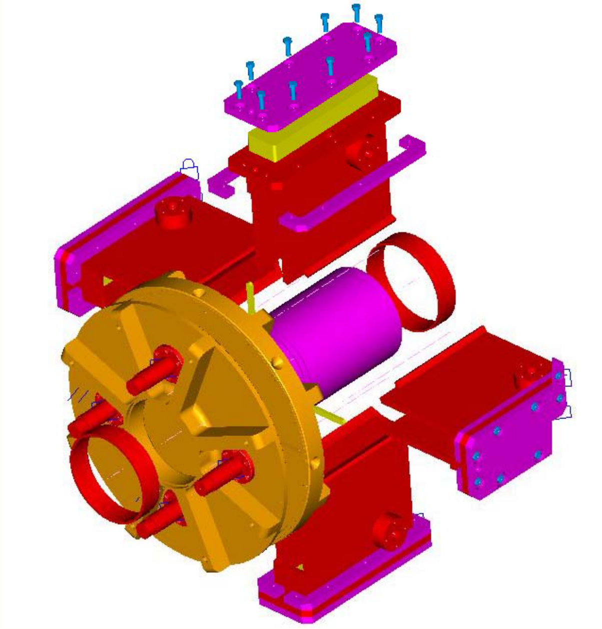
Frequency, [GHz]	1.120
Q, External Q, Surface (Cu) Q, Ceramic(AL_2O_3)	550 19500 7.9E6
Test charge, [coulomb] (X=0, Y=1mm)	1E-9
Stored energy, [joule]	6.1E-8
Output Voltage at T=0*, [V]	6.1
Coupling with TM_{11} port, Output Voltage at T=0*, [V]	5.6E-5

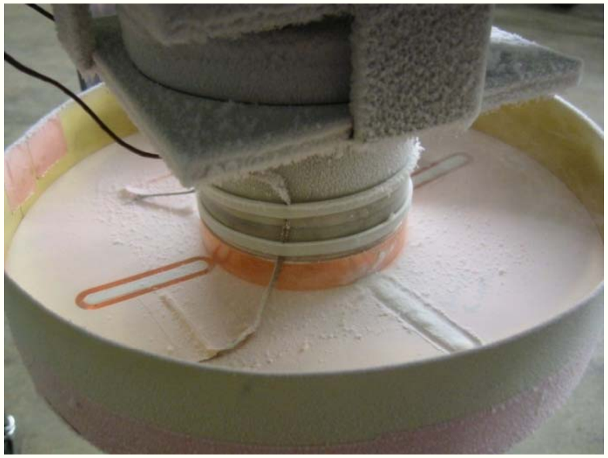


* Normalized to 50 Ohm,
The total signal combines with four ports

Cold L-Band ILC BPM R&D

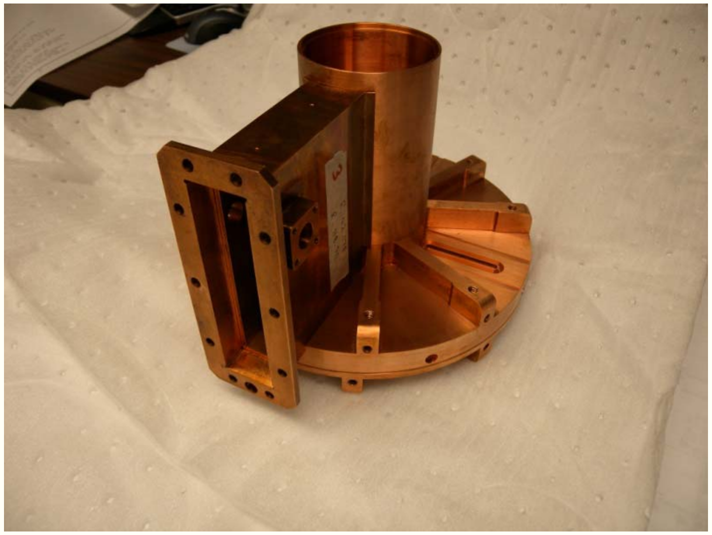






- **Status:**
  - **EM simulations & construction finalized**
  - **Brazing and low temperature UHV tests**
  - **All parts manufactured, brazing underway**
  - **Prototype has "warm" dimensions**

Cold ILC L-Band Cavity BPM



ILC Cavity BPM Summary

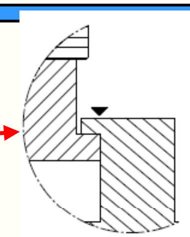
- Cold L-Band cavity BPM, fits in an ILC cryostat, 78 mm aperture.
- Waveguide-loaded pillbox with slot coupling.
- Dimensioning for f_{010} and f_{110} symmetric to f_{RF},
  f_{RF} = 1.3 GHz, f_{010} = 1.125 GHz, f_{110} = 1.468 GHz.
- $(R_{sh}/Q)_{110} \approx 14\ \Omega$ (1 mm beam displ.), providing < 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

ILC Cavity BPM Status & Outlook

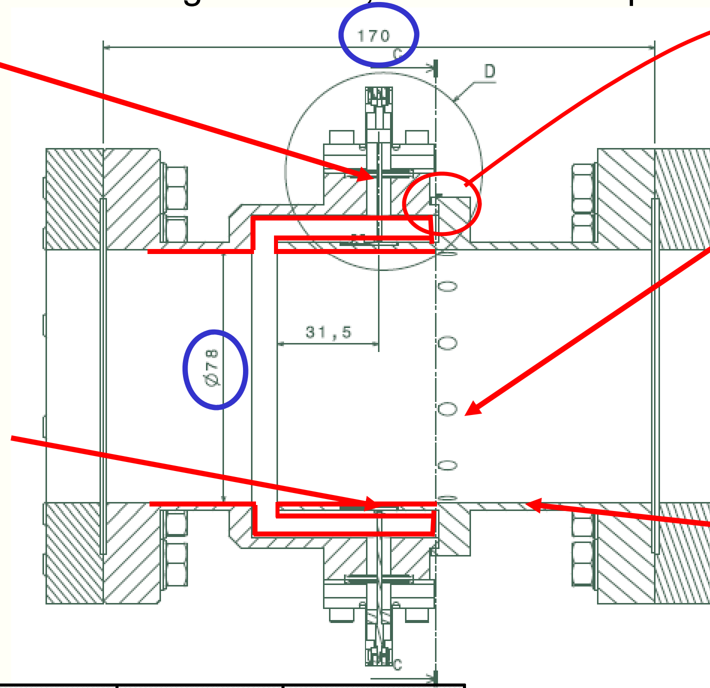
- **Status of the "warm" prototype**
  - 2 of 3 brazing cycles completed (WGs are the last brazing cycle)
- **Next steps**
  - Mounting of feedthroughs, WG ceramics, vacuum certification, RF characterization and tuning, AND: beam measurements.
- **Personal observations**
  - The cold L-Band cavity BPM is a complex, complicated, and heavy beam instrument. It is not cheap!
  - But: it has high measurement potential (Resolution!)
  - Very long R&D time, little support
  - Development under difficult, variable conditions, uncertain funding, and a moving target machine (ILC -> Project X)
  - We will continue the development at a low rate, including a cold prototype.

Reentrant Cavity BPM for the XFEL (1)

- 30 reentrant cavity BPM will be installed in XFEL cryomodules
- For the XFEL, mechanical design improved to respect tolerances of the BPM :
  Roll Angle **3 mrad**, Transverse displacement **0.2 mm**



Cryogenics tests at 4 K on feedthroughs is OK



Twelve holes of 5 mm diameter drilled at the end of the re-entrant part for a more effective cleaning (Tests performed at DESY).

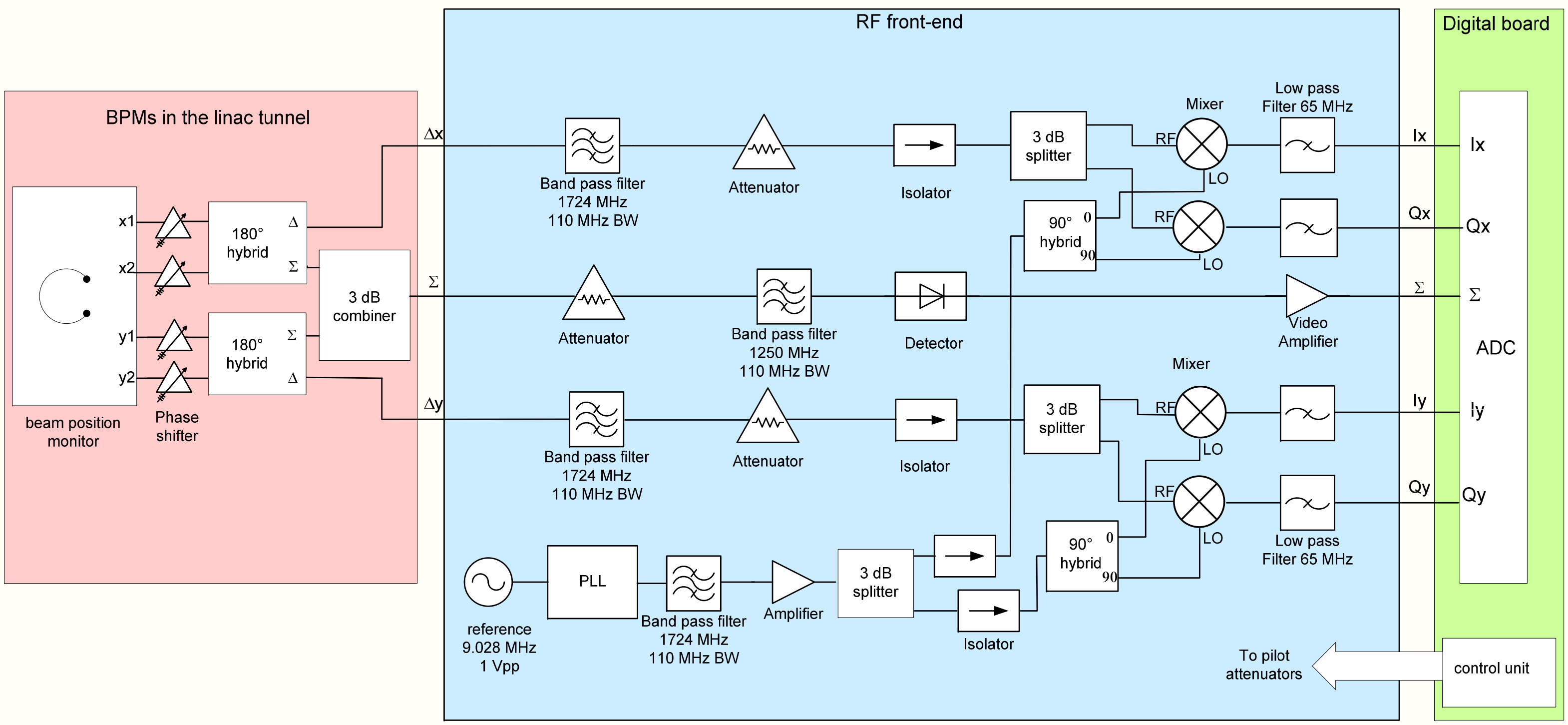
Cu-Be RF contacts welded in the inner cylinder of the cavity to ensure electrical conduction.

Copper coating (depth: 12 µm) to reduce losses. Heat treatment at 400°C to test: OK

Eigen modes	F (MHz)	Q_l	$(R/Q)_l$ (Ω) at 5 mm	$(R/Q)_l$ (Ω) at 10 mm
	Measured	**Measured**	**Calculated**	**Calculated**
Monopole mode	1255	23.8	12.9	12.9
Dipole mode	1724	59	0.27	1.15

Reentrant Cavity BPM for the XFEL (2)

- Hybrids will be installed near the BPM
- Signal processing electronics uses a single stage down conversion
- Electronics based on an PCB with low cost surface mount components



Reentrant Cavity BPM for the XFEL (3)

- Beam tests carried out with the room temperature reentrant BPM

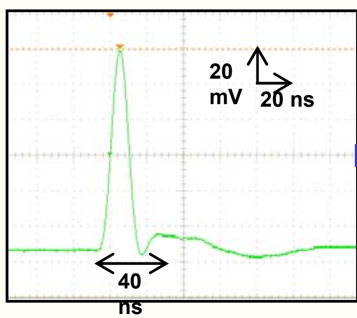
➡ **Good linearity in a range ± 12 mm**

➡ **RMS resolution: ~4 µm on the Y channel / ~8 µm on the X channel** — **with 1 nC and dynamic range +/- 5 mm**

- **Simulated resolution with 1 mm beam offset: < 1 um**

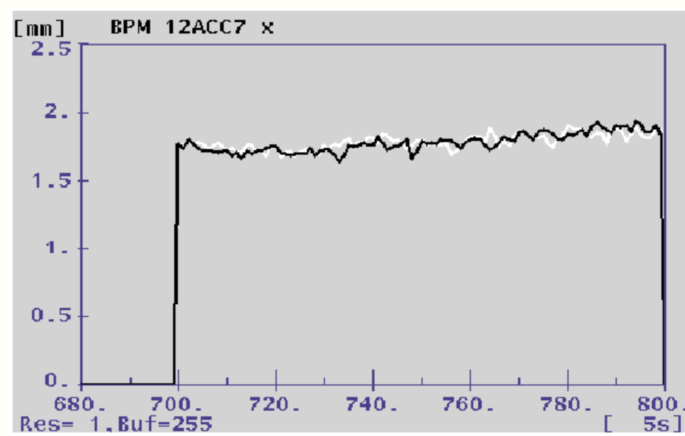
Damping time (Cavity): 9.4 ns

Time resolution (Cavity + electronics): ~40 ns



IF signal behind Lowpass Filter on channel Δ

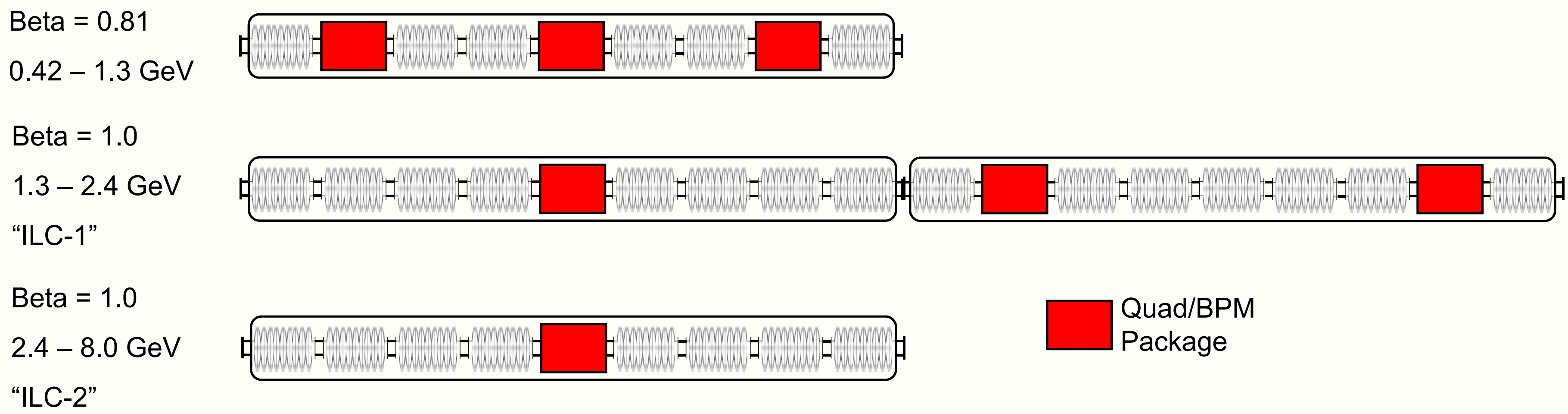
Possibility bunch to bunch measurements



100 bunches read by the reentrant BPM

PX Cryomodule Configurations

Project X



- **Need a very reliable, cost effective solution**
  - **5x more BPMs than for the ILC**
  - **Difficult to access & repair (vacuum leak, signal connections).**
- **Project X operates with an H^- beam, and has different beam conditions and requirements for the BPM system**

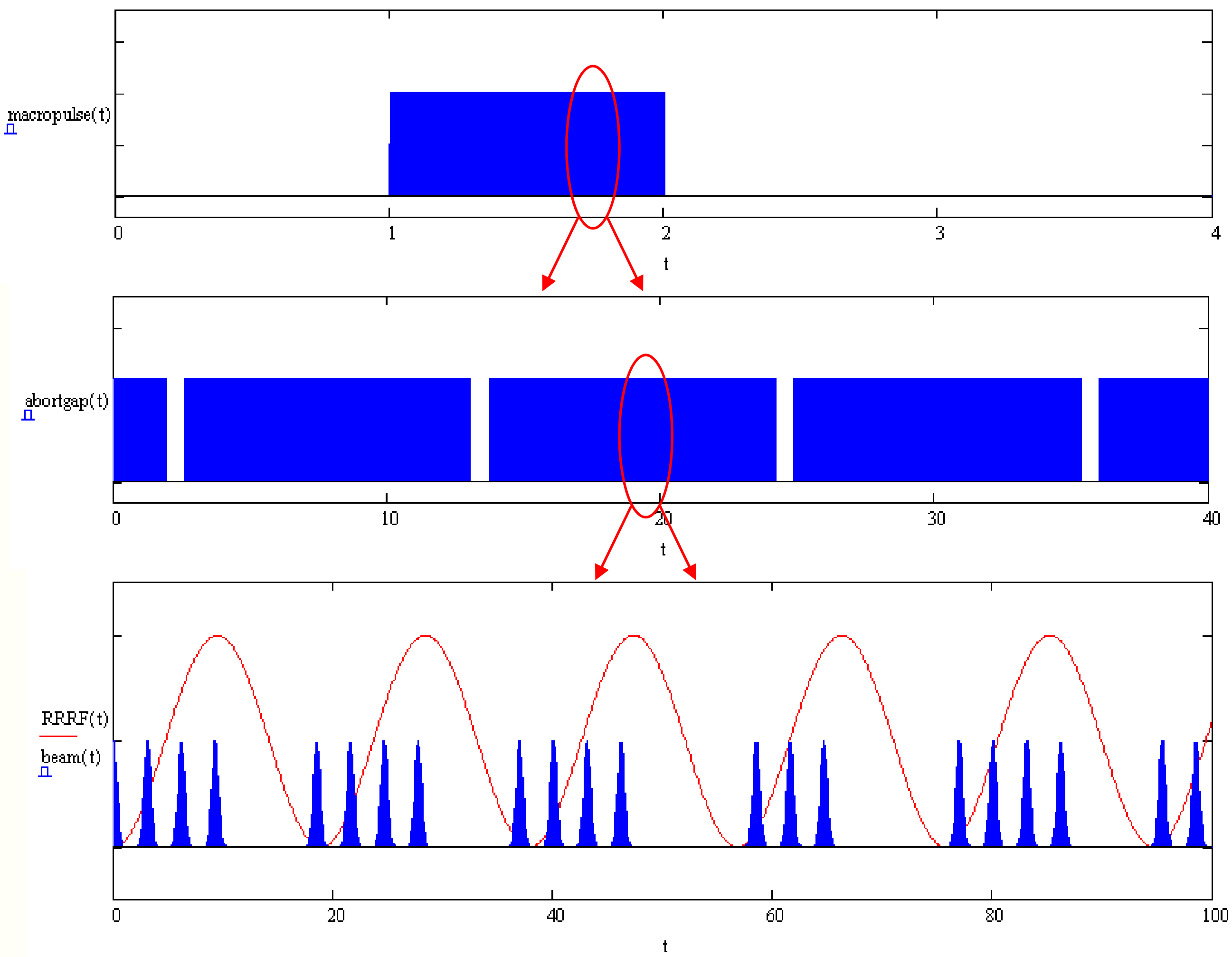
PD/HINS/PX Beam Parameters

	Proton Driver Phase 1 Design	Proton Driver Phase 2 Design	HINS capability	Project X Base Design (Nov-07)	Project X ICD (Sep-08)	
Particle	H-	H-	H+ then H-	H-	H-	
Nominal Bunch Frequency/Spacing	325 3.1	325 3.1	325 3.1	325 3.1	325 3.1	MHz nsec
Particles per Pulse	15.6	15.6	37.5 *	5.6	15.6	E13
Pulse Length (beam)	3	1	3/1	1	1.25	msec
Average Pulse Current	8.3	25	~20	9	20	mA
Pulse Rep. Rate	2.5	10	2.5/10	5	5	Hz
Chopping -6% @ 89KHz and 33% @ 53MHz	37.5%	37.5%	0 - 37.5%	37.5%	37.5%	
Bunch Current	13.3	39.8	32	14.3	32	mA
Bunch Intensity	2.5 41	7.6 122	6.1 98	2.7 ** 44	6.1 98	E8 pCoul

* full un-chopped 3 msec pulse at klystron-limited 20 mA

** ILC bunch intensity is 2E10 (electrons)

PX Beam Time Structure



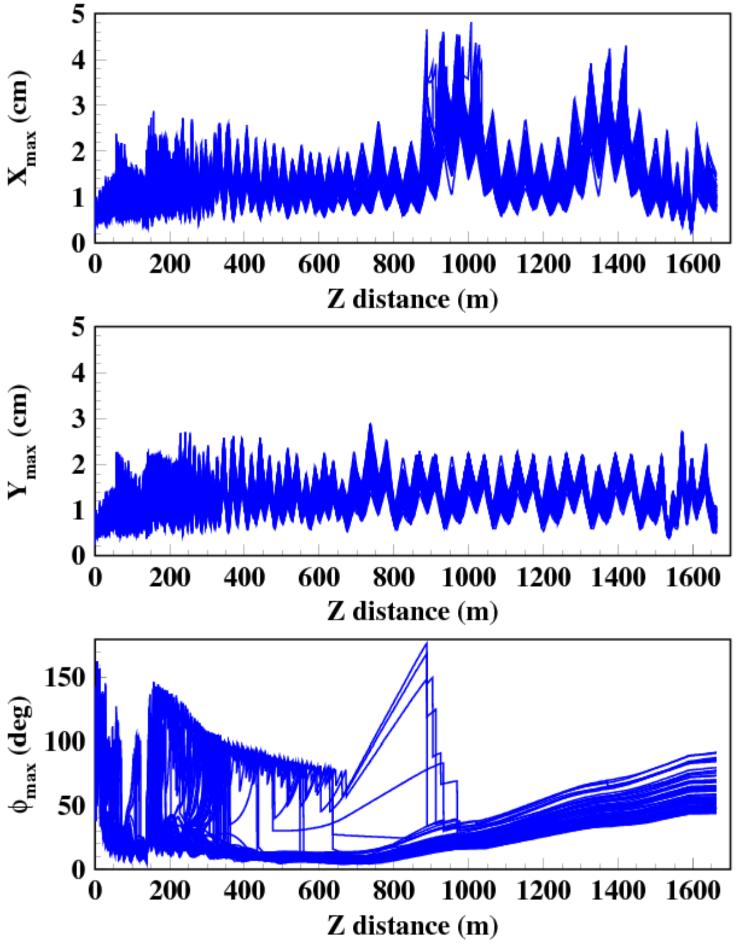
1 msec Linac beam pulse
4 msec full scale

Linac beam chopped for
700 nsec RR Abort Gap
40 μsec full scale

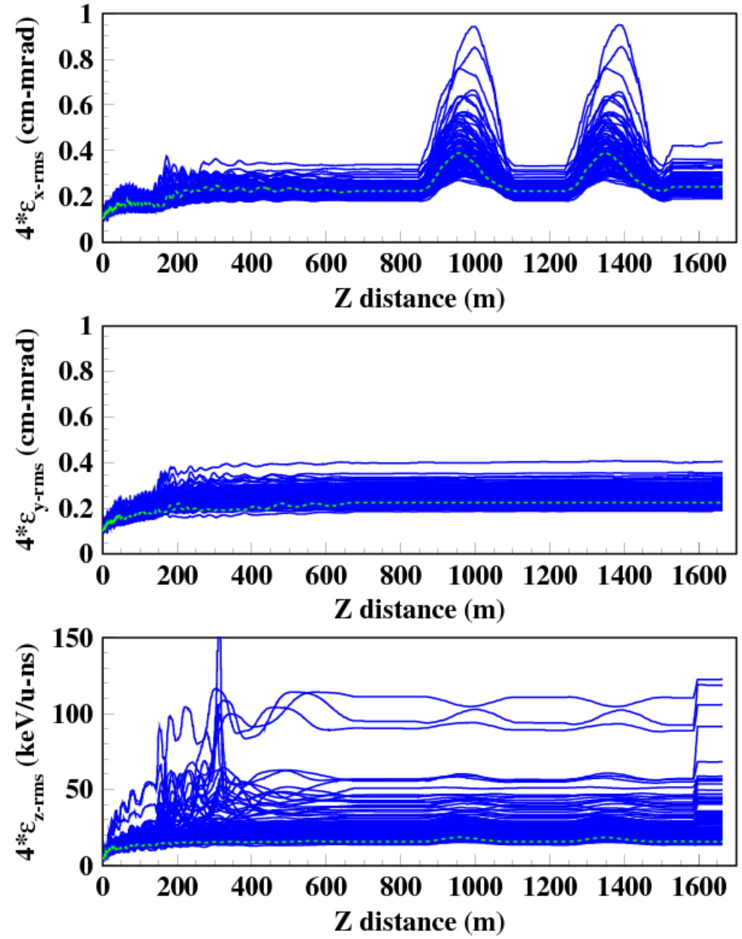
Linac 325 MHz beam
chopped for RR RF
3-5 linac bunches per
53 MHz RR RF cycle
100 nsec full scale

PTRACK Error simulations of the FNAL 8 GeV linac at 45 mA (100 seeds, 10M each, 4096 processors, ~1H30, BlueGene, ANL)

Beam Envelopes



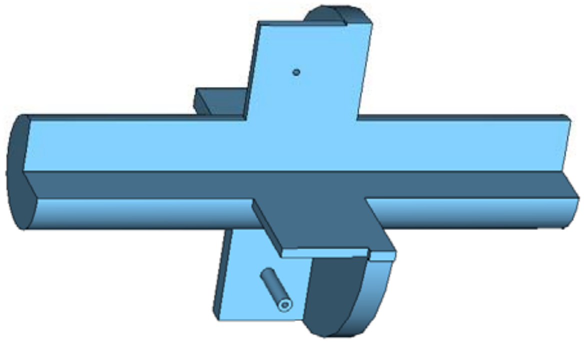
Beam Emittances

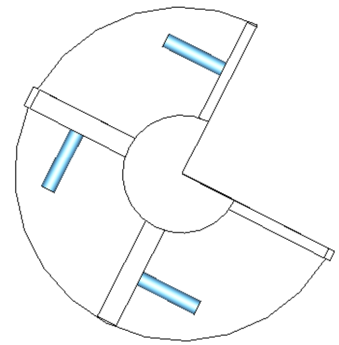


Cold BPM for PX Cryomodule

- **Project X / HINS beam conditions and parameters are very different from ILC**
  - H^- instead of electrons
  - Different timing structure, no Fourier component at f_{110}
    -> L-Band ILC cavity BPM does not work with a PX beam!
  - Bunch dimensions are mm, not µm
    -> No µm resolution required! (No requirements defined yet)
  - No need of single bunch monitoring
  - -> ~10 µm integrations time seems adequate (1 turn MI/RR)
- **Cryomodule BPM proposal for Project X / NML**
  - Plan A: Simple button style BPM, based on *Meggitt* BPM feedthroughs, and SiO_2 insulated RF signal cables (LHC)
    - Analog down-converter, digital receiver read-out system (ATF DR)
  - Plan B: Continue CM_free cavity BPM R&D

1.3 GHz Cavity BPM Design

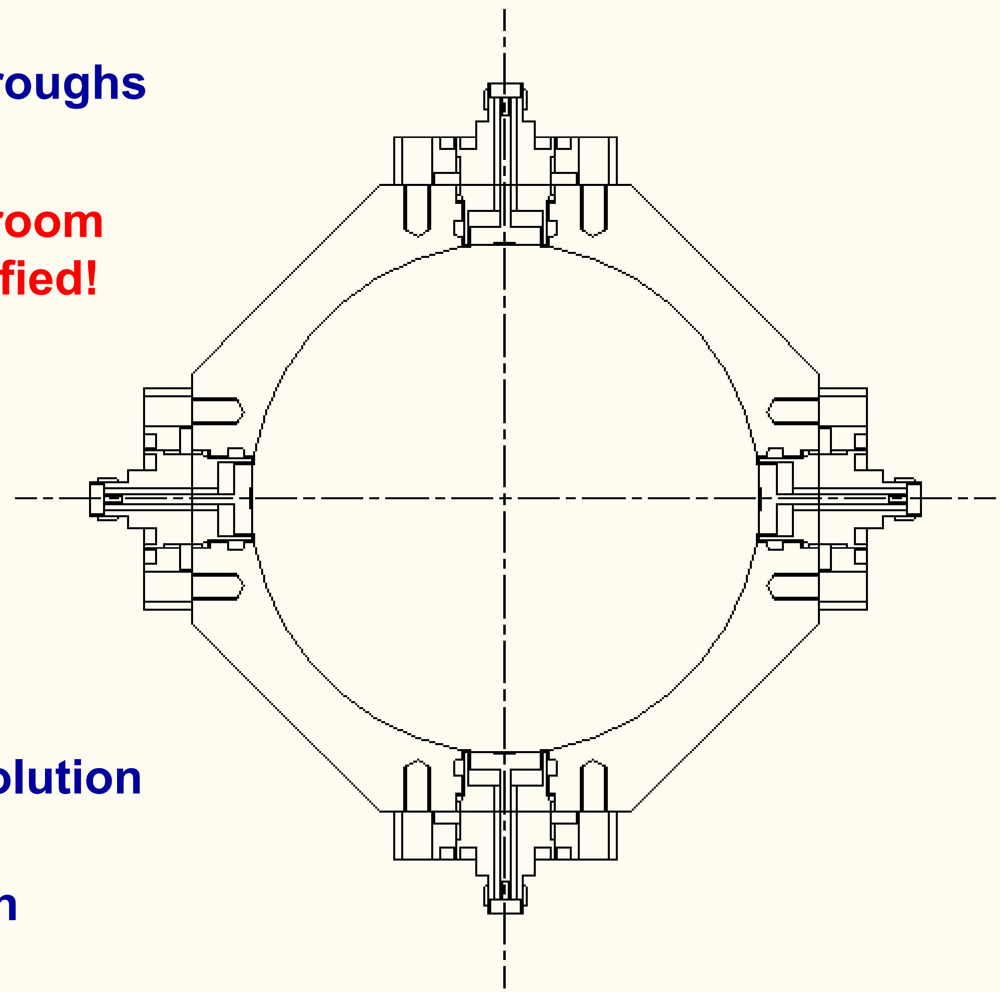




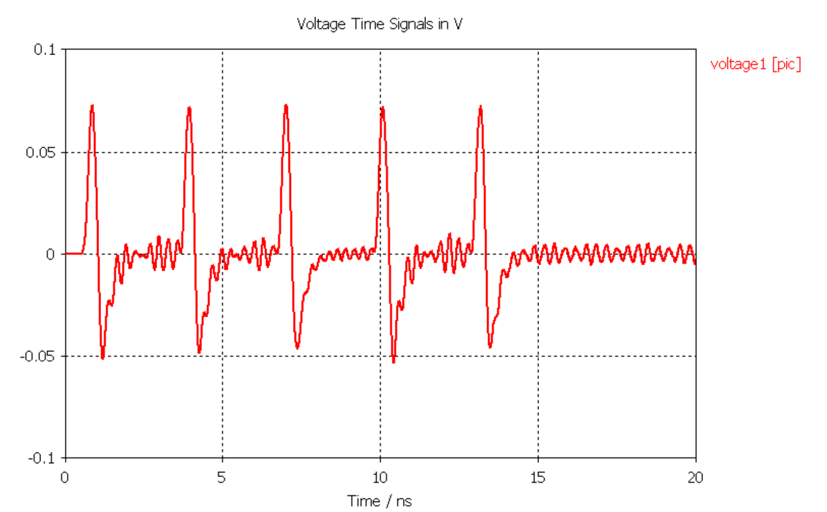
- **All previous requirements apply:**
  - **Cryogenics, dimensions, resolution, etc.**
  - **f_{110} = 1.3 GHz, to operate with Project X (multi-bunch) and ILC (single bunch) like beams**
- **Cavity diameter ~230 mm (to fit into the cryomodule), aperture: 78 mm.**
- **Rectangular cavities (waveguides)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

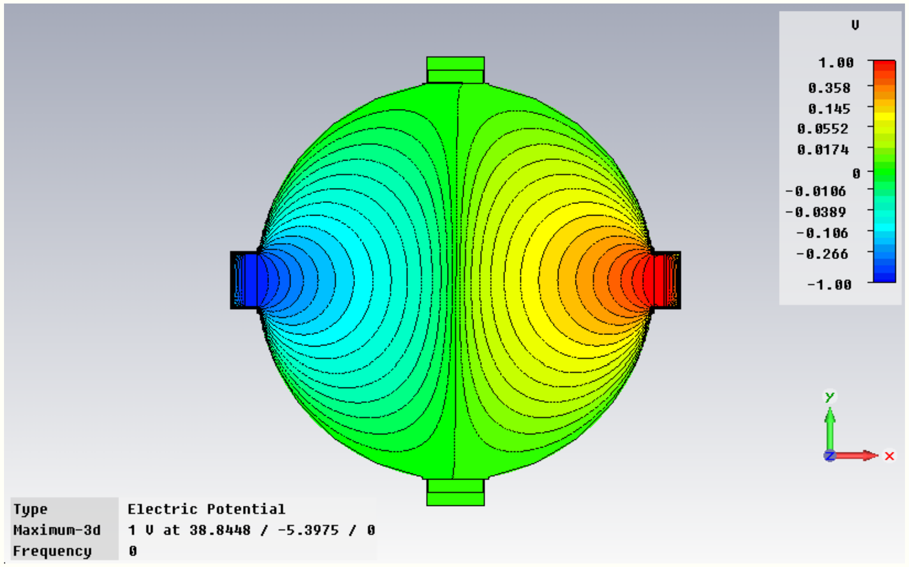
Cryomodule Button BPM

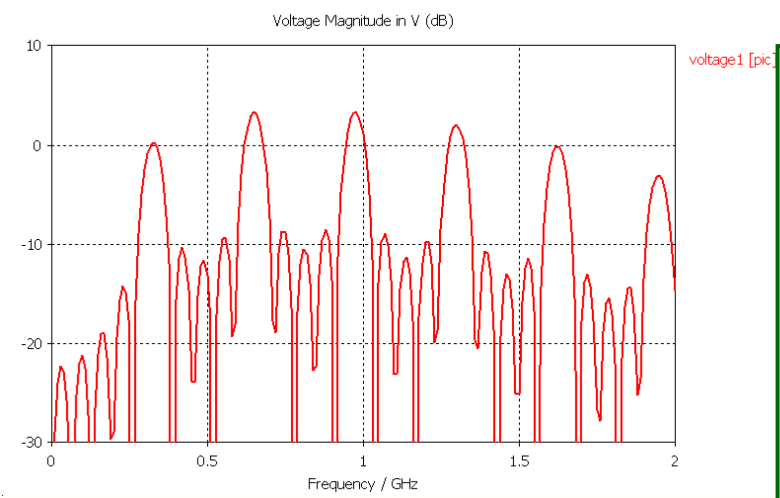
- **Well known construction**
  - **Flange mount button feedthroughs**
  - **Minimum real-estate**
  - **Cryo temperature and cleanroom compatibility need to be verified!**
- **Simple design**
  - **Milled, single piece SS body**
  - **Tolerances <200μm**
  - **Conflat sealed feedthroughs**
  - **Flange mount (?)**
- **Button BPM system**
  - **20…50 μm single bunch resolution (ILC-like beam)**
  - **< 1 μm multibunch resolution (Project X like beam)**



Preliminary Simulation Results

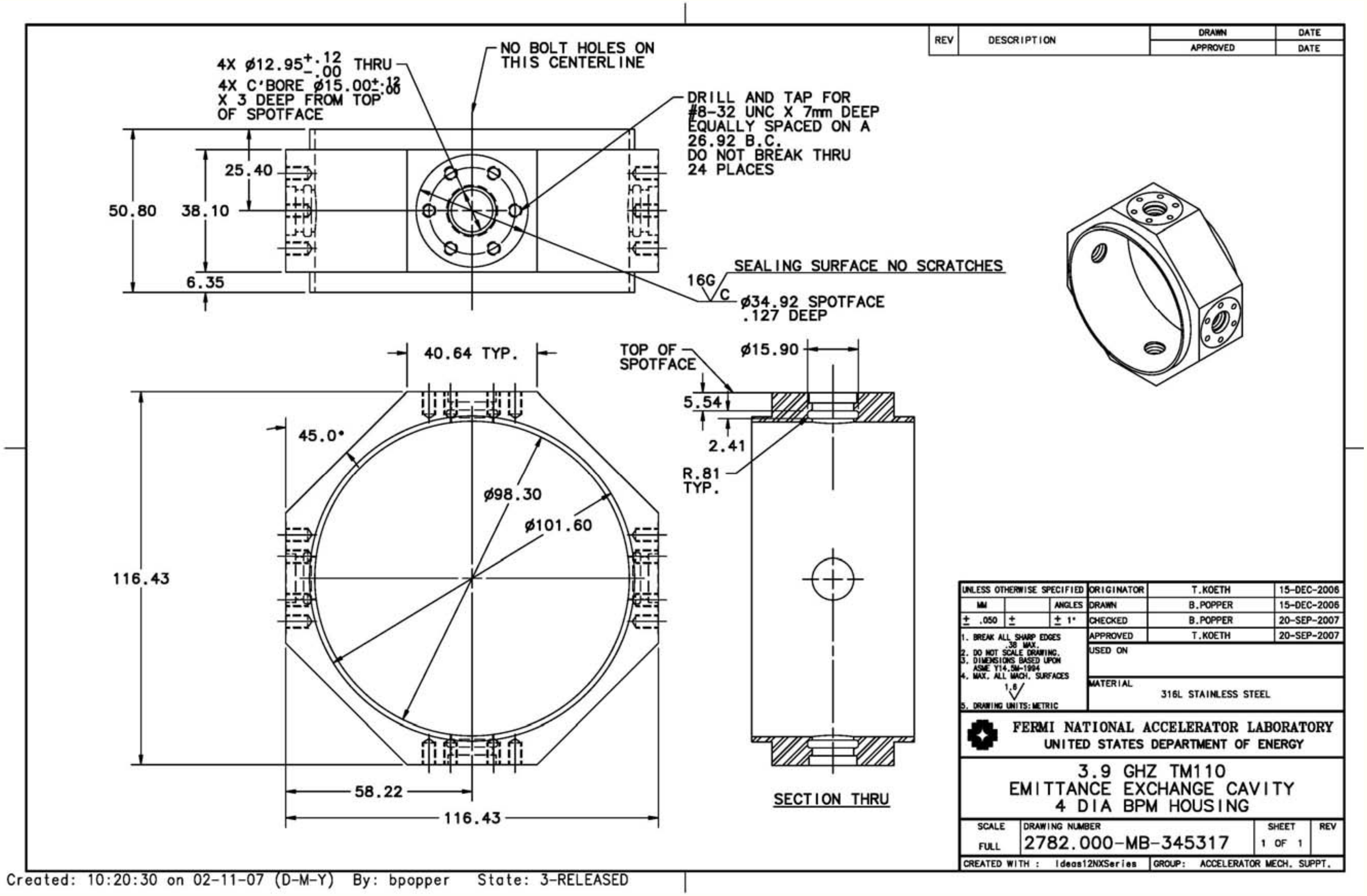






- **Position characteristic (2D electrostatic)**
- **3D PIC solver, 5 bunches, 100 pC, 100 ps RMS**
  - **TD & FD results, good response at 650 MHz!**

EEX 4-inch Button BPM



A0PI Button BPM

Button BPM Feedthrough

- 11 mm button diameter
- Al_2O_3 hermetic ceramic
- 316L SS, cryo compatibel
- 1-⅓” mini-flange
- Conflat flange sealing
  (here: VAT seal)
- Canted spring RF grounding

Conclusions

- **A cold L-Band cavity BPM prototype with 78 mm aperture, $Q_{load} \approx 600$, resolution < 1 µm, is in fabrication.**
  - **As of its complexity, and as of its incompatibility with Project X beam conditions, this cavity BPM will not be considered for immediate installation in a cryomodule!**
- **A design study of a 1.3 GHz CM-free cavity BPM demonstrates ILC and PX beam compatibility**
  - **Concerns are the dark current error signal, and the high power RF EMI!**
- **A well know Button BPM construction is proposed as default for the Project X / NML cryomodules**
  - **Needs cryogenic temperature and cleanroom verification.**
  - **Needs prototyping.**