Status of the ILC Main Linac BPM R&D

Thibaut Lefevre
CERN
Claire Simon
CEA Sacley
Sebastien Vilalte
LAPP
Manfred Wendt
Fermilab

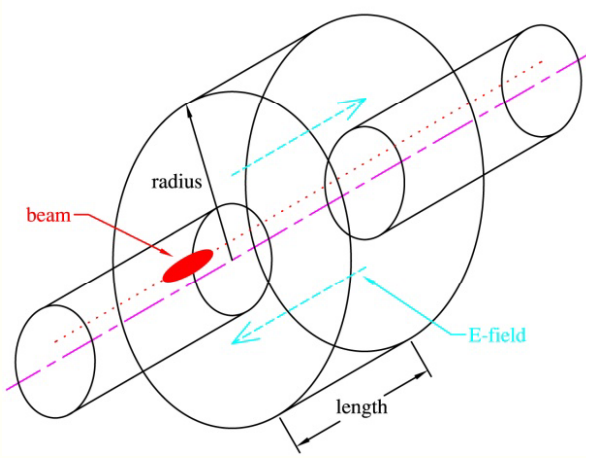
Agenda

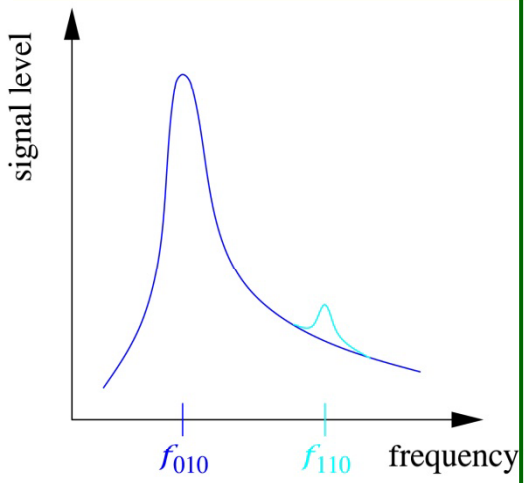
- Introduction
- CM-"free" cavity BPMs.
  The SLAC prototype BPM.
- Cold ILC cavity BPM R&D at Fermilab,
  Read-out hardware developments.
- Re-entrant BPM R&D for XFEL & CTF3
  at CEA-Saclay.
- Radiation tolerant read-out electronics R&D
  for CTF3 at LAPP.
- Conclusions

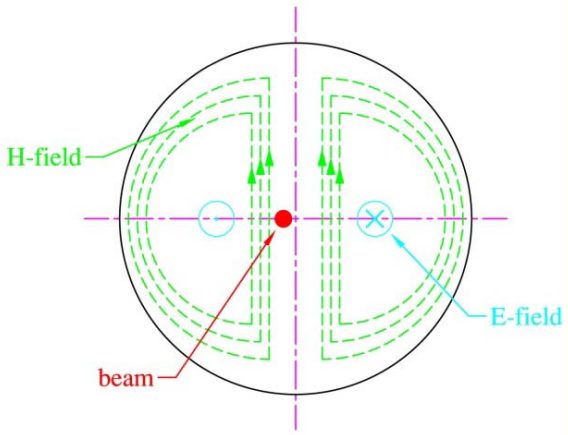
Cold BPM for an ILC Cryomodule

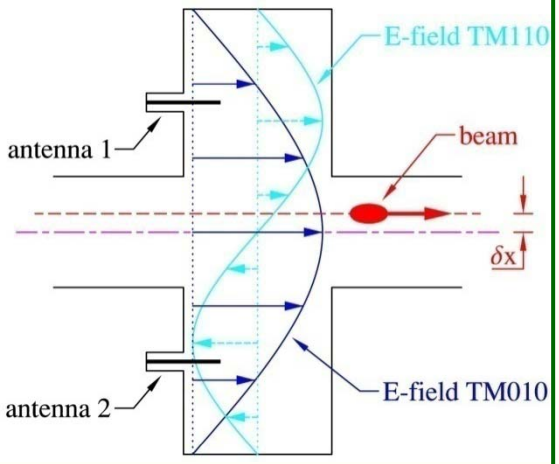
- **ILC beam parameters, e.g.**
  - Macro pulse length t_{pulse} = 800 μs
  - Bunch-to-bunch spacing $\Delta t_b \approx 370$ ns
  - Nominal bunch charge = 3.2 nC
- **Beam dynamic requirements**
  - < 1 μm resolution, single bunch (emittance preservation, beam jitter sources)
  - Absolute accuracy < 300 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

Cavity BPM Principle









- "Pillbox" cavity BPM
  - Eigenmodes:

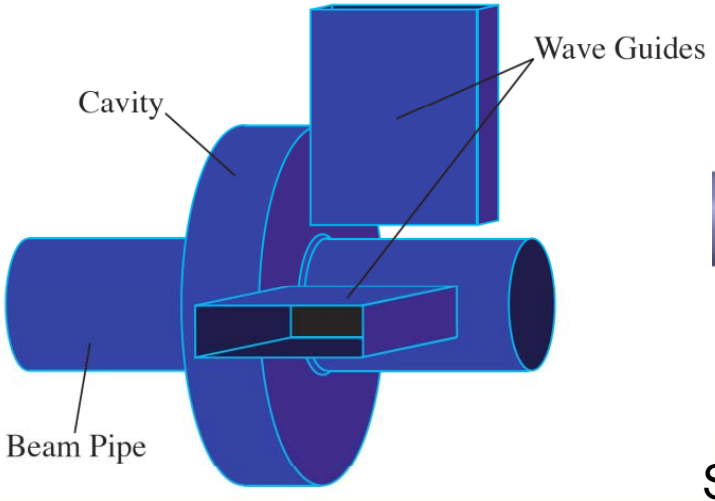
$$f_{mnp} = \frac{1}{2\pi\sqrt{\mu_0\varepsilon_0}}\sqrt{\left(\frac{j_{mn}}{R}\right)^2 + \left(\frac{p\pi}{l}\right)^2}$$

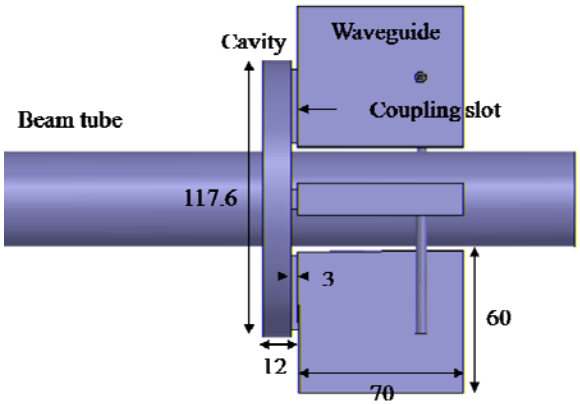
  - Beam couples to

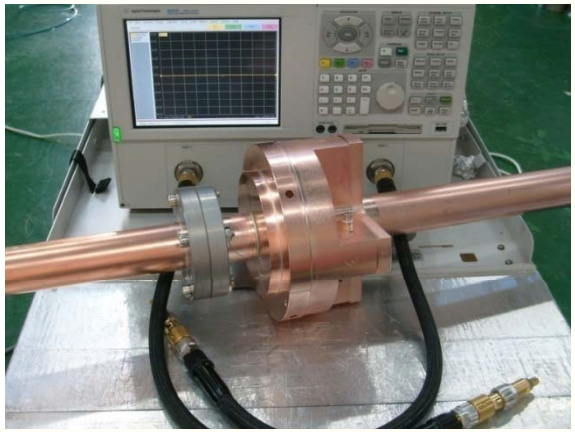
$$E_z = CJ_1\left(\frac{j_{11}r}{R}\right)\cos\phi\, e^{i\omega t}$$

    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

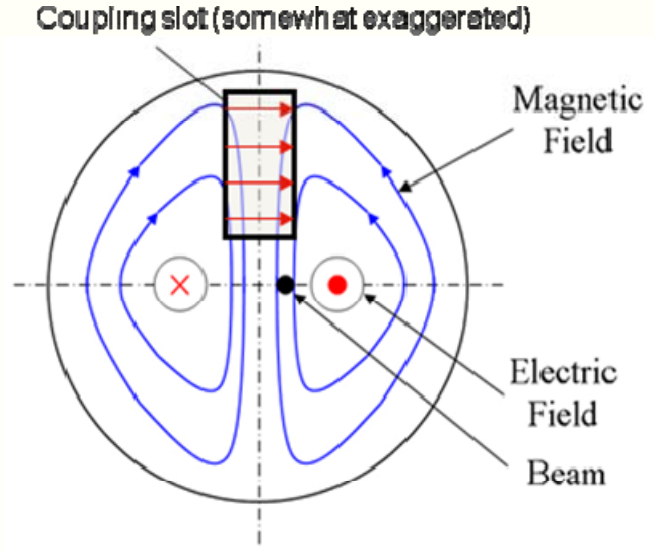
CM-"free" Cavity BPM







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



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

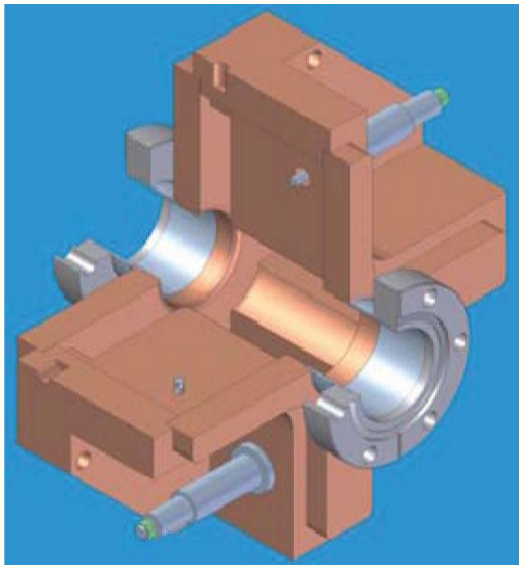
$$f_{010} < f_{10} = \frac{1}{2a\sqrt{\varepsilon\mu}} < f_{110}$$

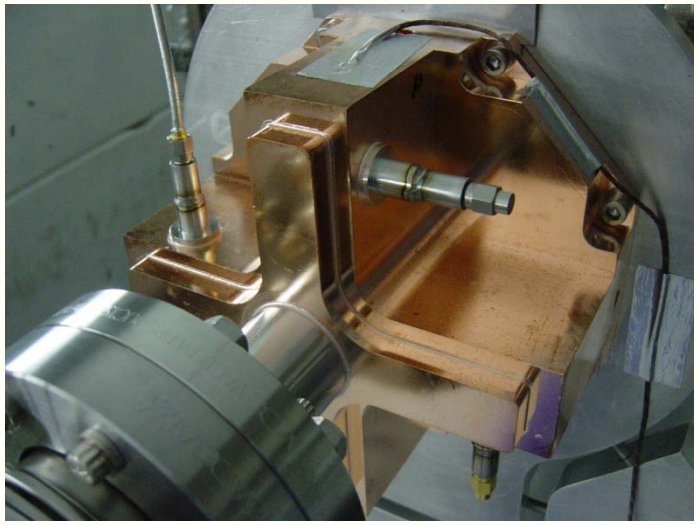
between cavity and coaxial output port

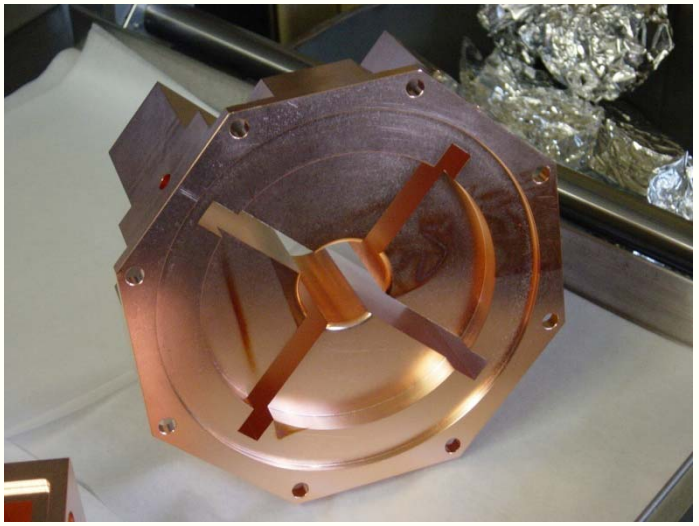
- **Finite *Q* of TM_{010} still pollutes the TM_{110} dipole mode!**

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

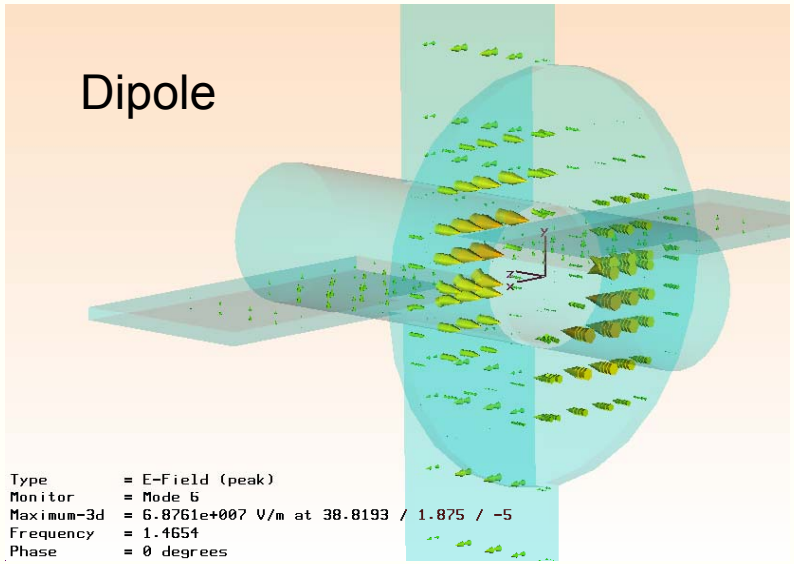


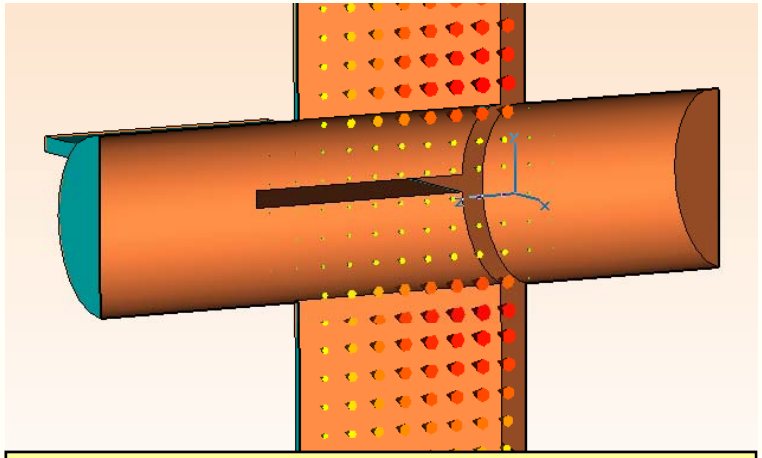




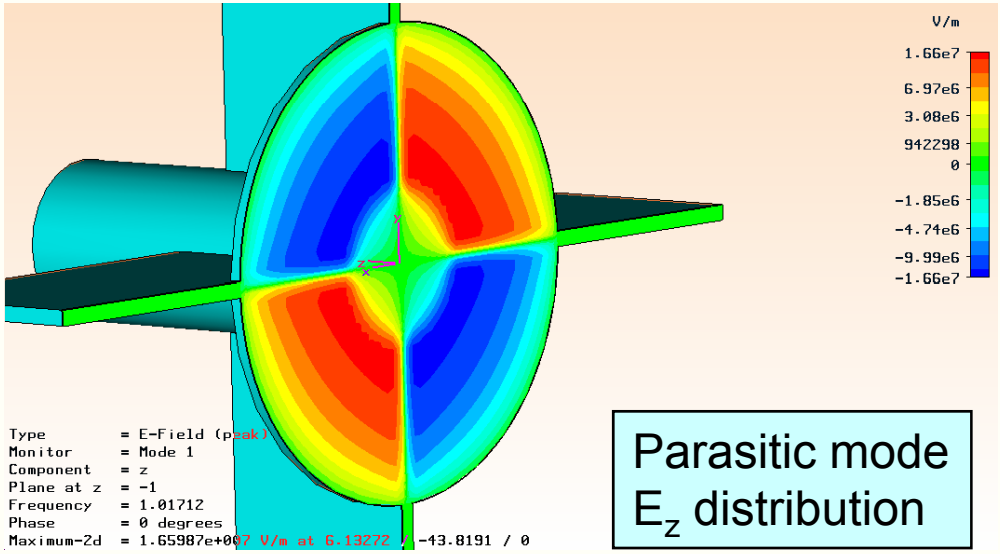
SLAC BPM Scaled to L-Band

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





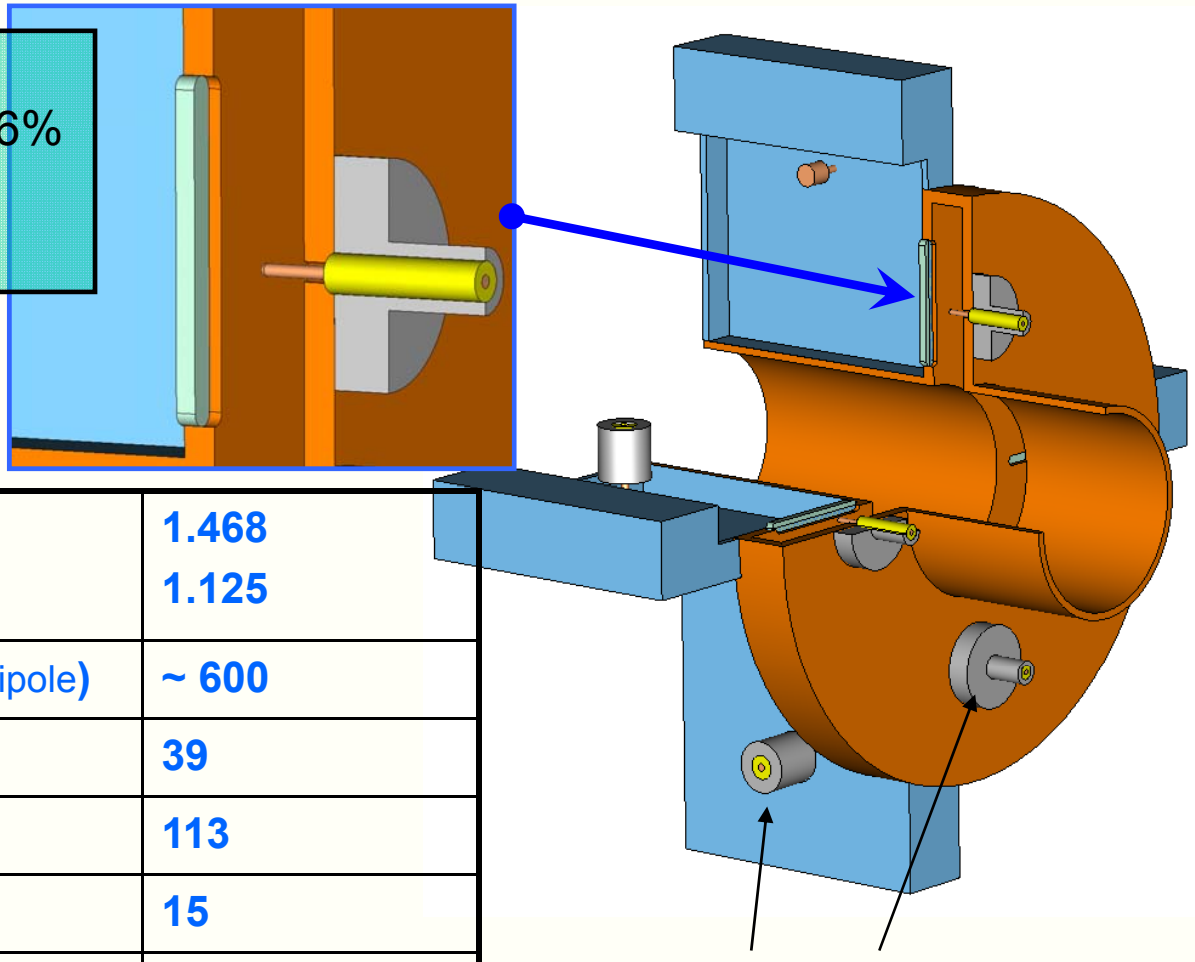
Parasitic mode. Coupling through horizontal slots is clearly seen



Parasitic mode E_z distribution

Fermilab L-Band Design

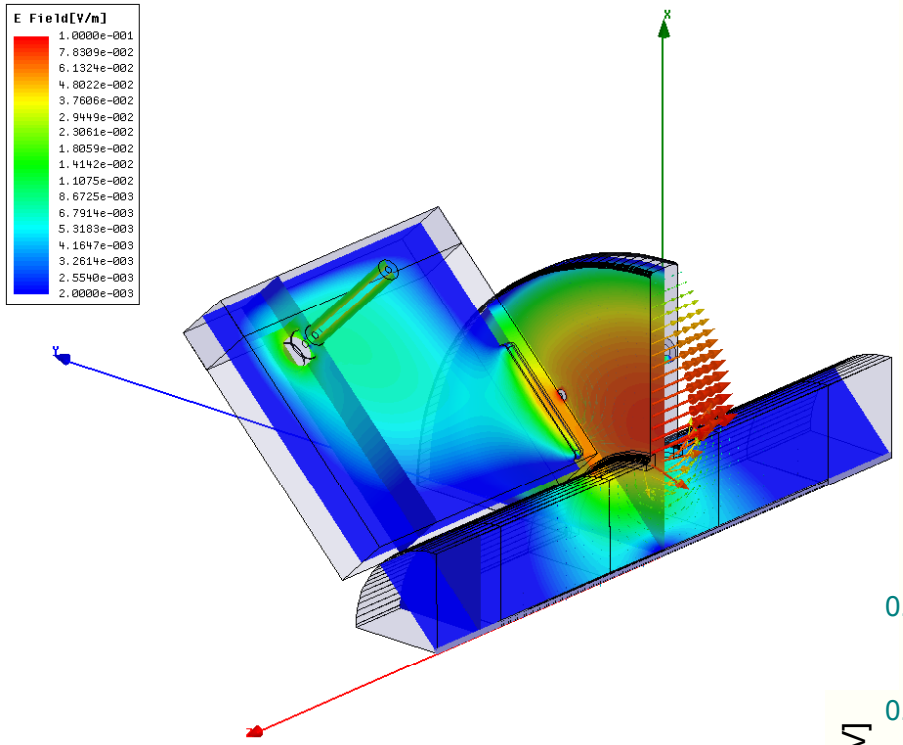
Window –
Ceramic brick of alumina 96%
$\varepsilon_r = 9.4$
Size: 51x4x3 mm



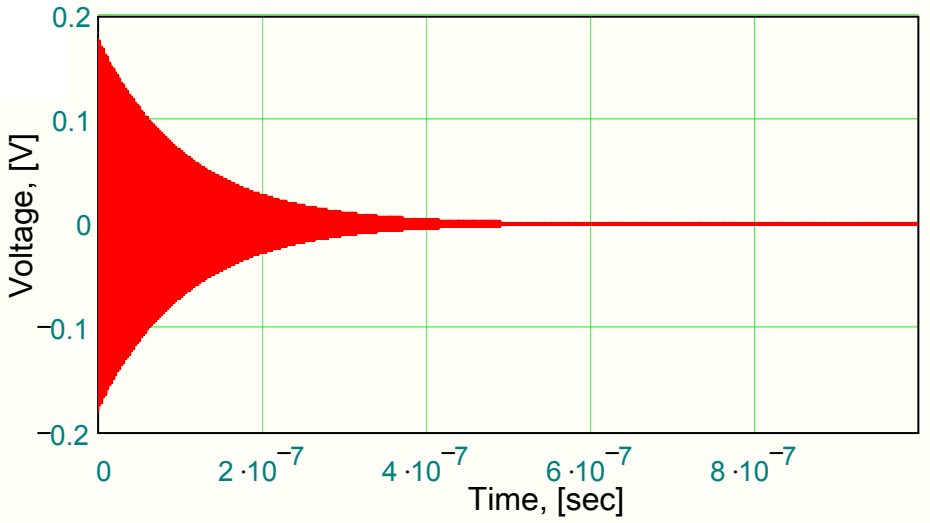
Frequency, GHz, dipole **monopole**	**1.468** **1.125**
Loaded Q (both monopole and dipole)	**~ 600**
Beam pipe radius, mm	**39**
Cell radius, mm	**113**
Cell gap, mm	**15**
Waveguide, mm	**122x110x25**
Coupling slot, mm	**51x4x3**

N type receptacles,
50 Ohm

HFSS Simulations: Dipole Mode

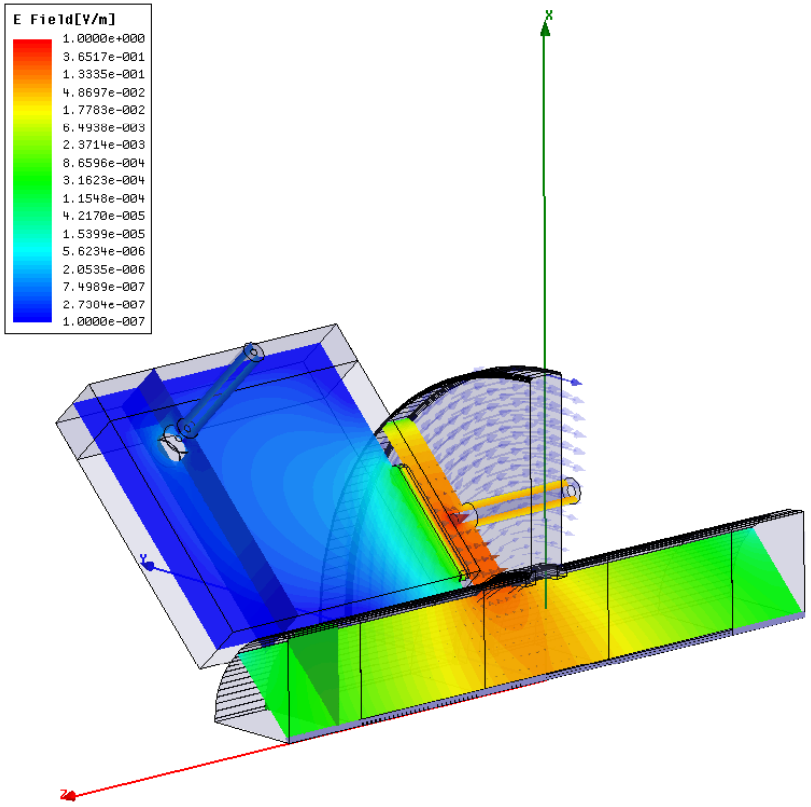


Frequency, [GHz]	1.480
Q, External Q, Surface (Cu) Q, Ceramic(AL_2O_3)	500 22000 5600
Test charge, [coulomb] (X=0, Y=1mm)	1E-9
Stored energy, [joule]	5.9.0E-11
Output Voltage at T=0*, [V]	0.24

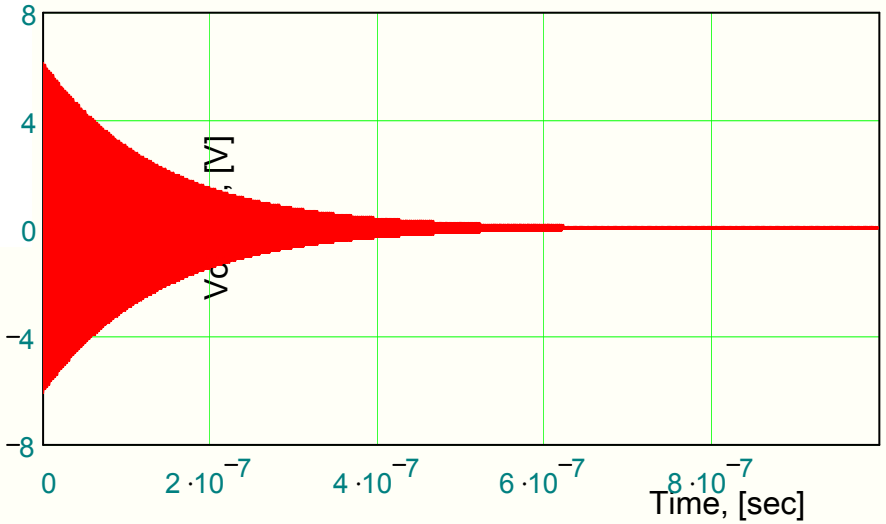


* Normalized to 50 Ohm,
The total signal combines with two ports

Simulations: Monopole Mode

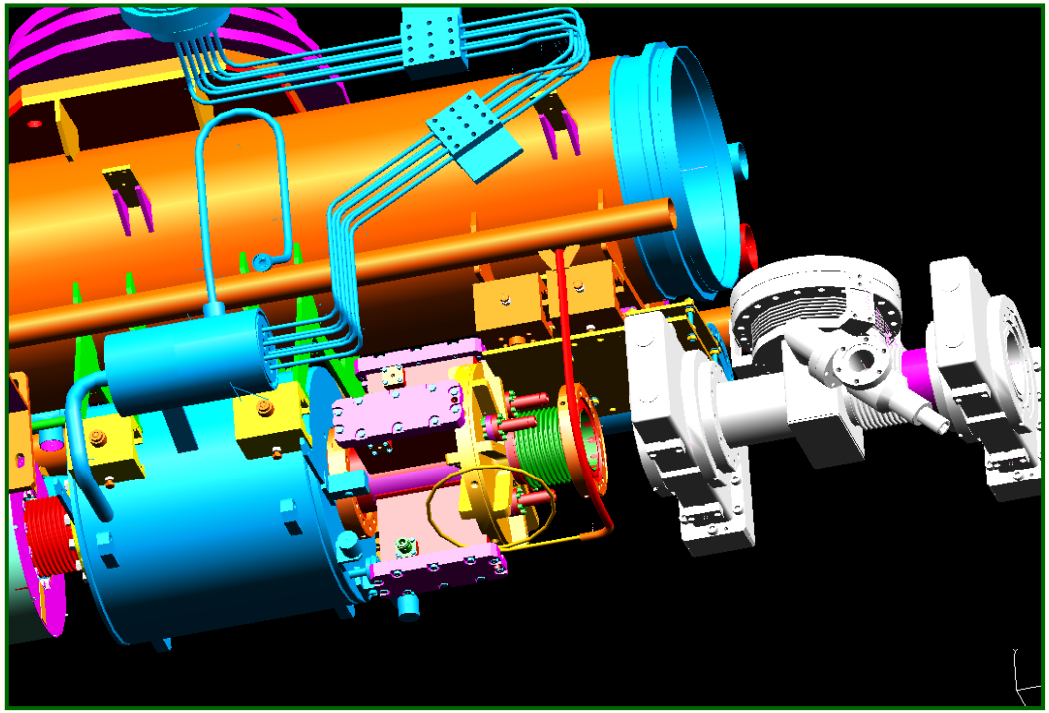


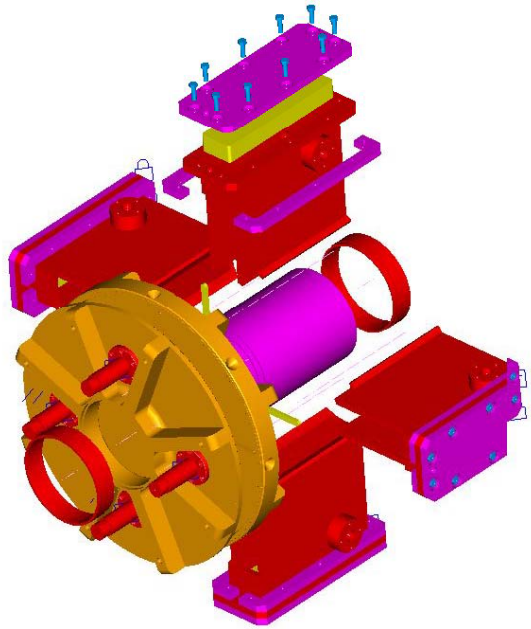
Frequency, [GHz]	1.120
Q, External Q, Surface (Cu) Q, Ceramic(AL_2O_3)	550 19500 7.9E6
Test charge, [coulomb] (X=0, Y=1mm)	1E-9
Stored energy, [joule]	6.1E-8
Output Voltage at T=0*, [V]	6.1
Coupling with TM_{11} port, Output Voltage at T=0*, [V]	5.6E-5

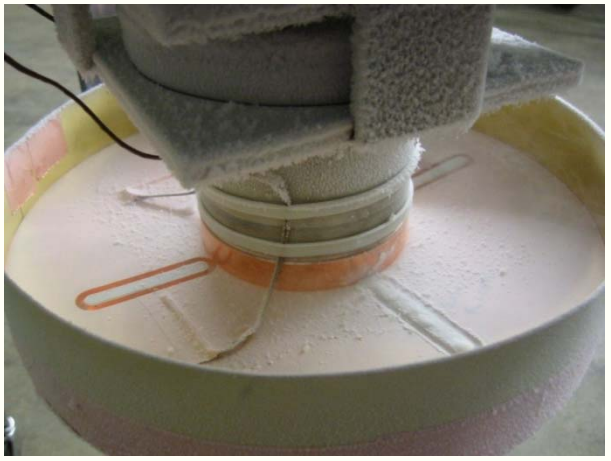


* Normalized to 50 Ohm,
The total signal combines with four ports

Cold L-Band ILC BPM R&D

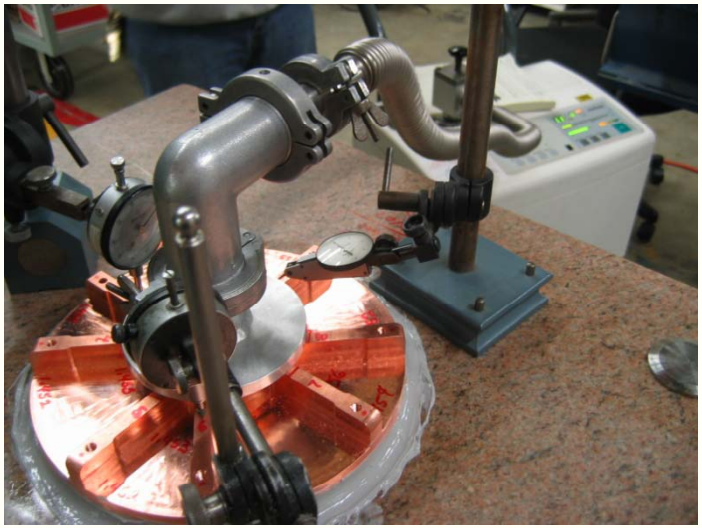


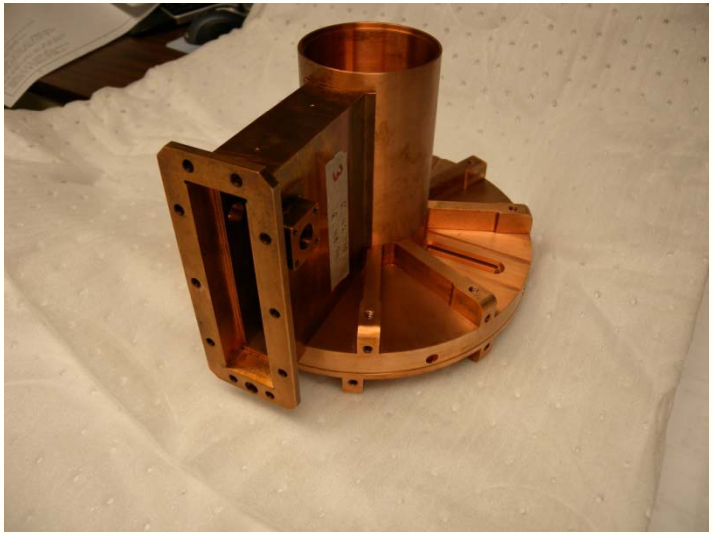




- **Status:**
  - **EM simulations & construction finalized**
  - **Brazing and low temperature UHV tests**
  - **All parts manufactured, ready for brazing**
  - **Prototype has “warm” dimensions**

Cold ILC L-Band Cavity BPM

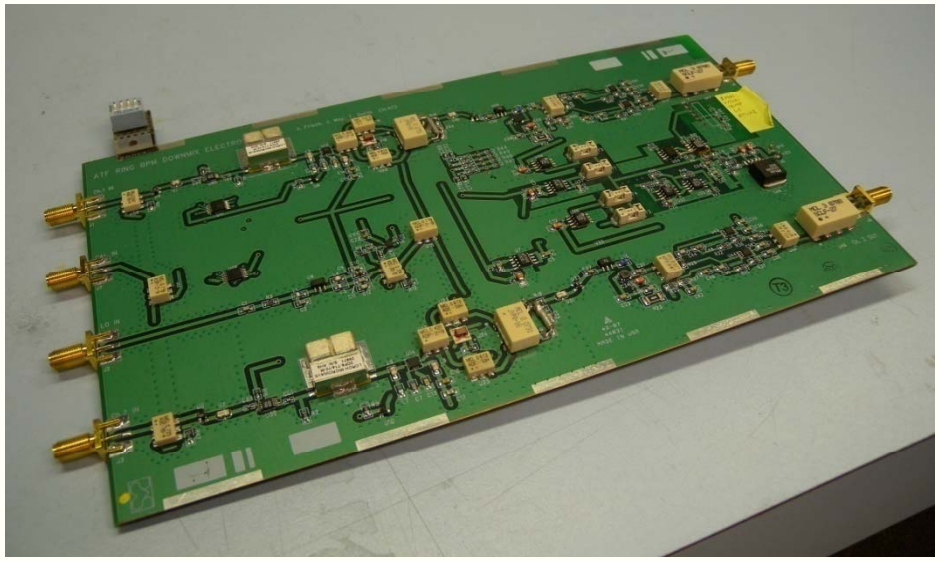




FNAL ILC Cavity BPM Summary

- 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. several thermal cycles 300 K -> 77 K -> 300 K
- Next Steps:
  - Warm prototype finalization (brazing), RF measurements, tuning, beam tests (at the A0-Photoinjector).

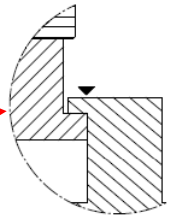
FNAL Read-out Electronics R&D



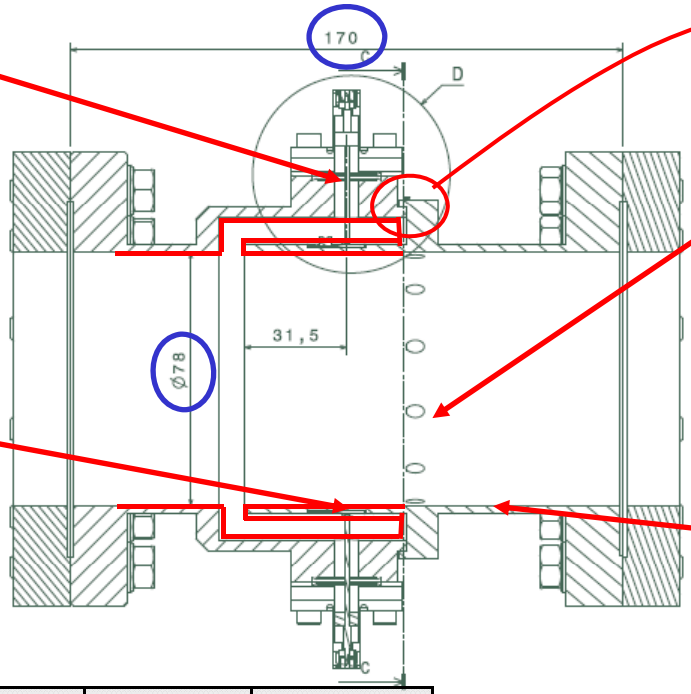
- Based on SLAC-style analog single stage down-converters (IF ≈ 30-50 MHz)
- Integrated calibration system
- VME digitizer (8-ch.,14-bit, 125 MSPS) with FPGA-based digital signal processing and down-converting to base-band.

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).

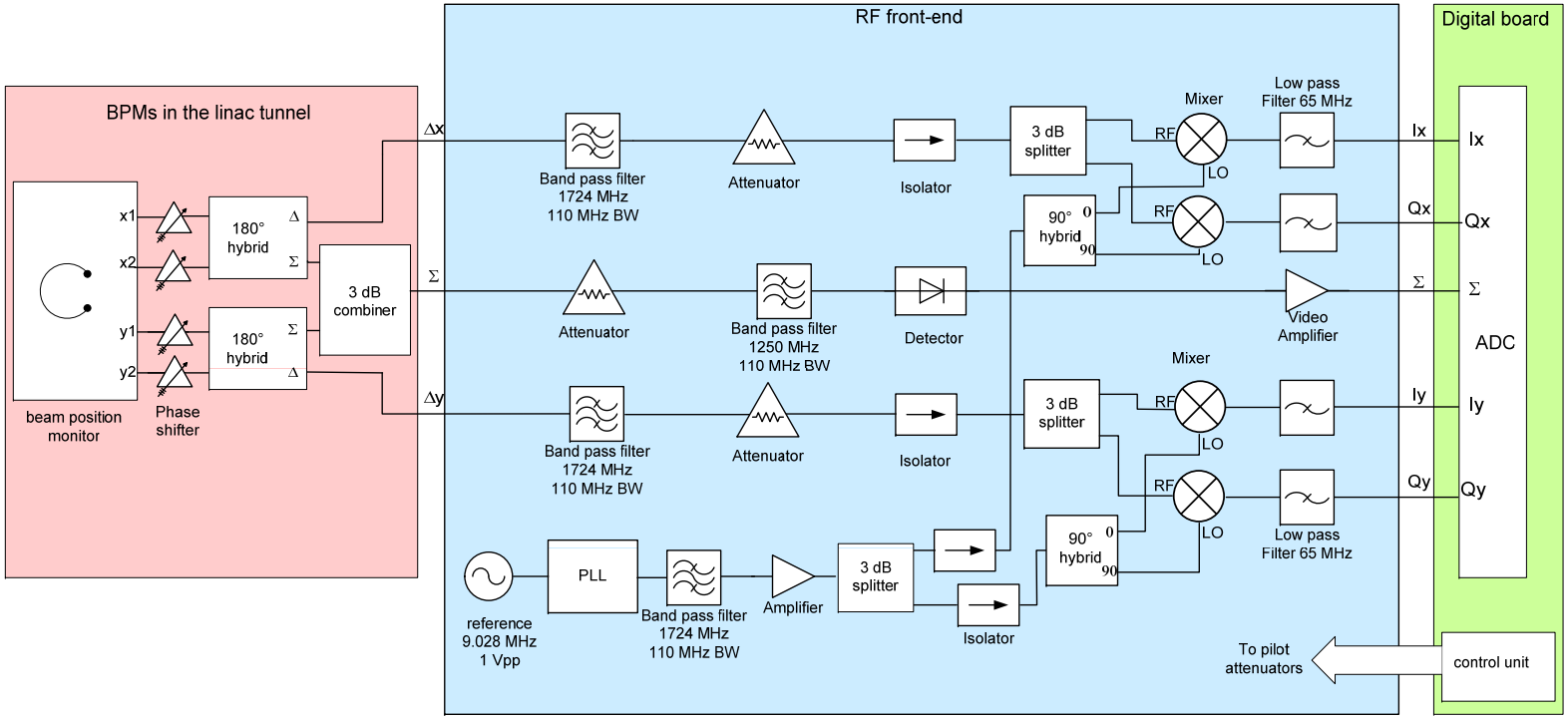
Cu-Be RF contacts welded in the inner cylinder of the cavity to ensure electrical conduction.

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

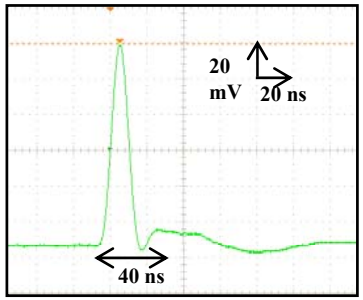
→ **Good linearity in a range ± 12 mm**

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

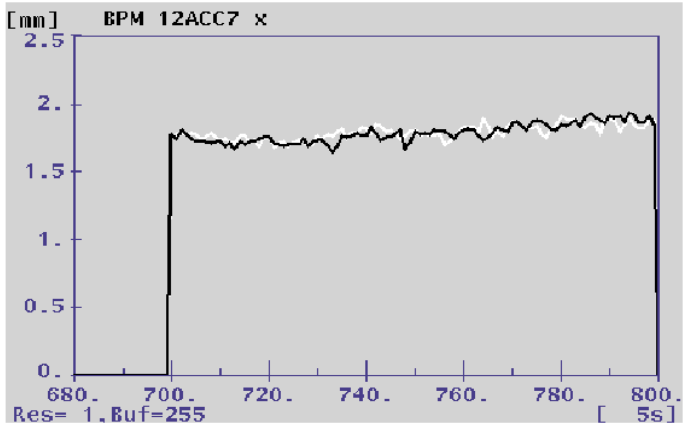
- **Simulated resolution with 1 mm beam offset: < 1 um**

Damping time (Cavity): 9.4 ns

Time resolution (Cavity + electronics): ~40 ns



IF signal behind Lowpass Filter on channel Δ

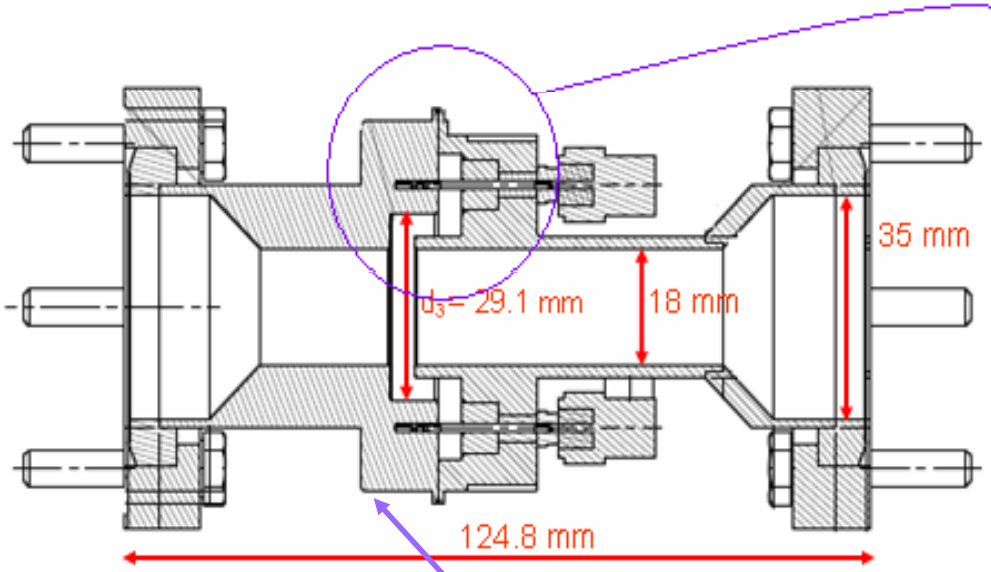


100 bunches read by the reentrant BPM

Possibility bunch to bunch measurements

Reentrant Cavity BPM at CALIFES (1)

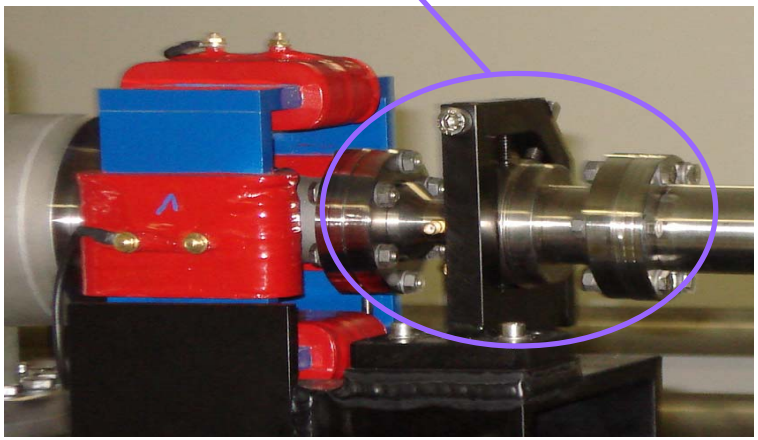
- Cavity BPM is designed for the **CTF3 probe beam (CALIFES)**
- It is operated in single and multi-bunches modes



Bent coaxial cylinder designed to have:

- a large frequency separation between monopole and dipole modes

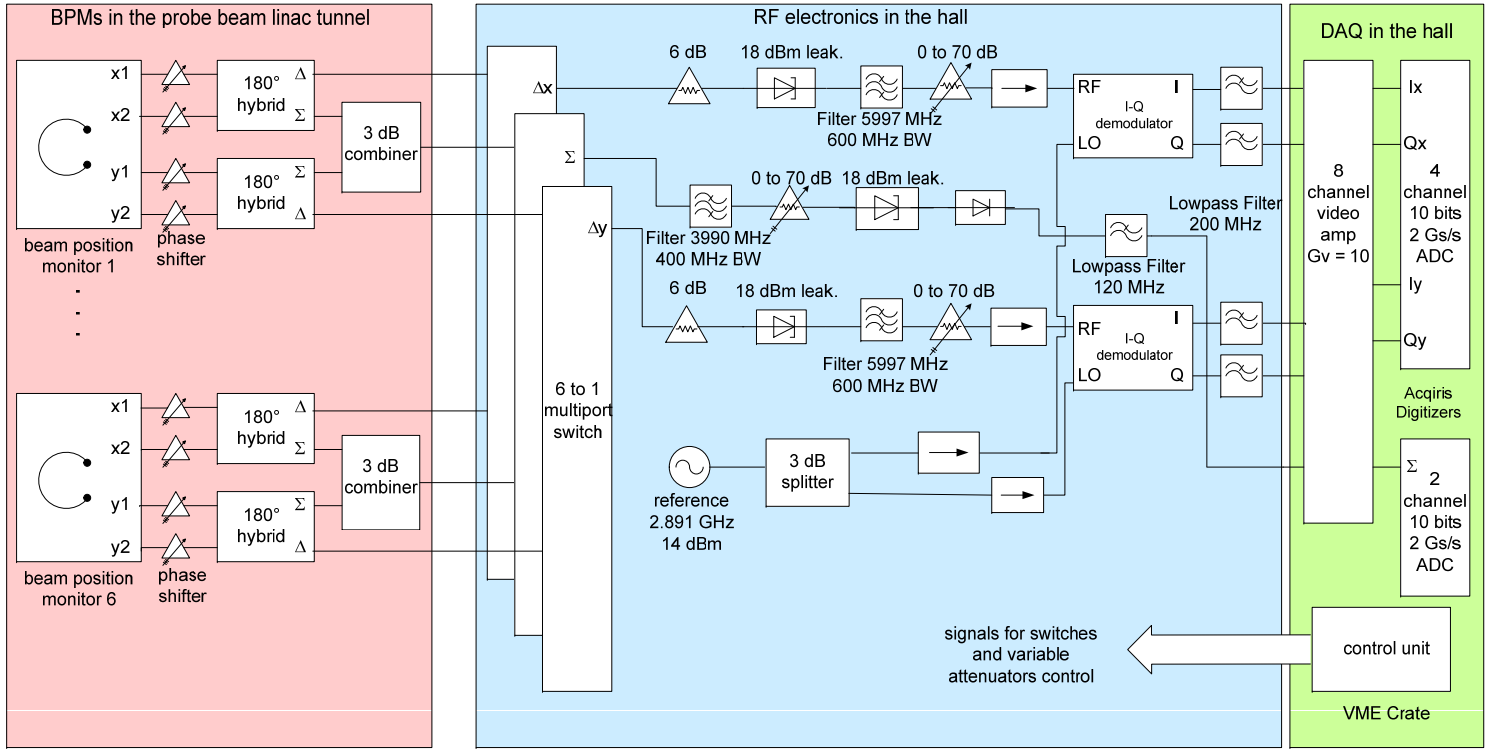
- a low loop exposure to the electric fields



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	3988	29.76	22.3	22.3
Dipole mode	5983	50.21	1.1	7

Reentrant Cavity BPM at CALIFES (1)

➢ Signal processing electronics



Reentrant Cavity at CALIFES

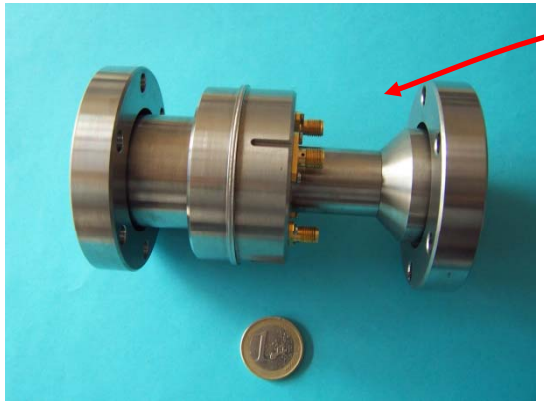
Δ signal (gain adjusted to get an RF signal ~ 0 dBm, simulated in single bunch)

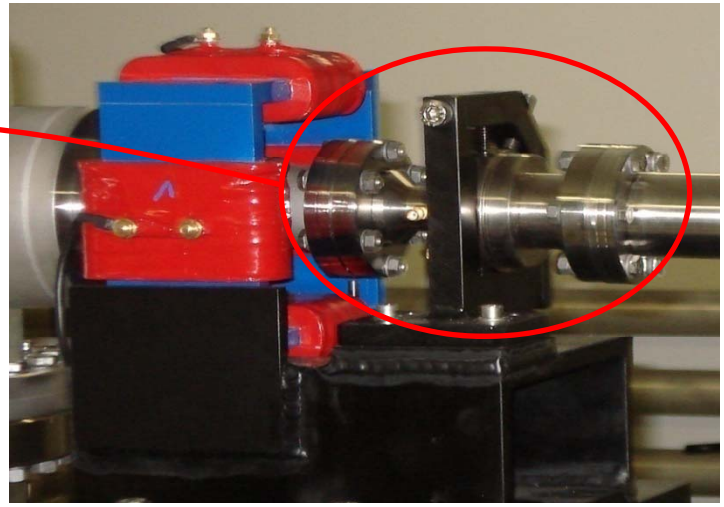
with 5 mm offset : 590 mV (simulated), **Noise:** 0.5 mV (calculated) ⇒ **Resolution :** 3.2 µm (simulated)

with 0.1 mm offset : 555 mV (simulated), **Noise:** 0.1 mV (calculated) ⇒ **Resolution :** 100 nm (simulated)

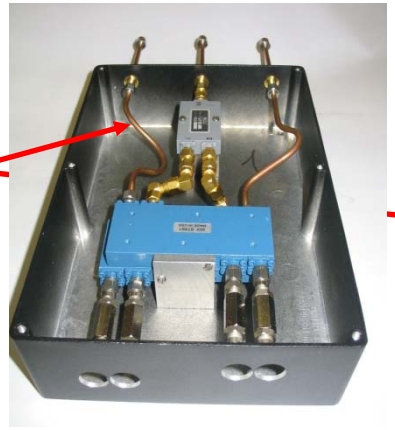
Reentrant Cavity BPM at CALIFES

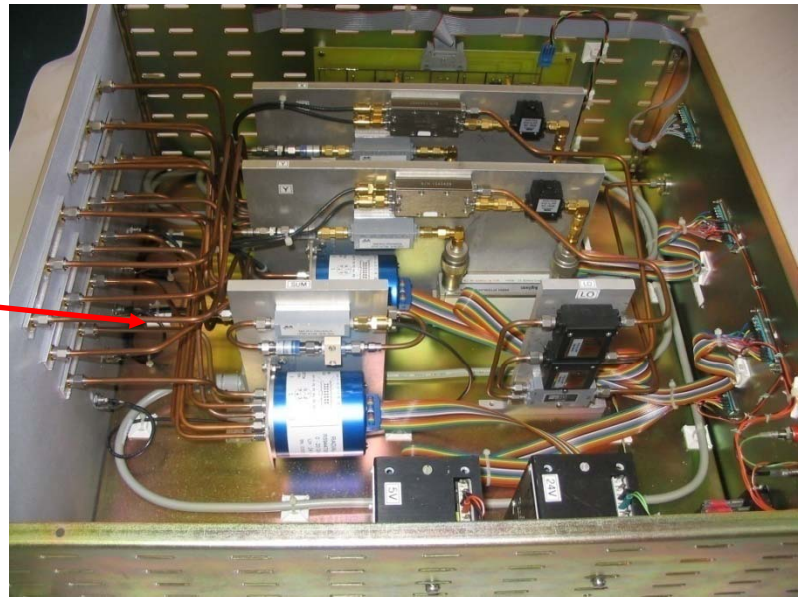
6 BPMs are installed on the CTF3 probe beam





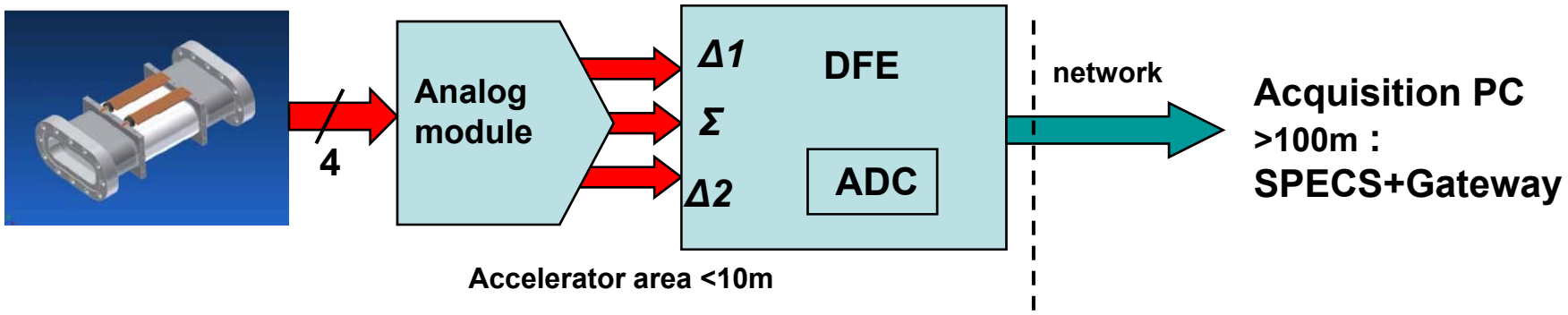
Signal processing electronics of the re-entrant BPM





BPM Acquisition architecture

Aim: ***reduction of costs of long analog cables/ADC***
→ Rad-hard acquisition electronics close to beam.



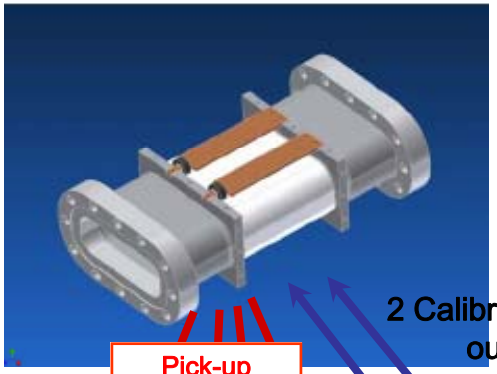
Analog module: *Intensity & deviations processing BPI or BPM.*

DFE board: *- digitalization* ***3channels, 12 bits / 200MSps****.*
- Feed-back for analog modules: gains, calibration and attenuations.
- Daisy chain acquisition: 1 network cable per crate.

Acquisition PC : *FESA-OASIS soft and specialist requirements feed-back.*

→ Cost divided by a factor 3 comparing to a « far » acquisition.

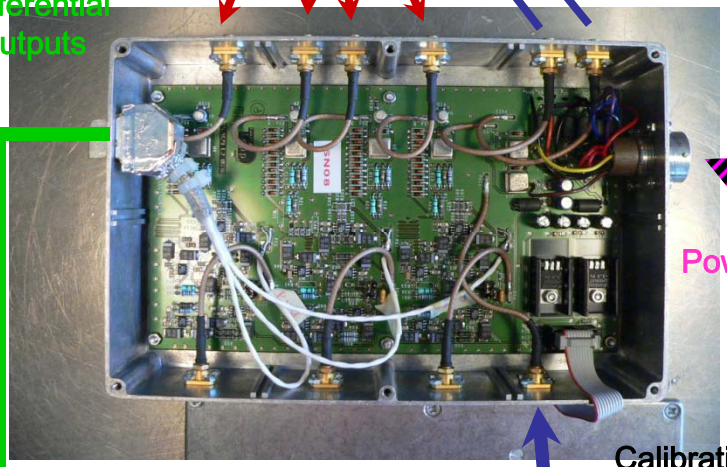
Read-out



2 Calibration pulse outputs

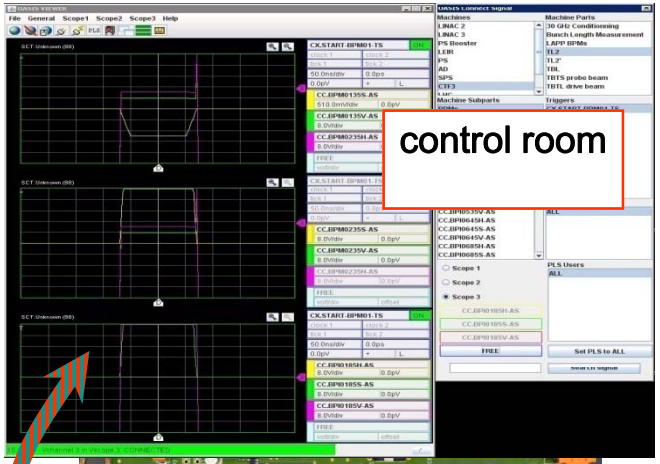
Pick-up electrodes

Differential outputs

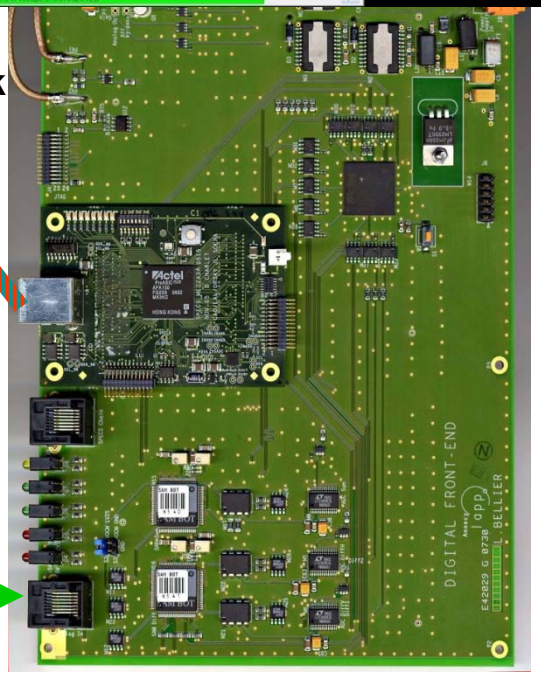


Power supplies Controls

Calibration pulse input

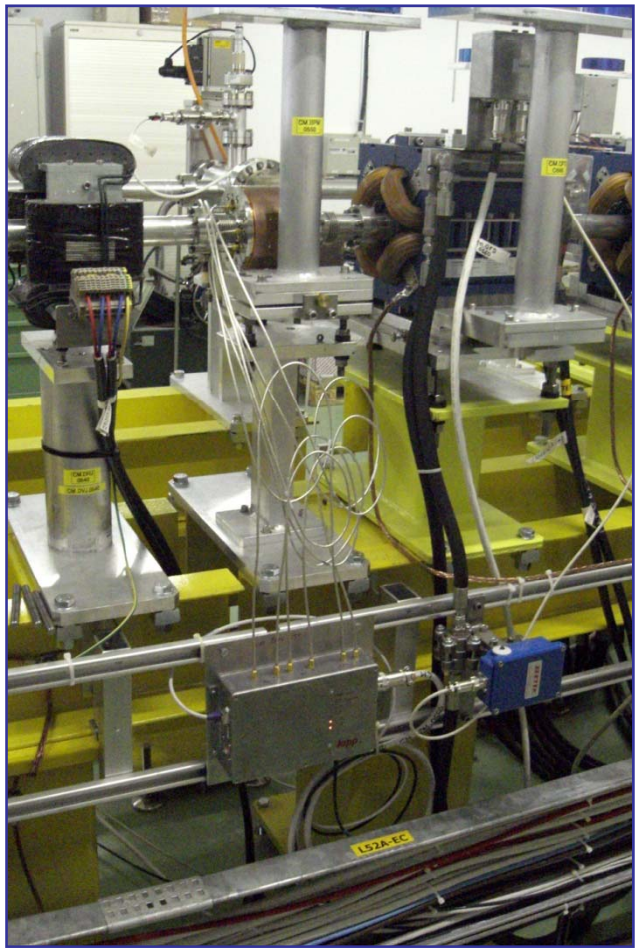


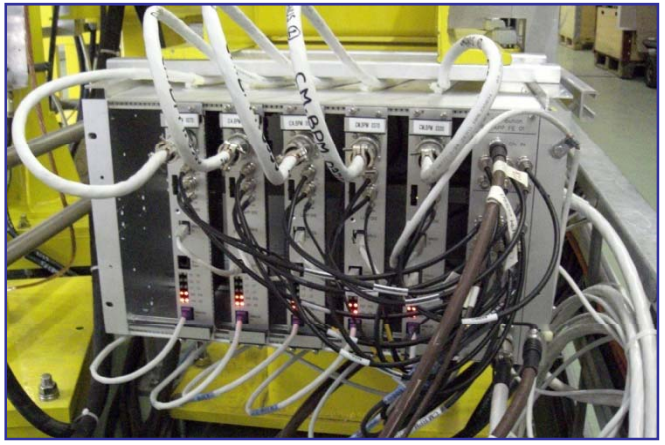
Network

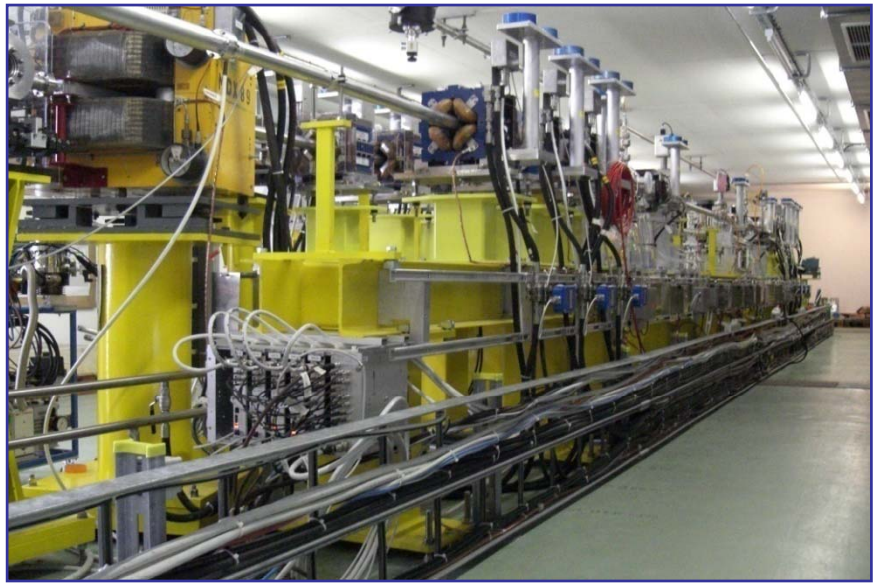


8 crates in TL2-CLEX

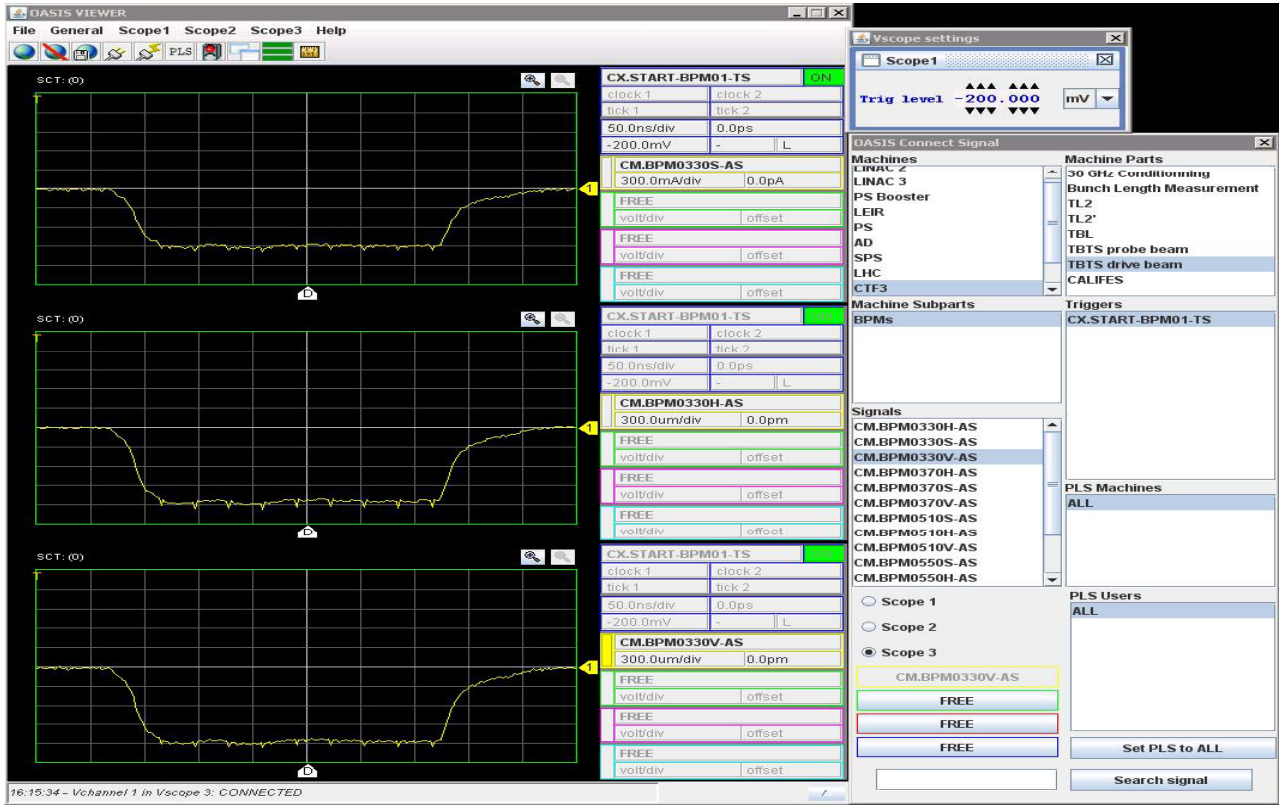
Uranus







Results



Debug during summer 2008:

several problems on sampling electronics and transmissions currently solved by soft.

Jitter solved by a trigger, sampling memory still to be calibrated.

Thanks to operation team feedback and patience!

Future : acquisition for CLIC

The logical evolution of this system is to be dedicated to a larger accelerator as CLIC:

Rare acces from surface, high number of channels, rad-hard, low-cost, low consumption…

Most important points to develop: ***elimination of cables***

- ***Power supplies:*** *autonomous (220V sector, DC-DC converters…).*
- ***Local calibration****.*
- ***Network :*** *flexible data collection, repetition crates…*
- ***Acquisition architecture:*** *faster ADC, direct bpm read-out, continuous sampling…*
- ***FPGA processing:*** *raw data, processed data…*
- ***Radiations.***

Future : acquisition for CLIC

→ ***All-around accelerator standard acquisition.***

A lot of specifications to be discussed with the collaboration:

- Input stages and input dynamic ranges.

- Informations to collect: definition of transfer rates.
→ possible switching between FPGA local process of position/intensity and raw data for precision.

- Definition of a standard crate for a module (n channels)

- Infrastructure possibilities to study (see Lars concrete shielded crate…)

- ETC…

Future : R&D in LAPP

LAPP decided to get involved for a 2 years development:

~3 men/year and IN2P3 funding ~50k€/year.

New acquisition board:

- 4 analog inputs with several input dynamic ranges, continuous 500Msps-12bits sampling.

- 6GHz optical link for data, timing: no more cables, no EMC problems…

- A Clock-management architecture to get free from timing problems.

Conclusions

- Most R&D activates in the US were “on hold”.
  - Now restarted, on a lower budget, and a modified goal (NML test facility, Project X)
- At Fermilab a cold L-Band cavity BPM prototype with 78 mm aperture, $Q_{load} \approx 600$, is in its final fabrication (brazing) procedure.
- A re-entrant BPM was tested at FLASH, achieving ~5 μm resolution (CEA-Saclay).
- Radiation tolerant read-out electronics are developed at European and US laboratories.