Status and Update on Fermilab Linear Collider BPM R&D

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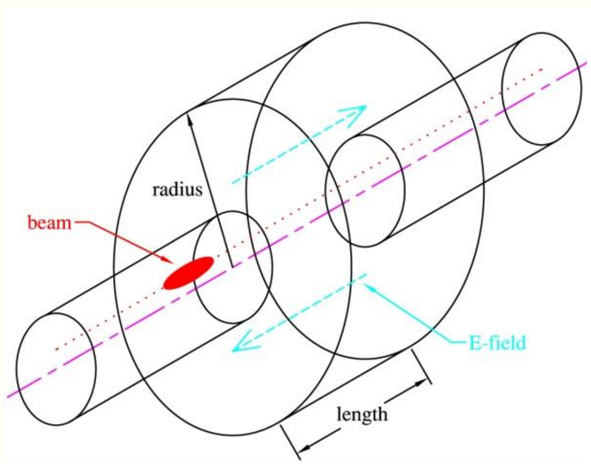
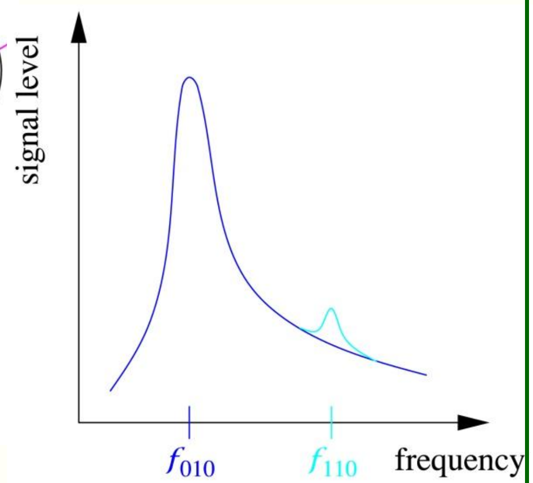
Thanks to the many colleagues from KEK, CERN and Fermilab, helping with these collaboration activities!

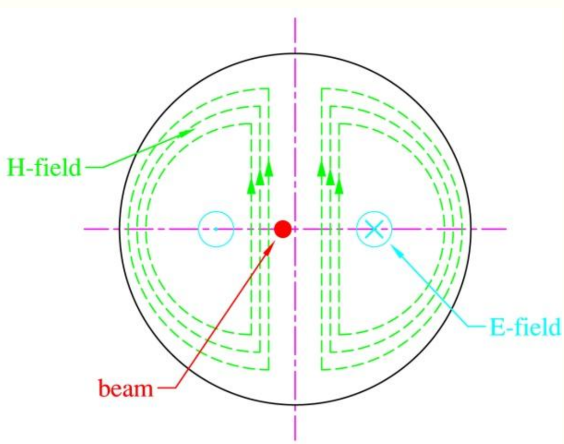
Agenda

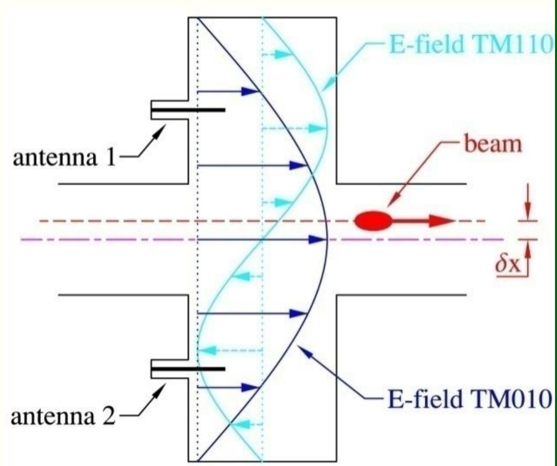
- Cavity BPM Introduction
- CLIC/CTF cavity BPM R&D
- Cold ILC cavity BPM R&D
- ATF Damping Ring BPM read-out system R&D
- Summary

Cavity BPM Principle









- **"Pillbox" cavity BPM**
  - **Eigenmodes:**

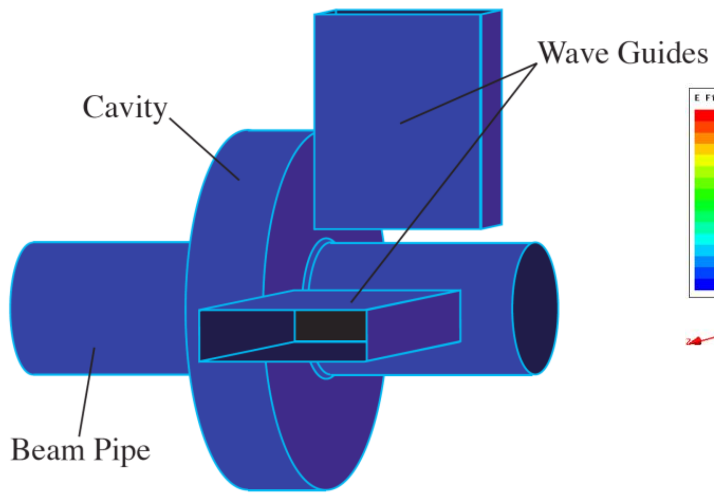
    $$f_{mnp} = \frac{1}{2\pi\sqrt{\mu_0\varepsilon_0}}\sqrt{\left(\frac{j_{mn}}{R}\right)^2 + \left(\frac{p\pi}{l}\right)^2}$$

  - **Beam couples to**

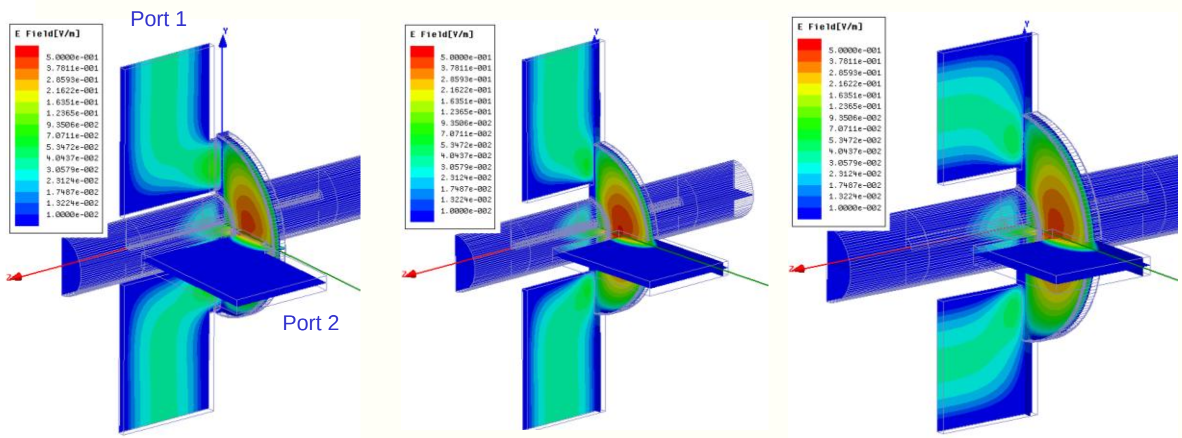
    $$E_z = CJ_1\left(\frac{j_{11}r}{R}\right)\cos\emptyset\, e^{i\omega t}$$

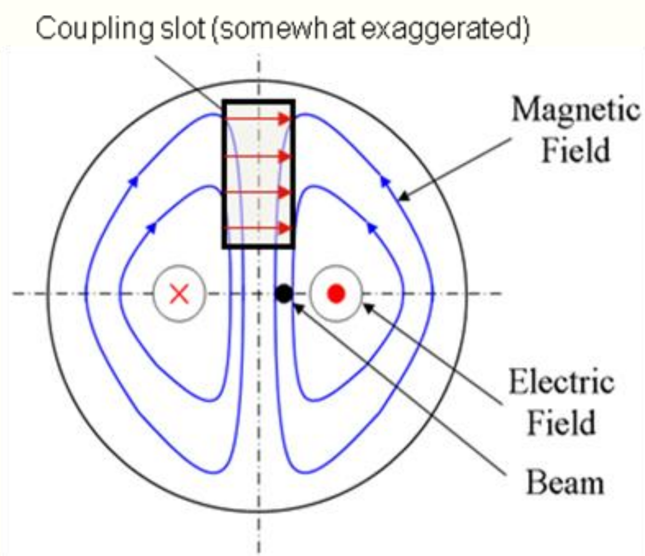
    dipole (TM_{110}) and monopole (TM_{010}) modes
  - **Common mode (TM_{010}) suppression by frequency discrimination**
  - **Orthogonal dipole mode polarization (xy cross talk)**
  - **Transient (single bunch) response (Q_L)**
  - **Normalization and phase reference**

CM-"free" Cavity BPM



Different cavity-WG coupling schemas





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

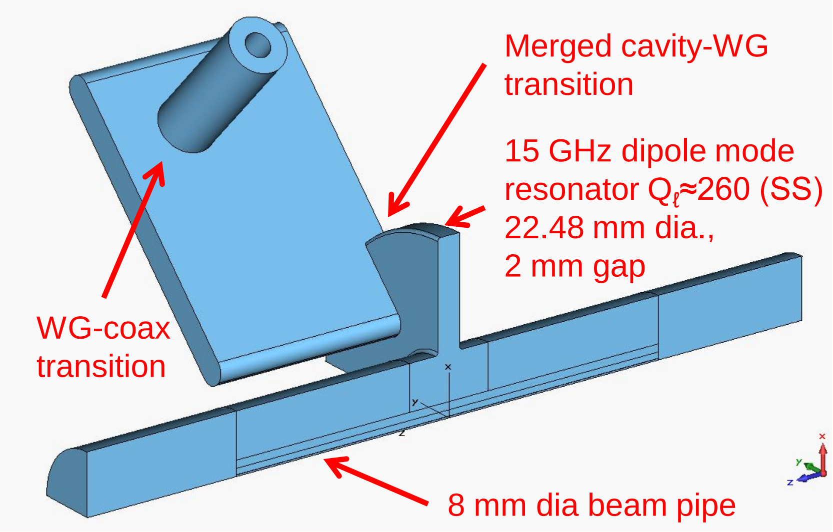
$$f_{010} < \quad f_{10} = \frac{1}{2a\sqrt{\varepsilon\mu}} \quad < f_{110}$$

between cavity and coaxial output port

- **Finite *Q* of TM_{010} still pollutes the TM_{110} dipole mode!**

CLIC/CTF Main Linac BPM

	CLIC	CTF / CALIFES
Nominal bunch charge [nC]	0.6	0.6
Bunch length (RMS) [μm]	44	225
Batch length, bunch spacing [nsec]	156, 0.5	1-150, 0.6667
Beam pipe radius [mm]	4	4
BPM time resolution [nsec]	<50	<50
BPM spatial resolution [nm]	<50	<50
BPM dynamic range [μm]	±100	±100
BPM dipole mode frequency f_{110} [GHz]	14.0000	14.98962
REF monopole mode frequency f_{010} [GHz]	14.0000	14.98962
Number of BPMs	~4000 (!)	>3
Longitudinal real estate	<90 mm	na

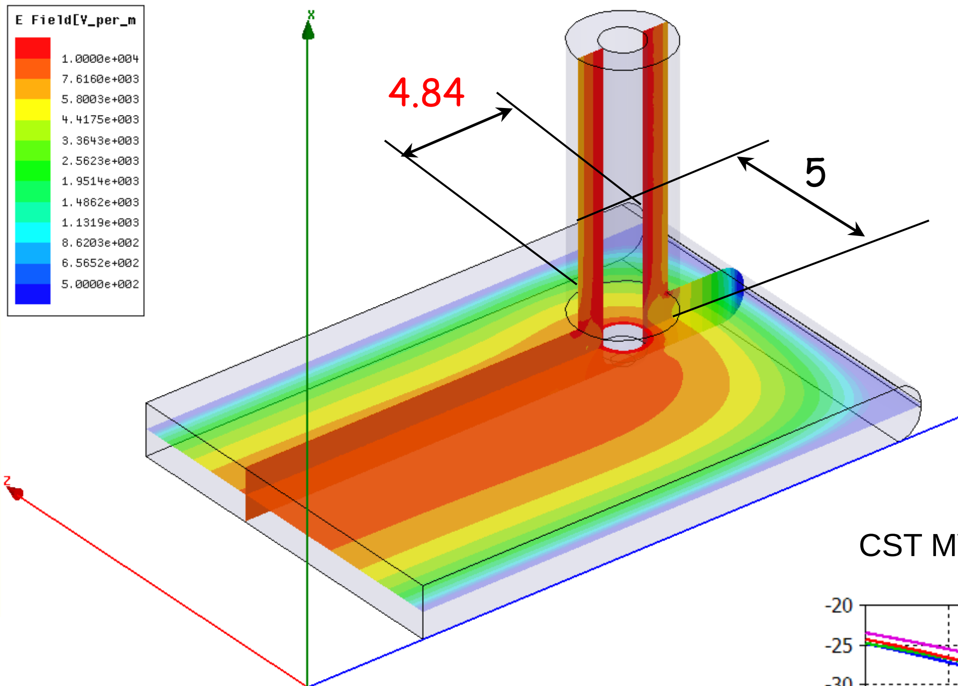


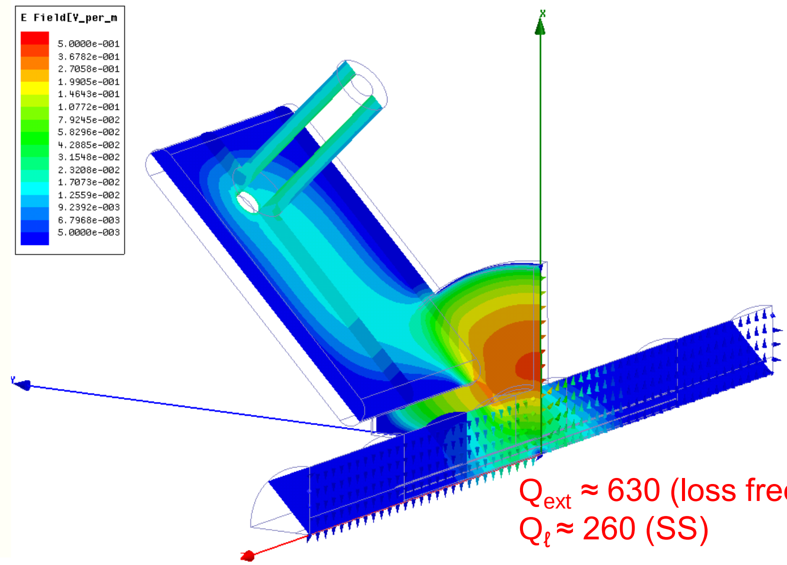
- WG-loaded, low-Q X-Band design (Fermilab-CERN)
  - $Q_\ell \approx 260$, resonator material: 304 stainless steel
  - CTF prototype includes a monopole mode reference cavity (same frequency)
  - ~50 nsec time resolution, <50 nm spatial resolution
- EM design, tolerances, signal characteristics, etc. finalized.
- CTF prototype mechanical design is almost finalized.

Design Steps

- Started CLIC ML BPM with f_{110} = 14 GHz
  - Analyzed beam spectrum response for single bunches and bunch trains, including WG TM_{010} mode suppression, etc.
  - Investigated different cavity-WG coupling schemas.
  - Detailed analysis of mechanical tolerances, e.g. on the cavity-WG coupling slot (tilt, shift, rotation, etc.)
    - Minimized TM_{010} mode leakage
  - Compared different WG-coax output symmetries
    - Minimize xy-cross coupling
  - Set limits to mechanical tolerances (<±5 μm)
- Added monopole-mode reference resonator f_{010} = 10 GHz
- Modified design to CTF bunch frequencies (S-band)
  - Both resonators now operate at 15 GHz
  - Verified sufficient distance (coupling due to evanescent fields)

EM Simulation Details

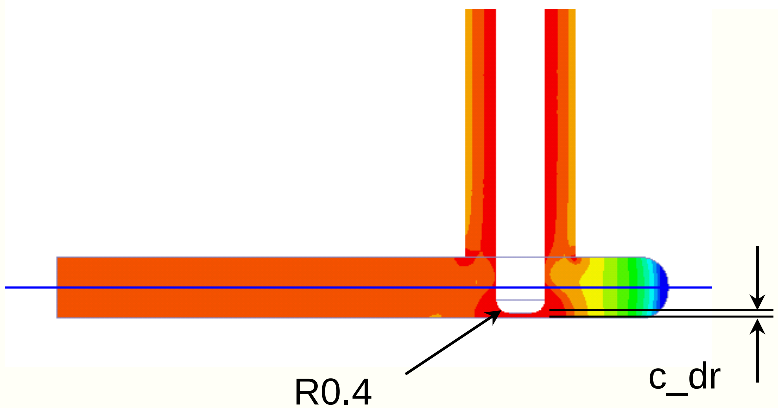


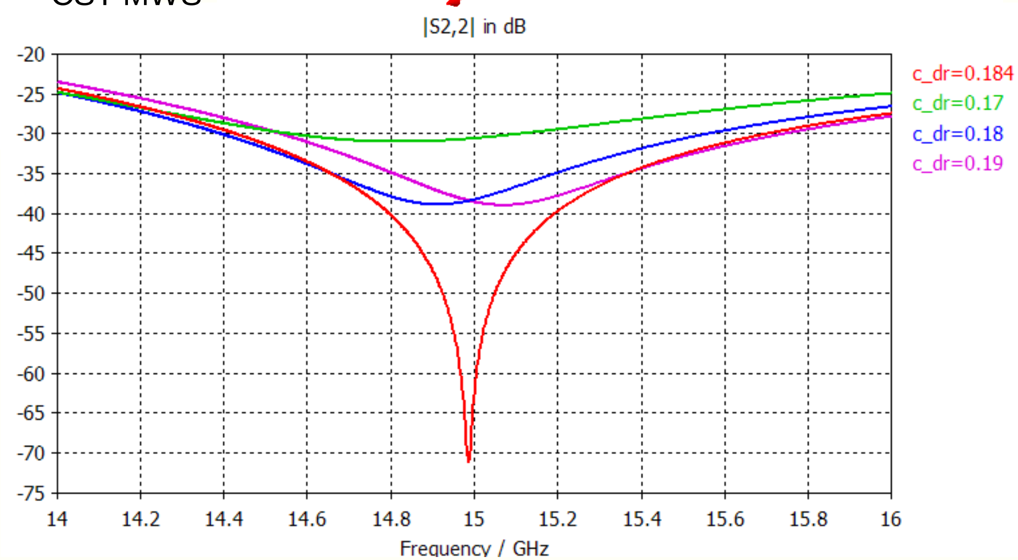


$Q_{ext} \approx 630$ (loss free)

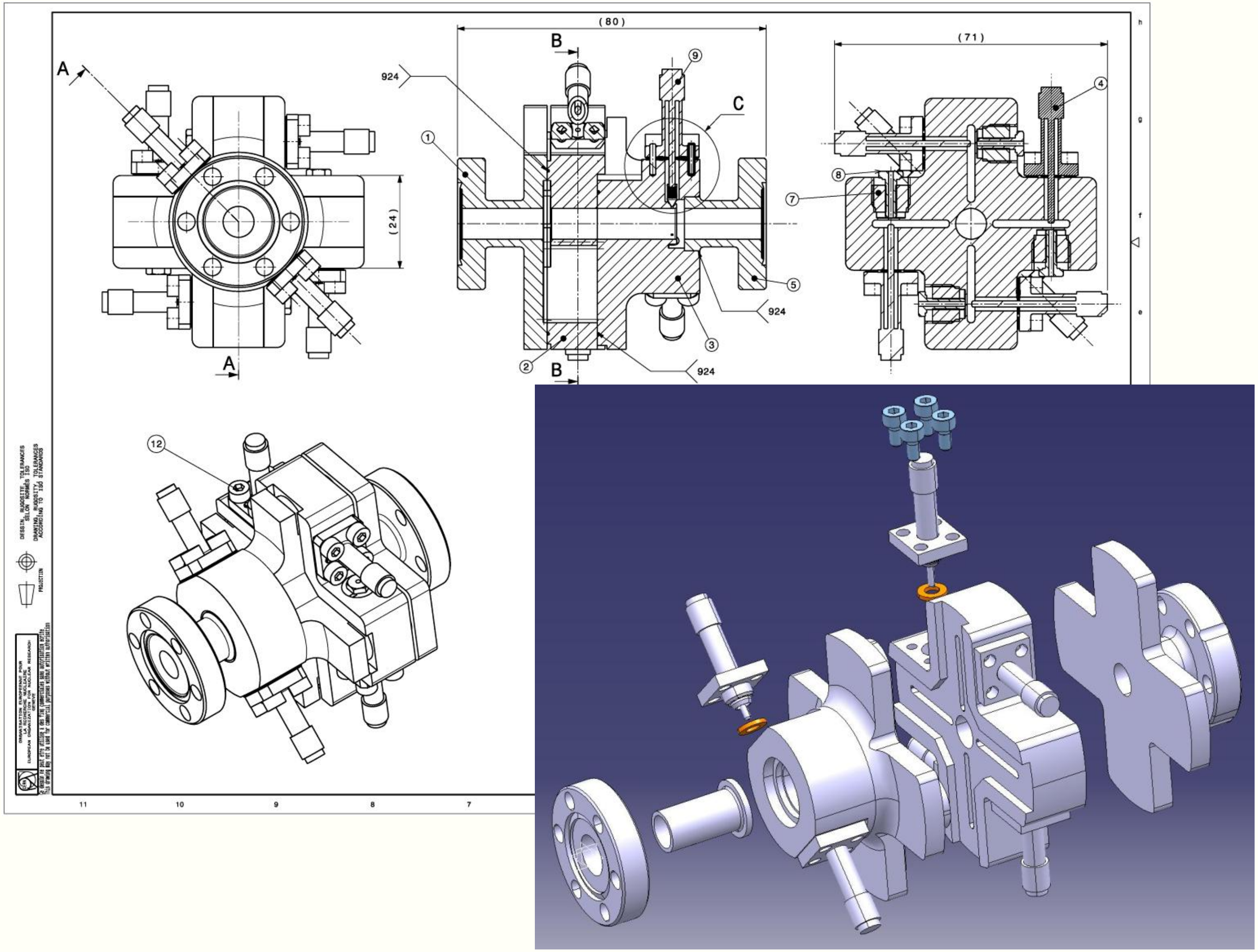
$Q_\ell \approx 260$ (SS)

CST MWS

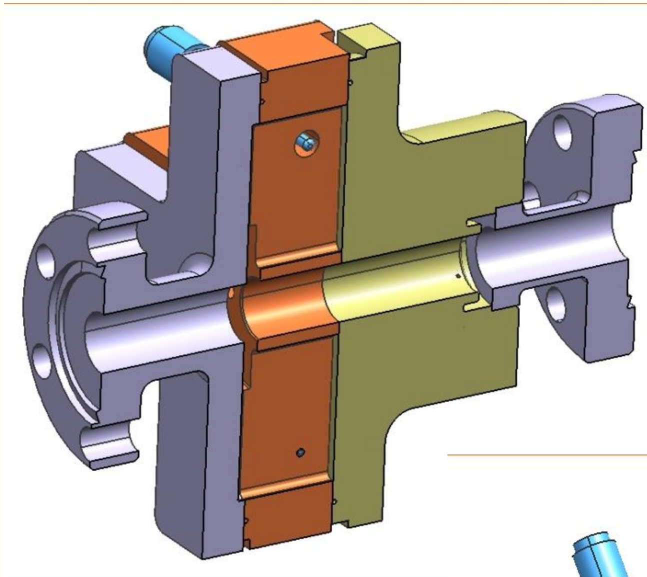


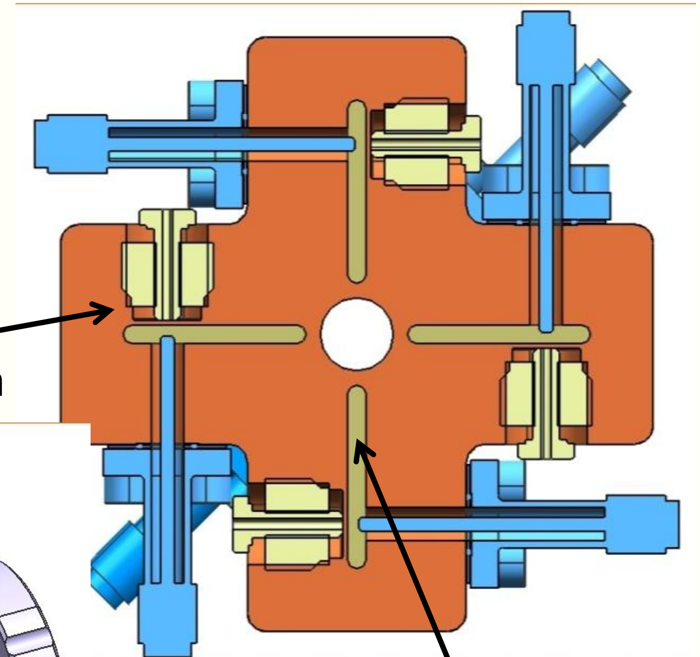


CTF Cavity BPM



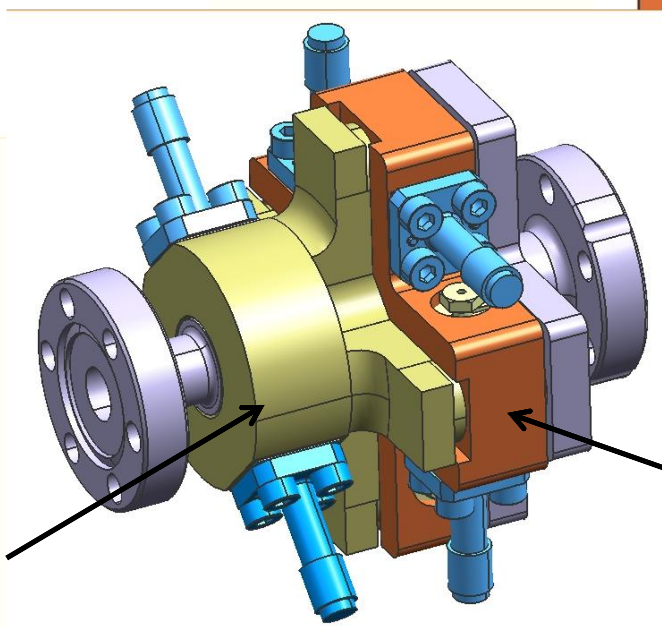
CTF Cavity BPM (cont.)





Tuning dimple
WG-coax transition

Waveguide

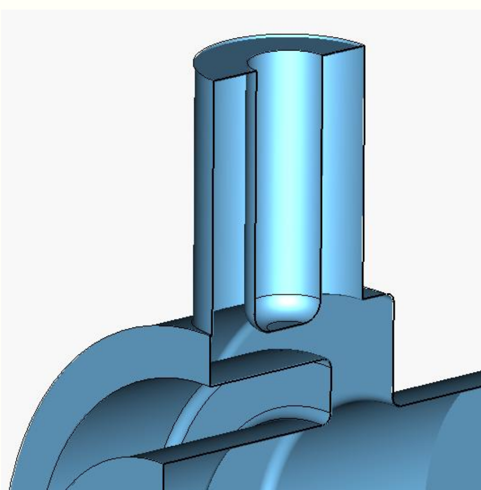


Monopole-mode
“REF” resonator

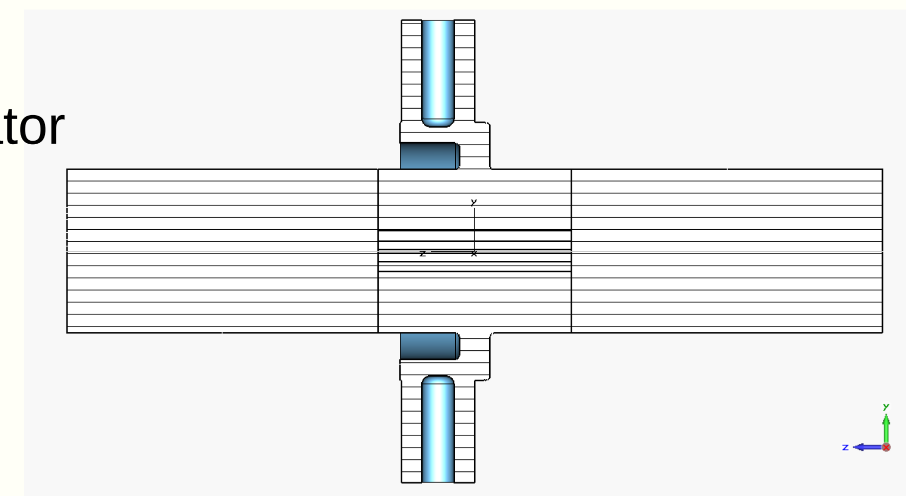
Dipole-mode
“BPM” resonator
& waveguide

Next Steps

- Manufacture 1st CLIC/CTF Main Linac BPM prototype
  - Have quotes for feedthroughs
  - Construction drawings are almost ready, dimensions are frozen.
  - RF tests and verification of the BPM, allow for small modifications to correct resonance frequencies / Q-values.
- Produce three CTF BPMs for installation in CTF3
- Start R&D on 15 GHz analog/digital read-out system



Monopole-mode reference resonator
f_{010} = 15 GHz

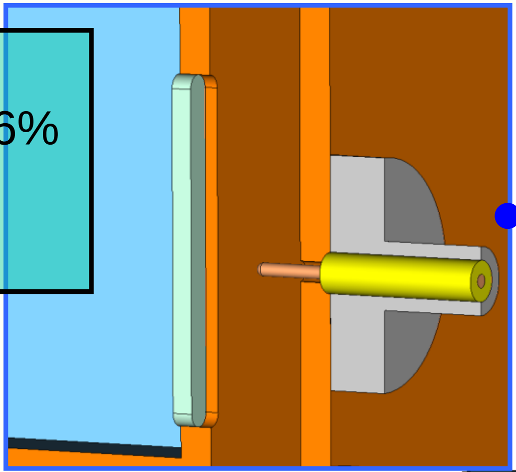


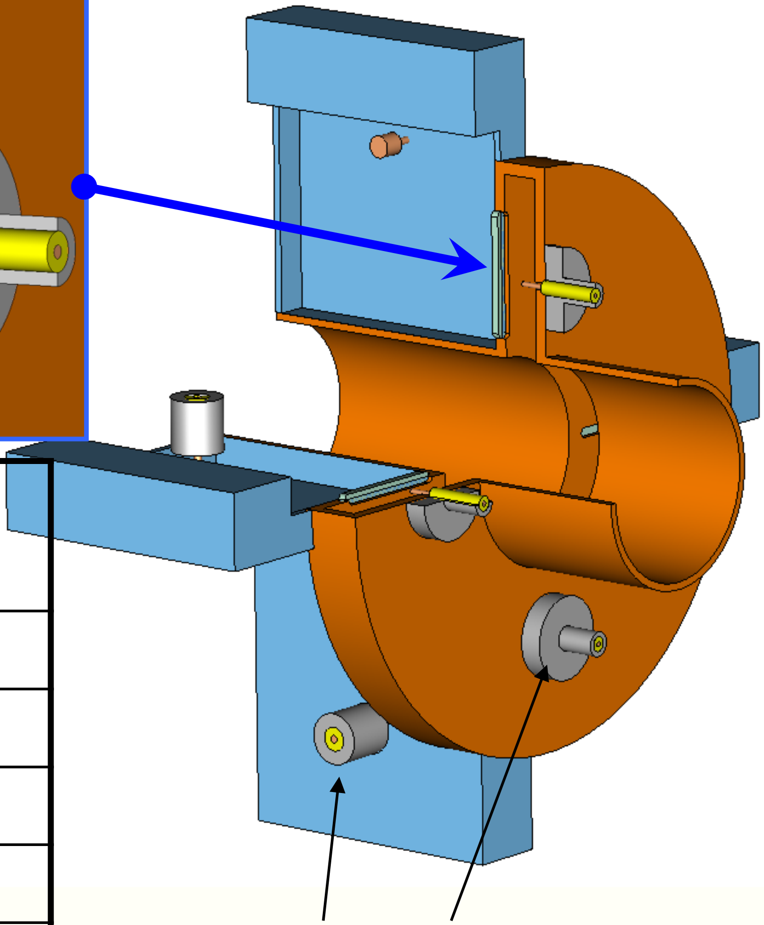
Cold BPM for an ILC Cryomodule

- 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

Fermilab L-Band Design

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

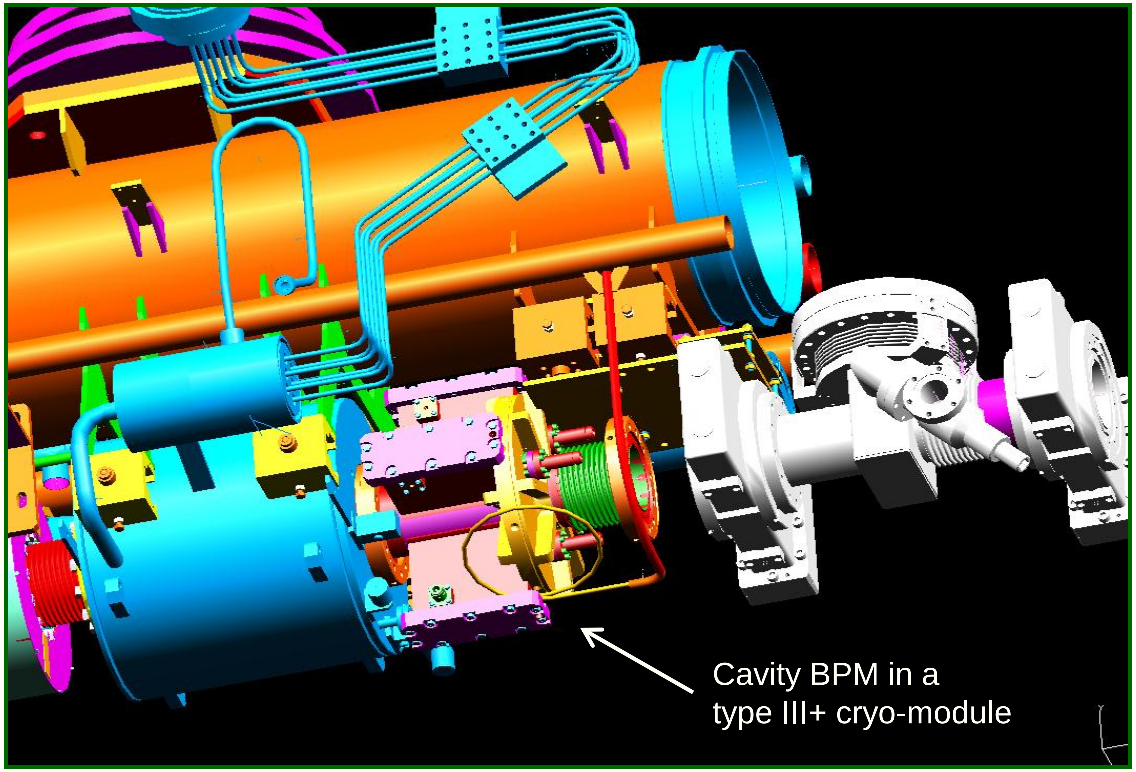


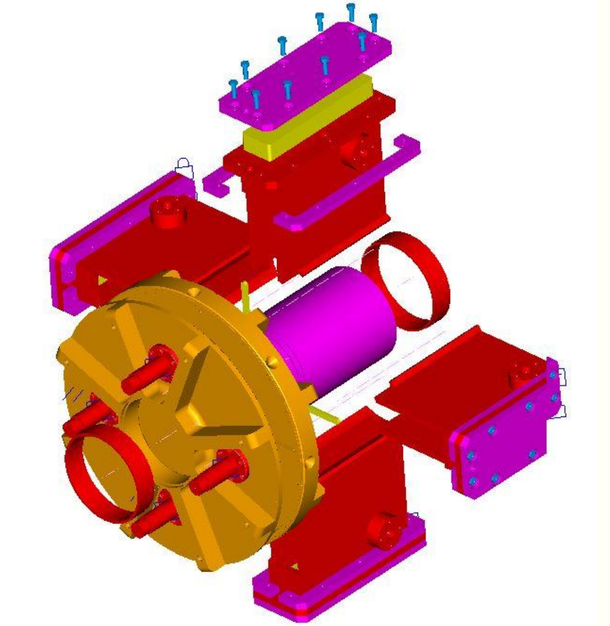


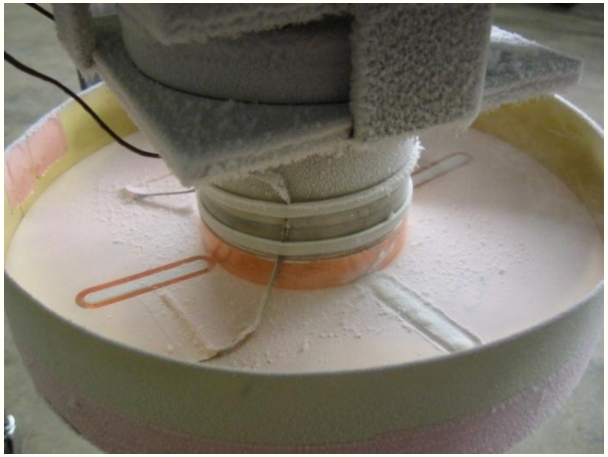
Frequency, GHz, dipole **monopole**	**1.468** **1.125**
Loaded Q (both monopole and dipole**)**	**~ 600**
Beam pipe radius, mm	**39**
Cell radius, mm	**113**
Cell gap, mm	**15**
Waveguide, mm	**122x110x25**
Coupling slot, mm	**51x4x3**

N type receptacles,
50 Ohm

Cold L-Band ILC BPM R&D

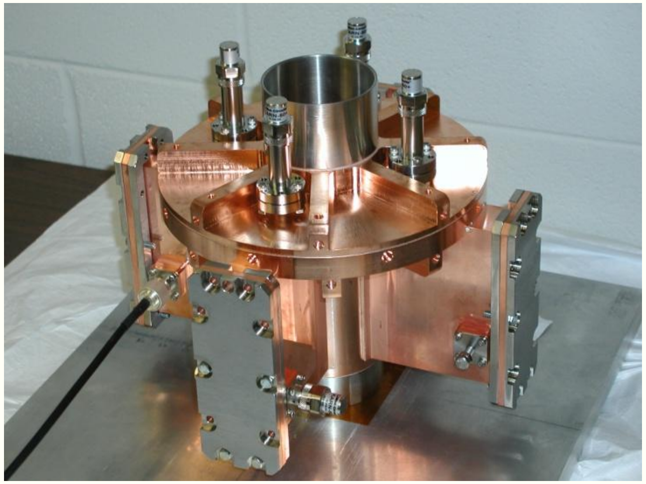


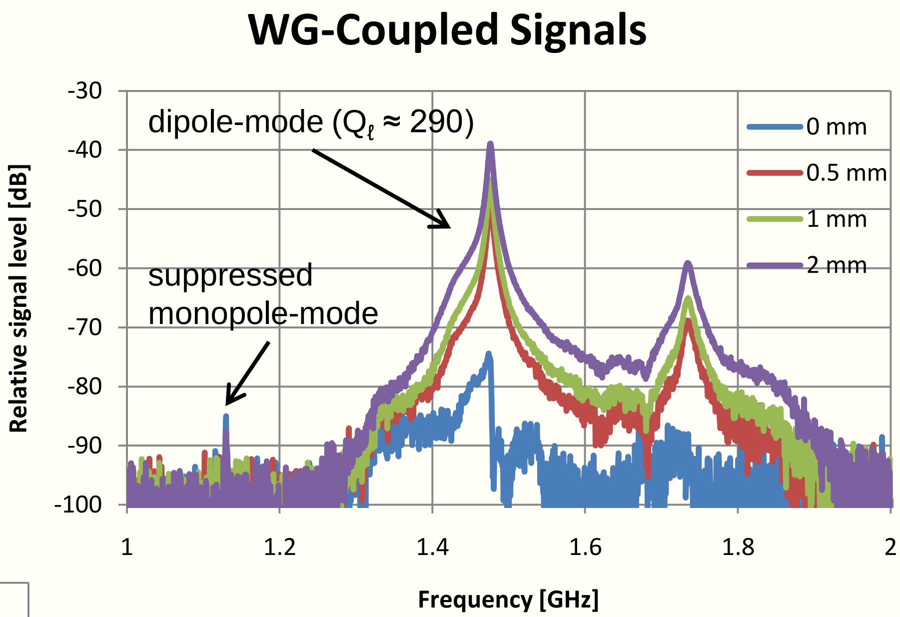


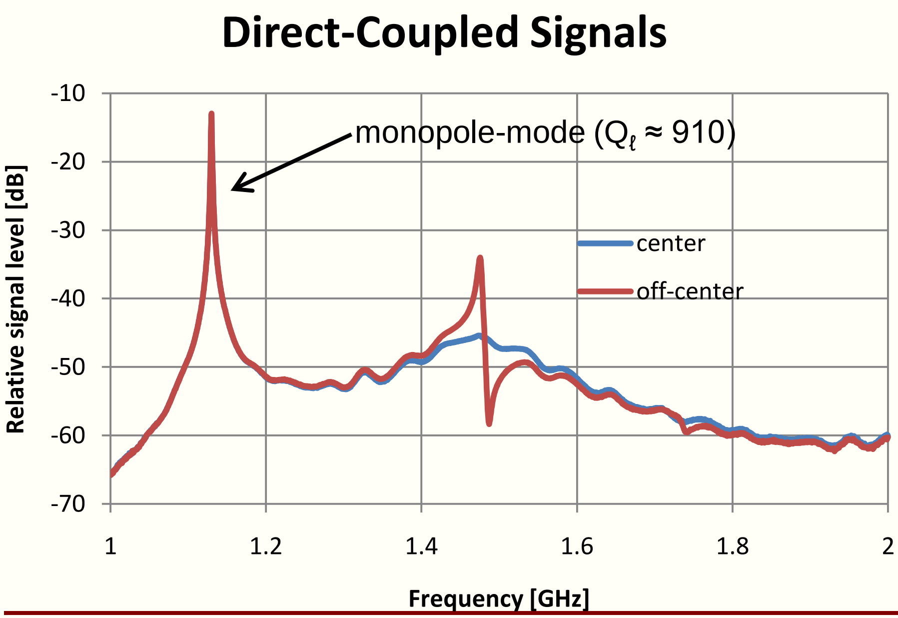


- **Status:**
  - **First "warm" prototype finalized**
  - **Started with RF characterization**
  - **Could be installed into a beam-line**

First RF Measurements

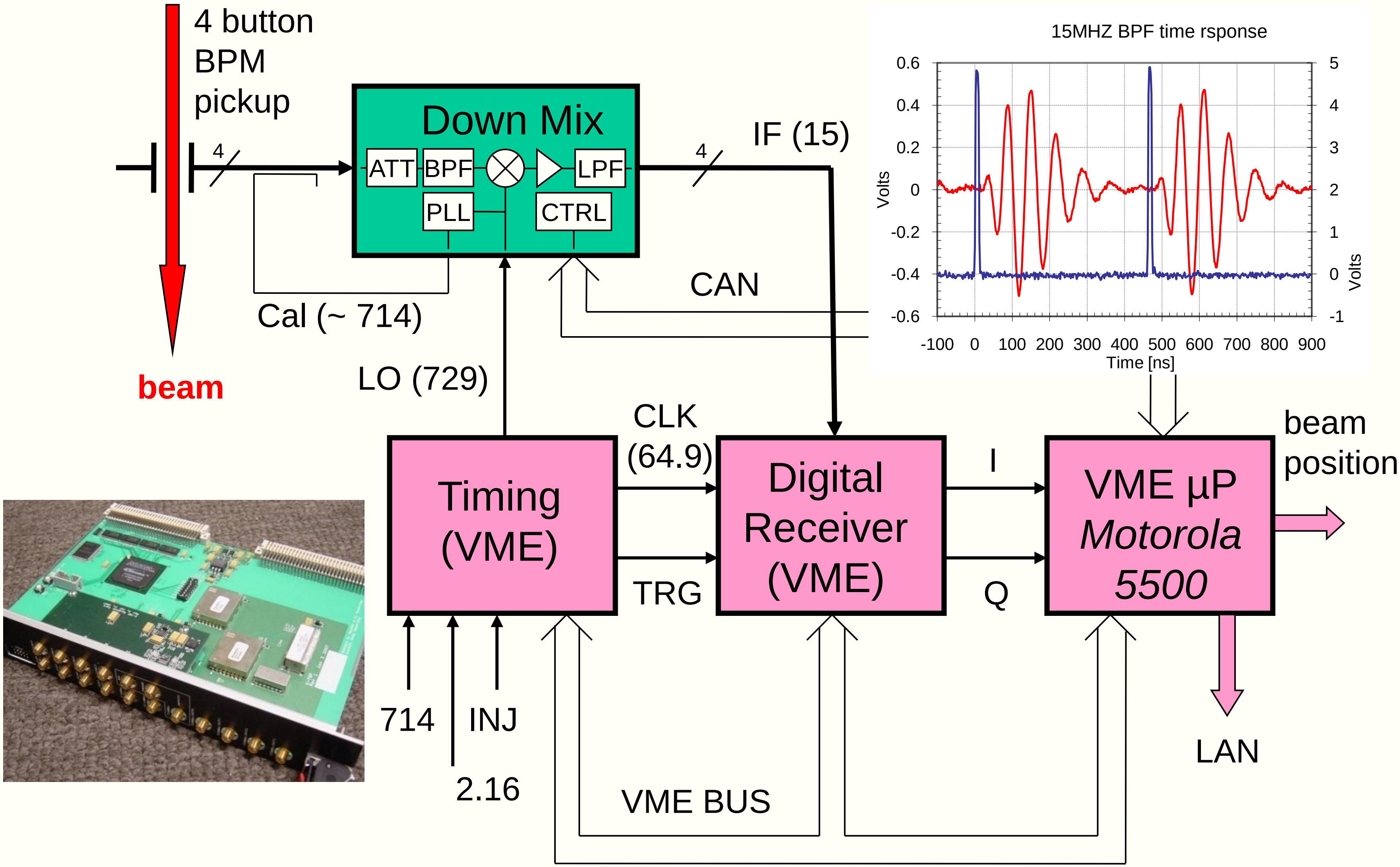






- **Very preliminary!**
  - **Setup not optimized**
  - **Cavity not yet tuned**
  - **xy-cross not analyzed**
  - **WG-coax transitions not tuned**

ATF Damping Ring BPM R&D



ATF DR BPMs: New Hardware

Improvements on the analog downconverter

- CAN-bus controls, IF filter, remote diagnostics, etc.

New RF, DC & CAN-bus distribution. Grounding of tunnel hardware.

Switch to in-house VME digitizer

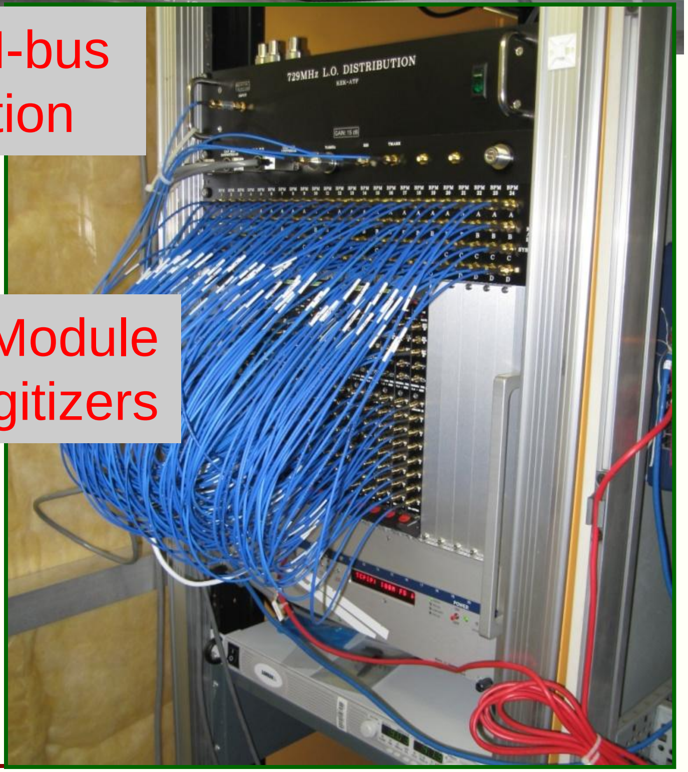
- 8-ch. ,125 MSPS ADC (serial outputs), Cylcone III FPGA, PLL-locked CLK distribution

- Able to measure Injection TBT, Narrowband Orbit, Narrowband Calibration , and Last Turn on every injection

New Downmix & Calibration

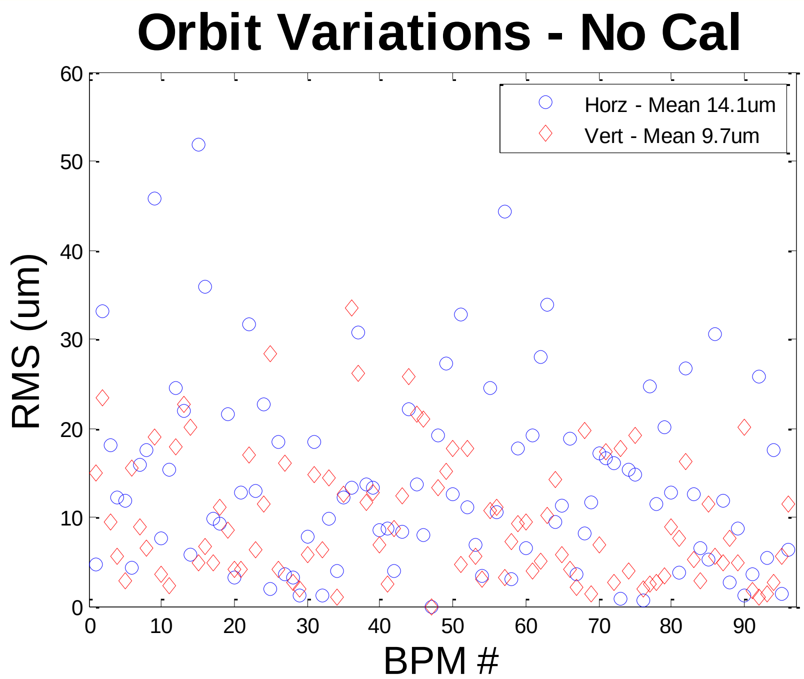
LO & CAN-bus Distribution

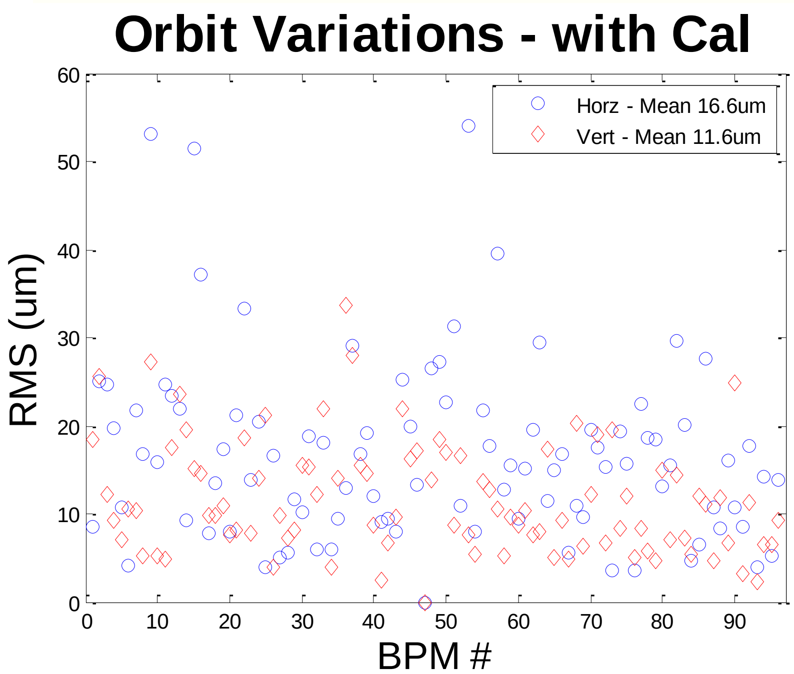
New Timing Module & Custom Digitizers



First Look at Narrowband Orbit

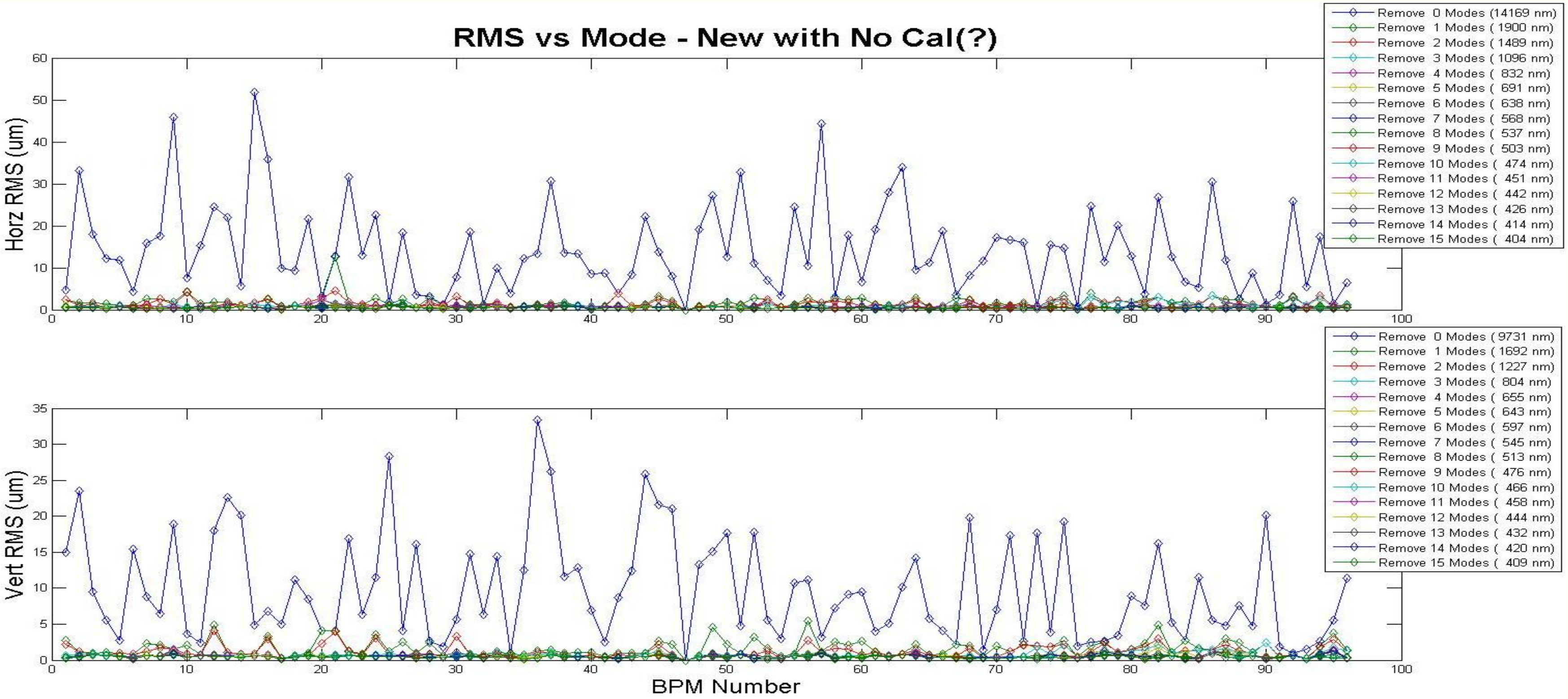
- Narrowband orbit for each injection (shot) is measured
  – The mean orbit and rms over 160ms is reported for Horz, Vert
- For each data set, 128 shots are collected
  – Large shot to shot mean orbit variations are observed in both
  – Horizontal shows larger RMS than vertical -> Beam related



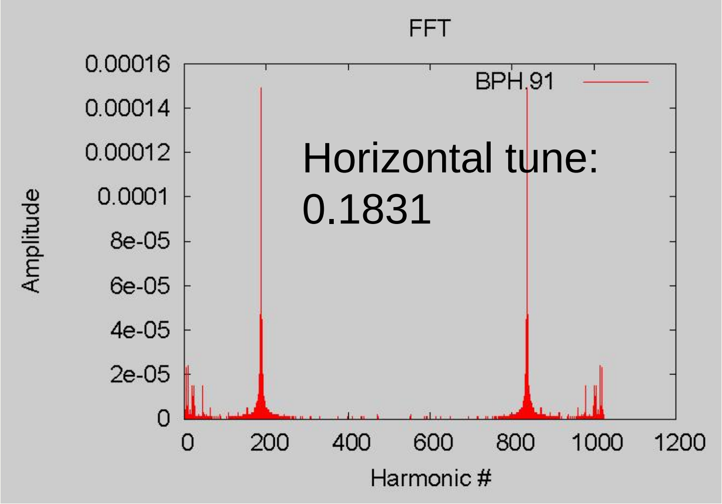


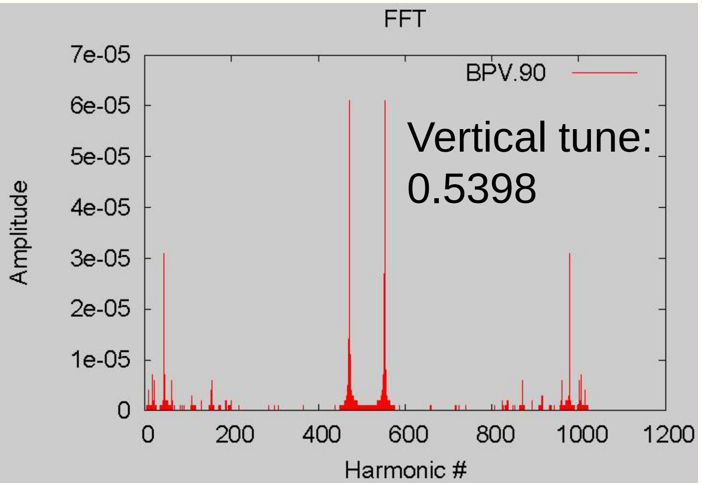
Preliminary SVD Orbit Analysis

- **Use SVD to look for correlated motion and estimate resolutions**
  - **Ignoring beam effects, the horizontal and vertical resolution of the pickup/electronics should be the same…**
  - **Remove first 8 modes: ~0.5 µm resolution (no CAL)**
  - **Indication of issues with the automatic gain correction system (CAL)**



ATF DR BPMs: TBT Studies





Theory:

- **TBT data at j^{th} BPM (single kick)**

$$z_n^j = \frac{1}{2}\sqrt{\beta_z^j}\, A_z\, e^{i(\mu_z + 2\pi Q_z n)} + c.c.$$

$$n \equiv \text{turn number}$$

$$A_z = |A_z| e^{i\delta_z} \equiv \text{constant of motion}$$

- **Beta functions at BPM locations**

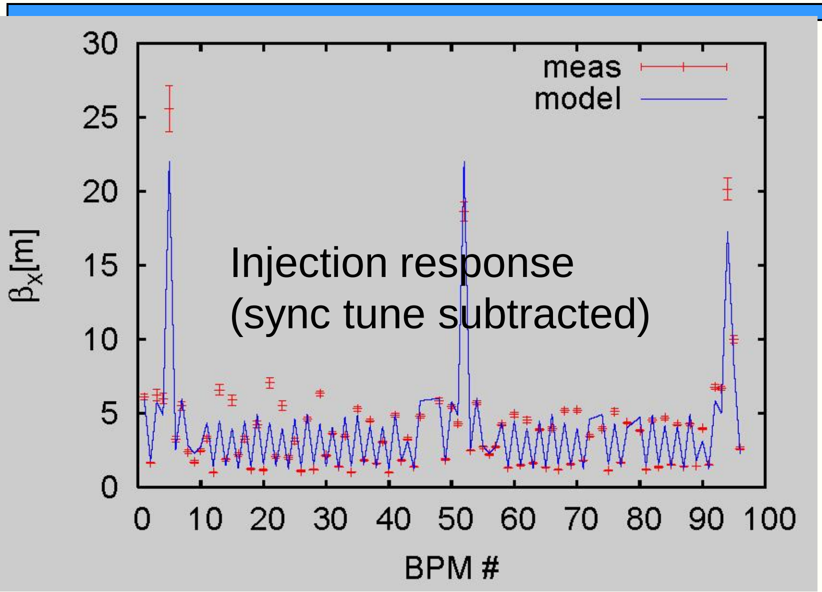
$$\beta_z^j = \frac{|Z_j(Q_z)|^2}{|A_z|^2} \qquad \mu_z^j = \arg(Z_j) - \delta_z$$

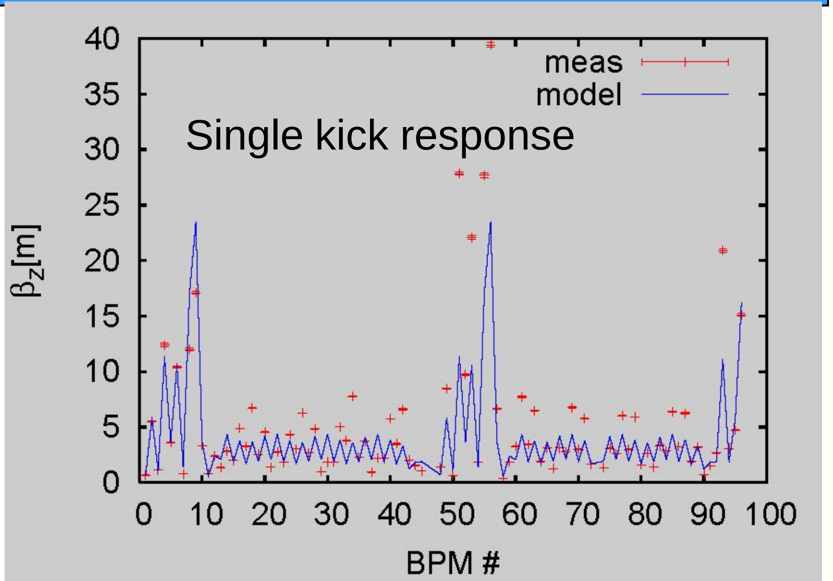
$$Z_j(Q_z) \equiv \mathit{Fourier}\ \text{component of}\ z_j$$

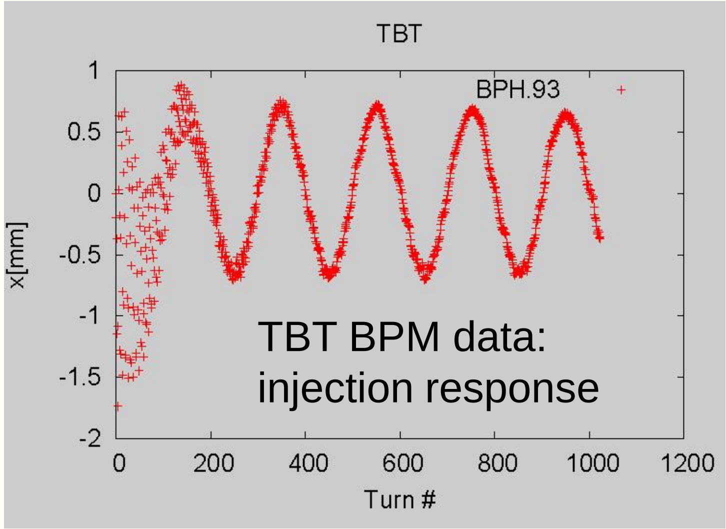
$$|A_z| = \sqrt{\beta_z^k}\,\theta_k \qquad \theta_k \equiv \text{kick}$$

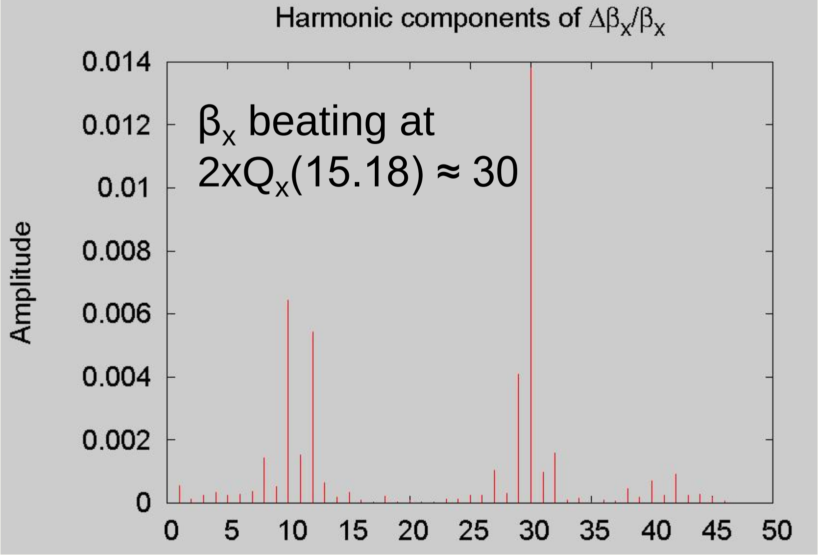
$$\delta_z = -\mu_z^k + (2n+1)\frac{\pi}{2}$$

ATF DR BPMs: TBT Results









Summary

- Fermilab continues to be an active member on LC beam diagnostics R&D; Slow, but with constant pace!
- A CLIC/CTF main linac BPM has been analyzed
  - Resolution potential: <50 nsec, <50 nm
  - CTF3 prototype dimensions and construction frozen.
  - Further modifications are under discussion, e.g. higher Q_{ℓ}, magnetic WG-coax transition
- An ILC cavity BPM prototype has been manufactured
  - RF measurements and tuning is underway
- A standard for analog / digital BPM read-out electronics has been established
  - Integrated automatic gain correction / calibration
  - Highly configurable to circular and linear machines, and different types of BPM detectors.