Cavity BPM Designs, Related Electronics and Measured Performances

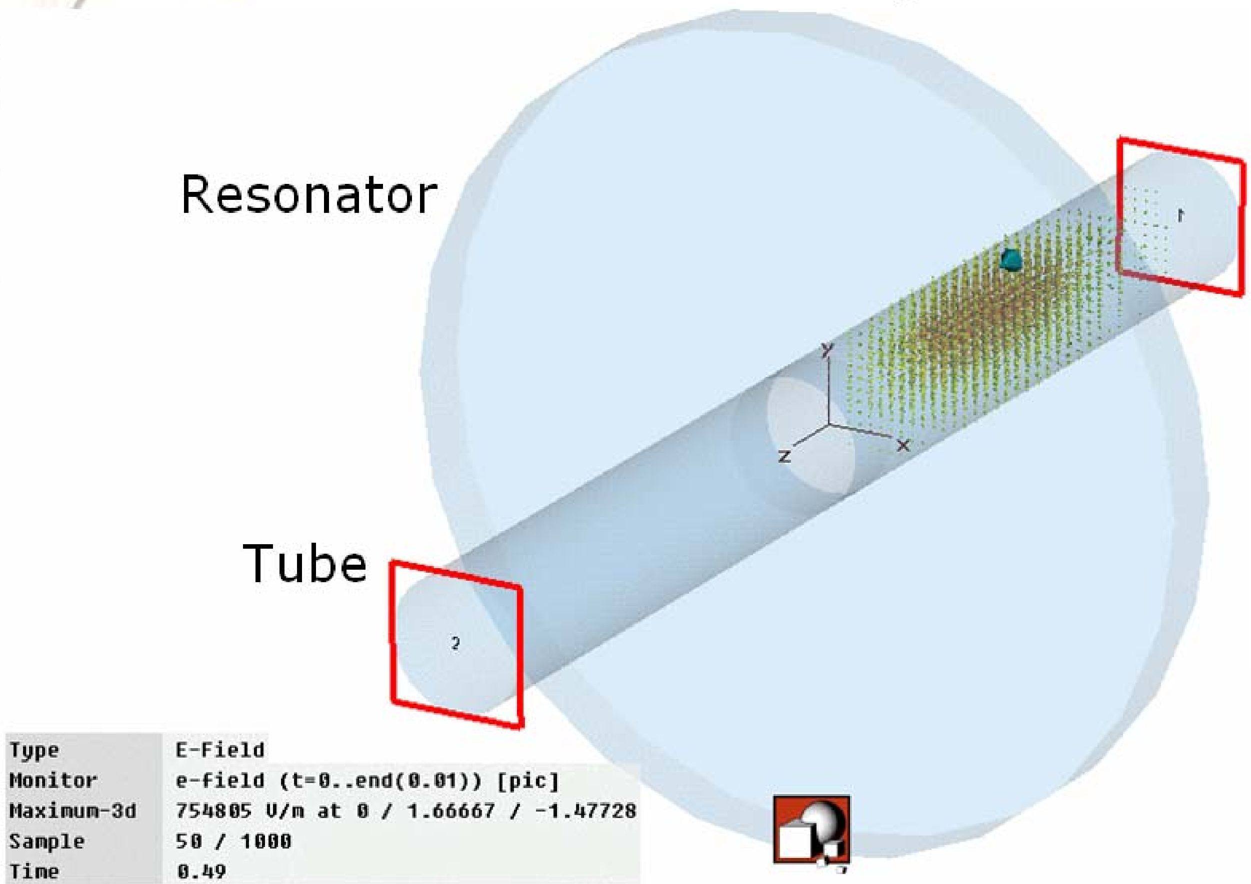
Dirk Lipka
MDI, DESY Hamburg

Outline

- Principle
- Brief history
- Filter monopole mode
- Influence of beam angle and bunch tilt
- Examples:
  - SPring-8
  - DESY
  - SACLAY: Reentrant
  - Fermilab
  - LCLS
  - ILC spectrometer
  - ILC interaction point
- Summary

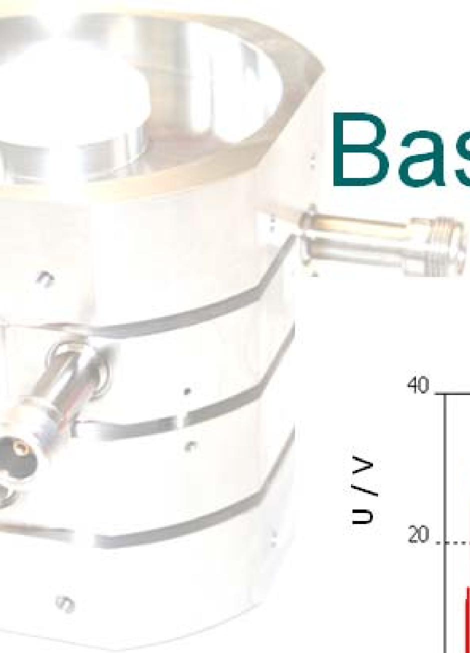
Basic Principle

Electric Field of a charged Bunch

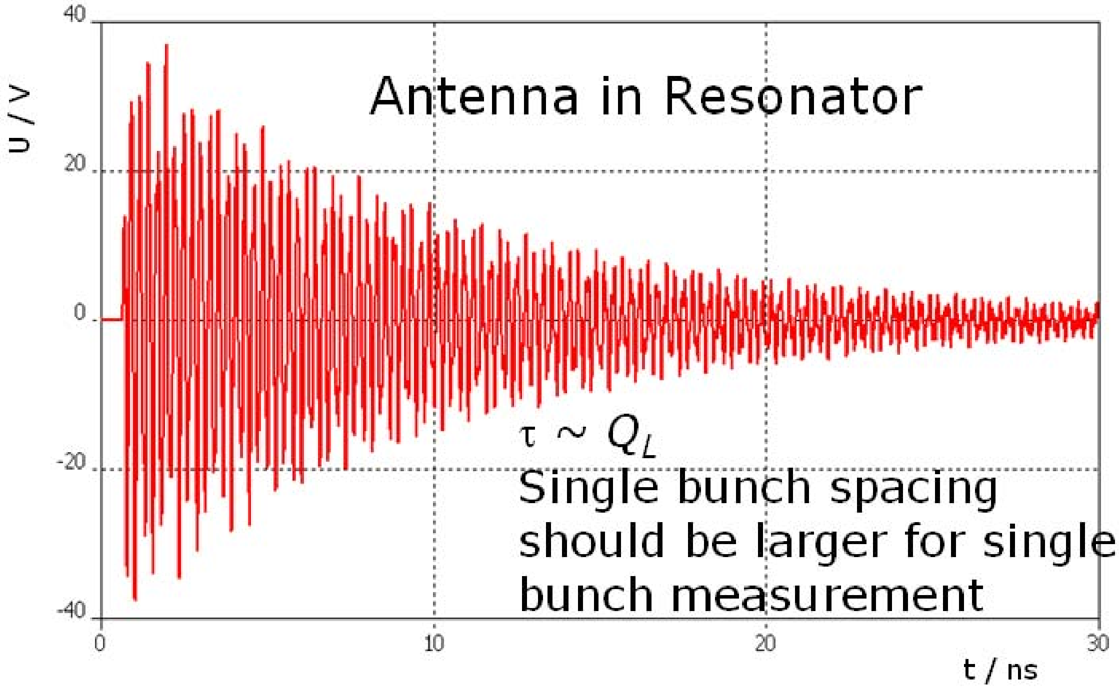


- Resonator can be produced with high accuracy
- With antenna: Measured voltages can be used to characterize beam with high resolution
- Non destructive Monitor

Basic Principle



Voltage vs. Time



τ = decay time
Q_L = loaded Quality factor

Damping of resonance with $\exp(-t/\tau)$

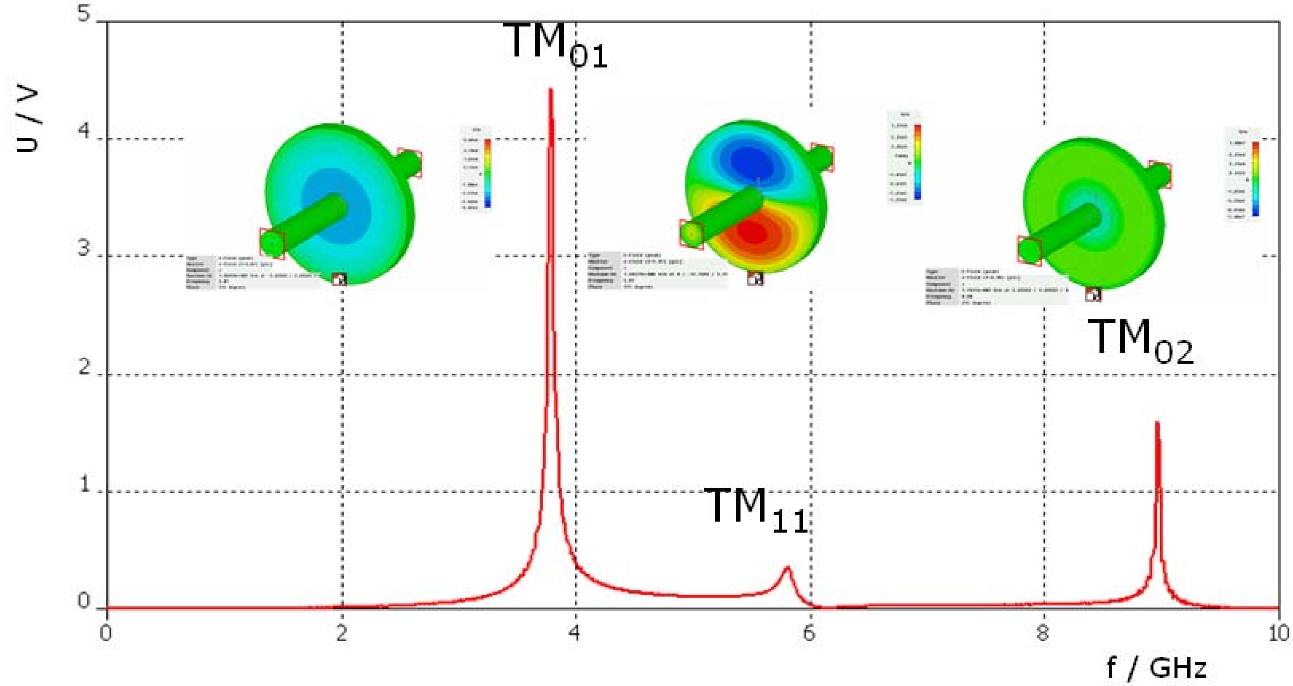
Q = Beam Charge
r = Beam offset

By measuring r the beam offset is obtained
→ Beam Position Monitor (BPM)

BTW: 2 ports per plane

Basic Principle

Frequency Domain



$U \sim Q$ $U \sim Qr$ $U \sim Q$

τ = decay time
Q_L = loaded Quality factor

Damping of resonance with $\exp(-t/\tau)$

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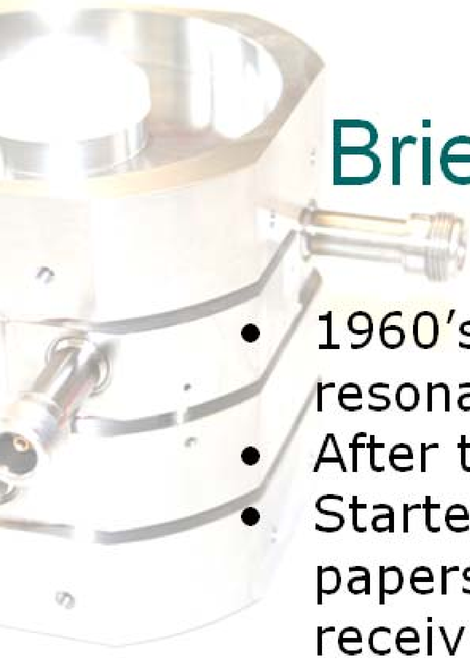
For charge normalization and sign: Reference Resonator or Monopole Mode

Problem: Monopole Mode (TM_0) leakage into Dipole Mode (TM_1)



Brief History of Cavity BPM until 1998

- 1960's at SLAC rectangular Cavity BPM with 2856 MHz dipole resonance frequency
- After that various configurations mostly for linear accelerators
- Started in 1980's with future e^+e^- linear colliders many papers: use of modern microwave technology, narrow-band receiver might be sufficient
- At that time use of a magic-T to filter TM_{11} and damp TM_{01} modes
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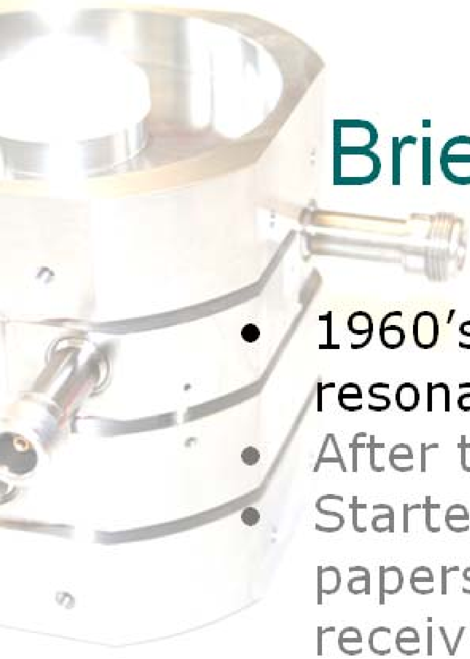
- At SLAC 1998 cylindrical cavity with TM_{11} at 5712 MHz and magic-T and narrow-band system with resolution near 25 nm



Ref: T. Shintake, HEAC 1999

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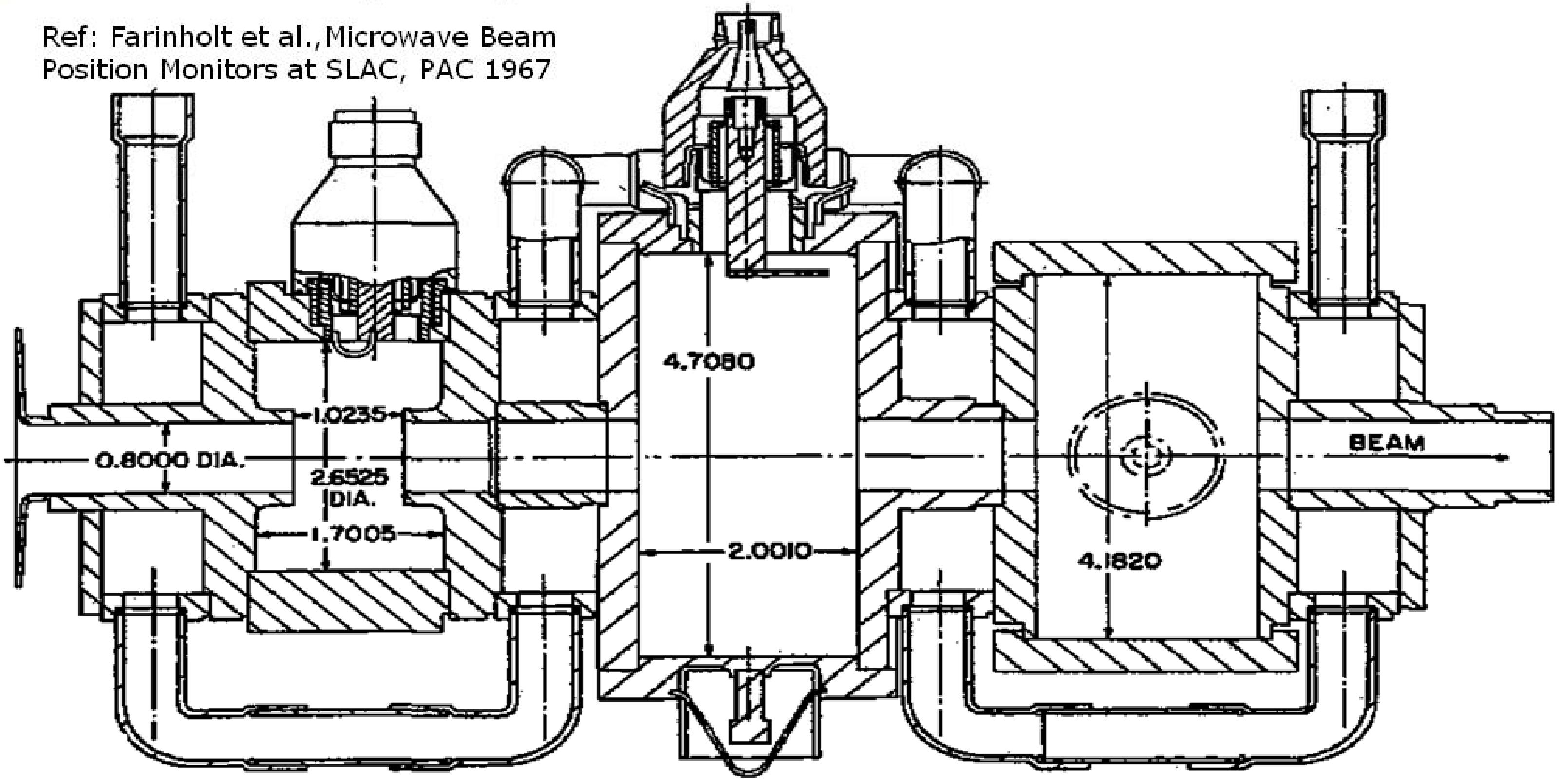
Ref: Farinholt et al.,Microwave Beam Position Monitors at SLAC, PAC 1967



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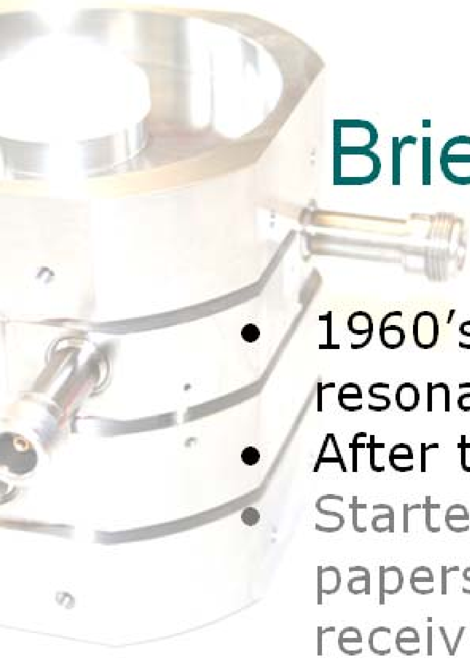

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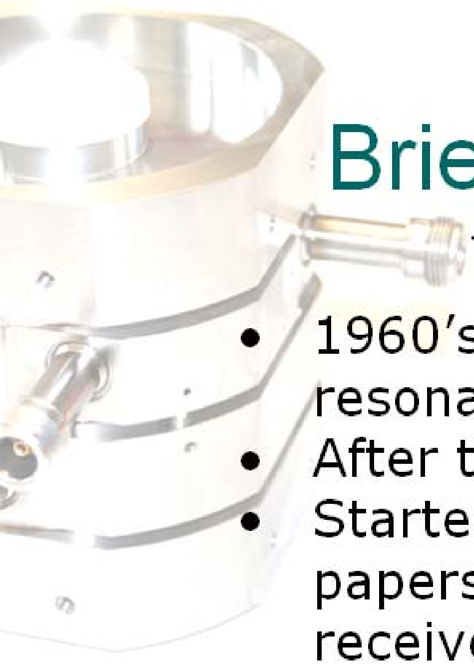

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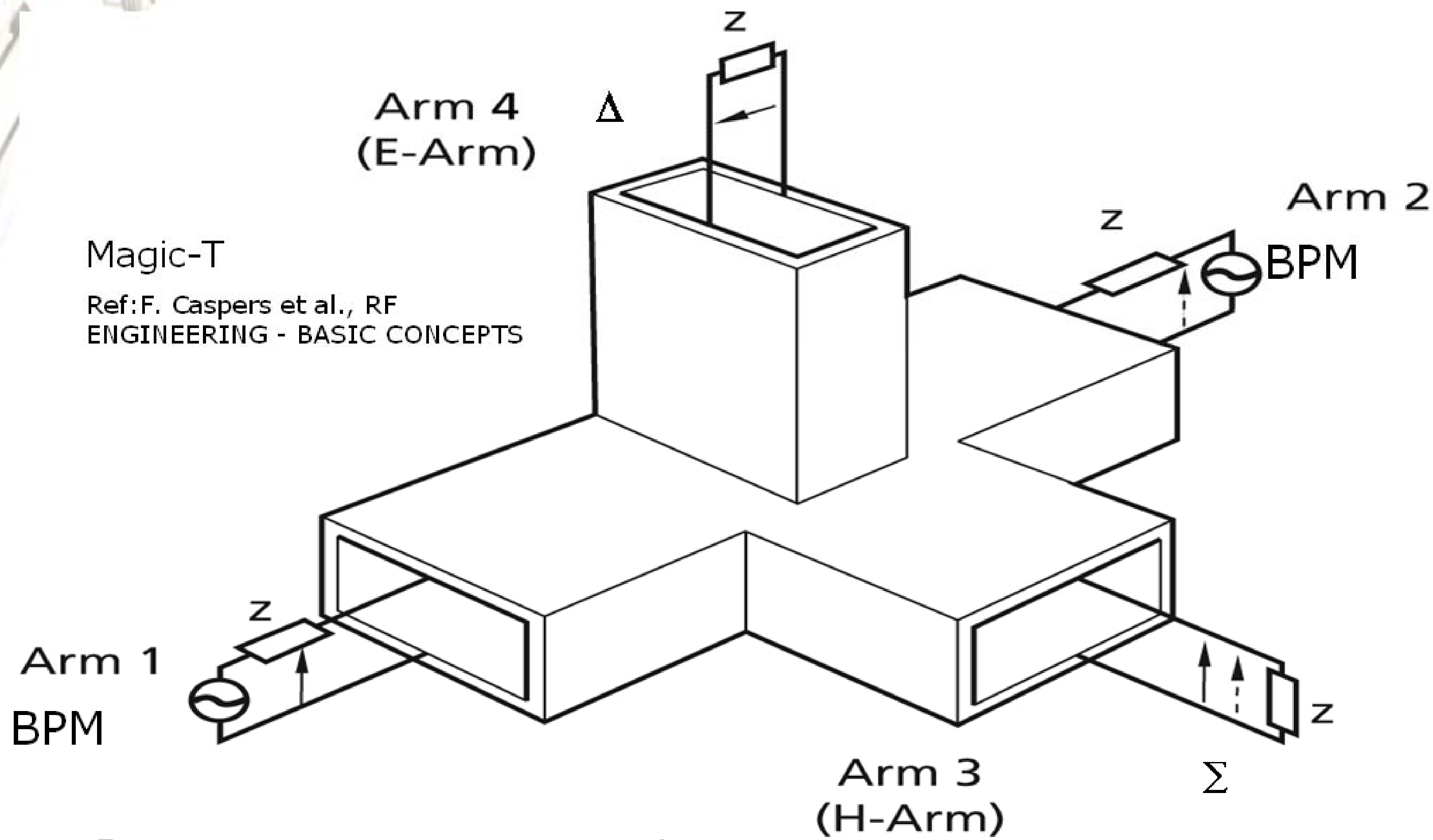
Brief History of Cavity BPM until 1998

Magic-T

Ref:F. Caspers et al., RF ENGINEERING - BASIC CONCEPTS



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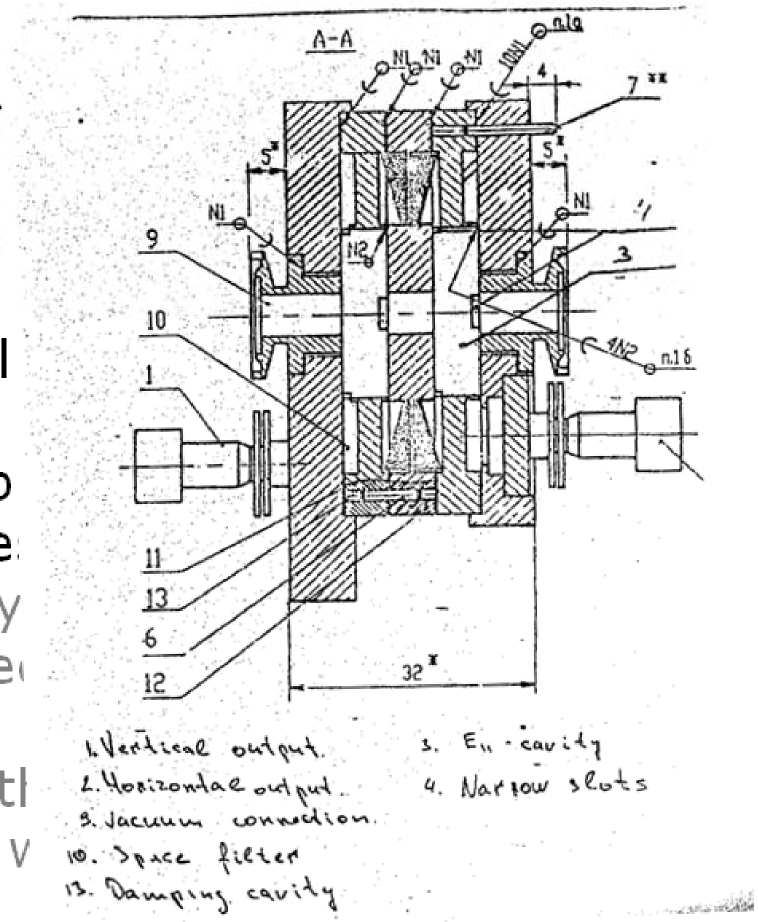
Ref: V. Balakin, V. Vogel, M. Solyak; LC91



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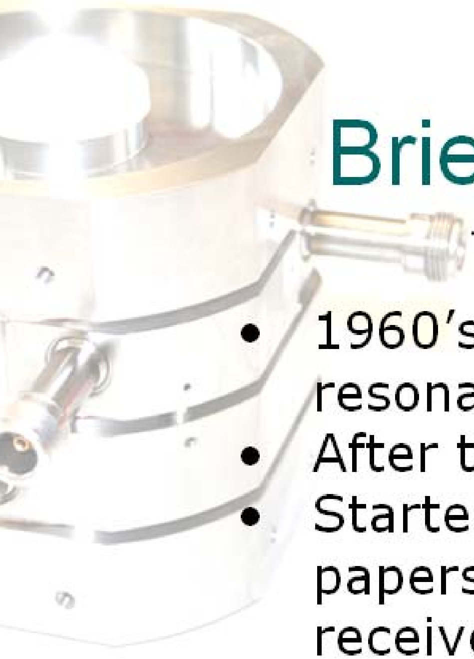

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Ref: T. Shintake, HEAC 1999

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Ref: J.P.H. Sladen et. al., EPAC96

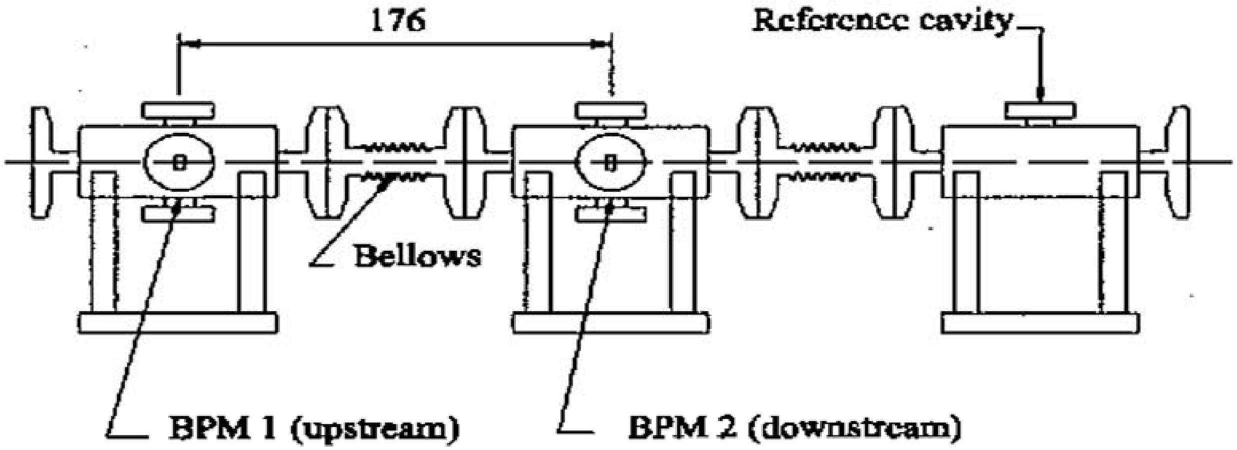

Figure 1: Test set up. From left to right BPM 1, BPM 2, and the reference cavity.

- Same time at CLIC 30 GHz TM_{11} cylindrical cavity with magic-T and narrow-band system: showed upper limit of resolution 4 μm
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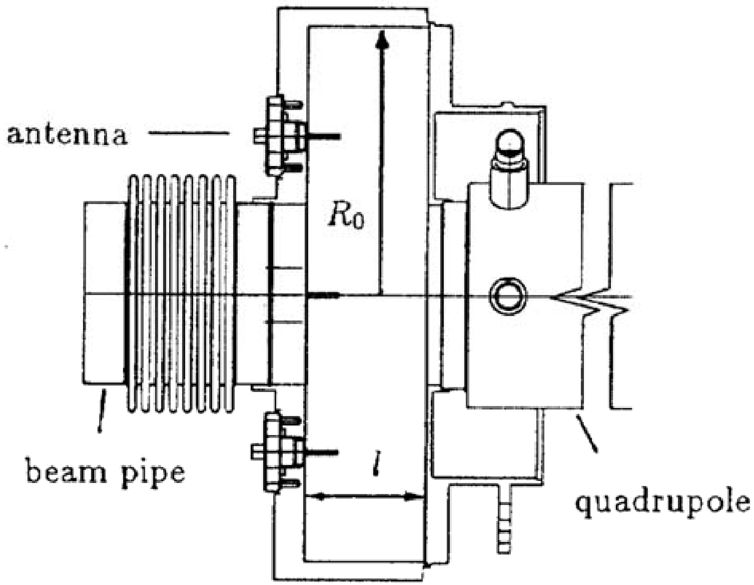

DESY: R. Lorenz for TTF cold module

Ref: EPAC 1994

f = 1.517 GHz

Pipe diameter = 78 mm

Present resolution: 10 μm with 1 nC

Ref: T. Shintake, HEAC 1999

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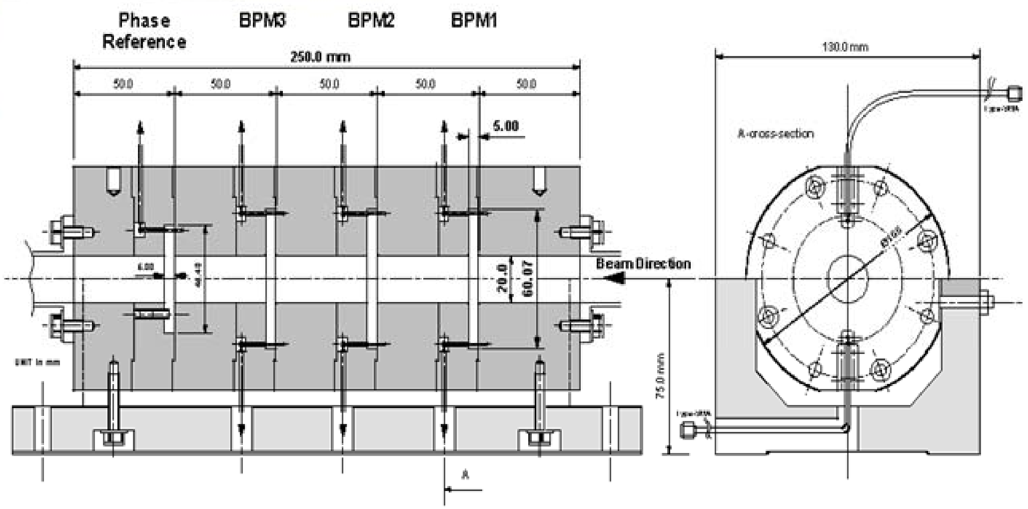


Fig. 1 C-band RF-BPM tested at FFTB. Three BPM cavities and one phase reference cavity were assembled in one block.

Ref: T. Shintake, HEAC 1999

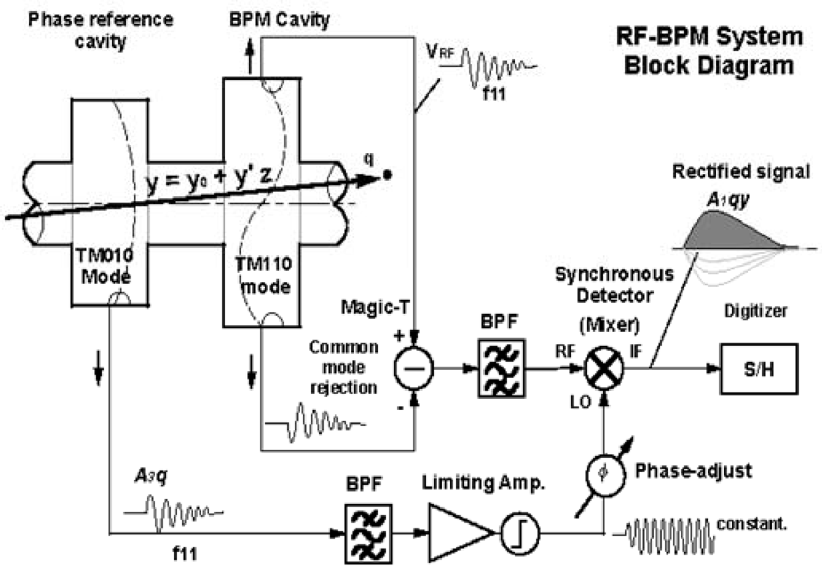
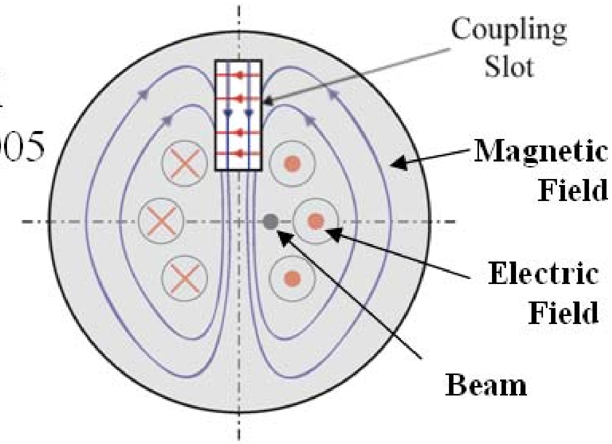


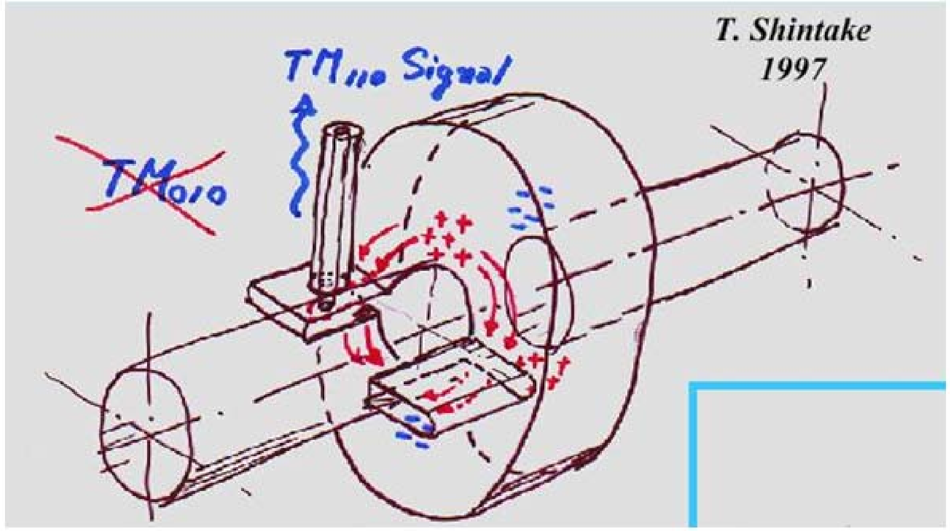
Fig. 2. Simplified RF-BPM Diagram.

- At SLAC 1998 cylindrical cavity with TM_{11} at 5712 MHz and magic-T and narrow-band system with resolution near 25 nm

Reject Monopole Mode

Ref: V. Vogel
Nanobeam 2005





Dipole Mode is surrounded by magnetic fields

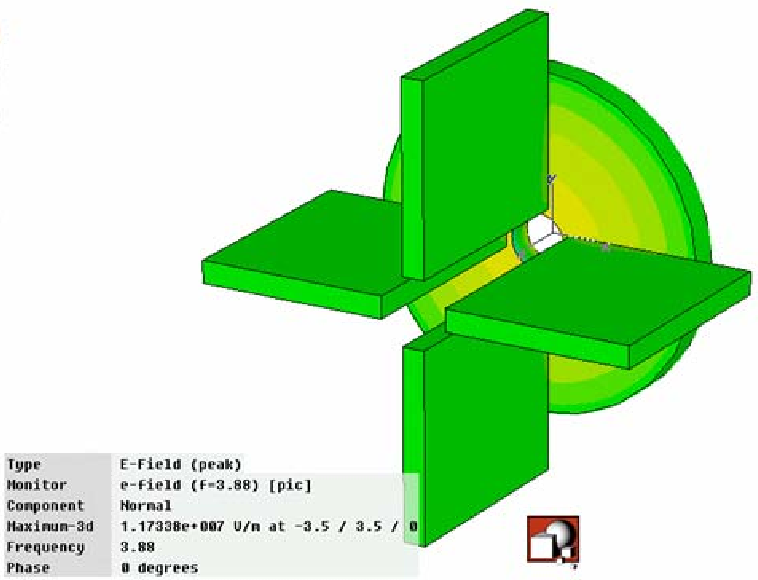
Between both magnetic fields a TE_{10} is produced which matches with boundary condition of wave guide and is propagating

Monopole Mode does not match with boundary condition of wave guide

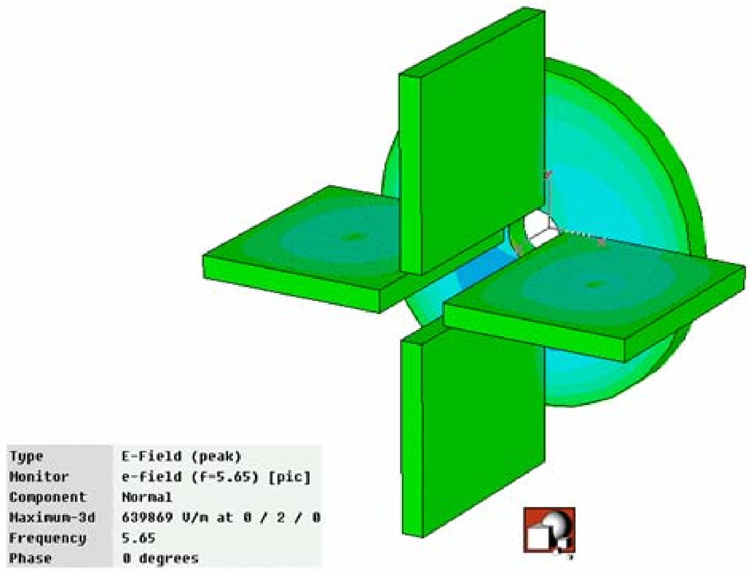
Ref: V. Balakin et al., PAC 1999

Reject Monopole Mode

Monopole Mode



Dipole Mode

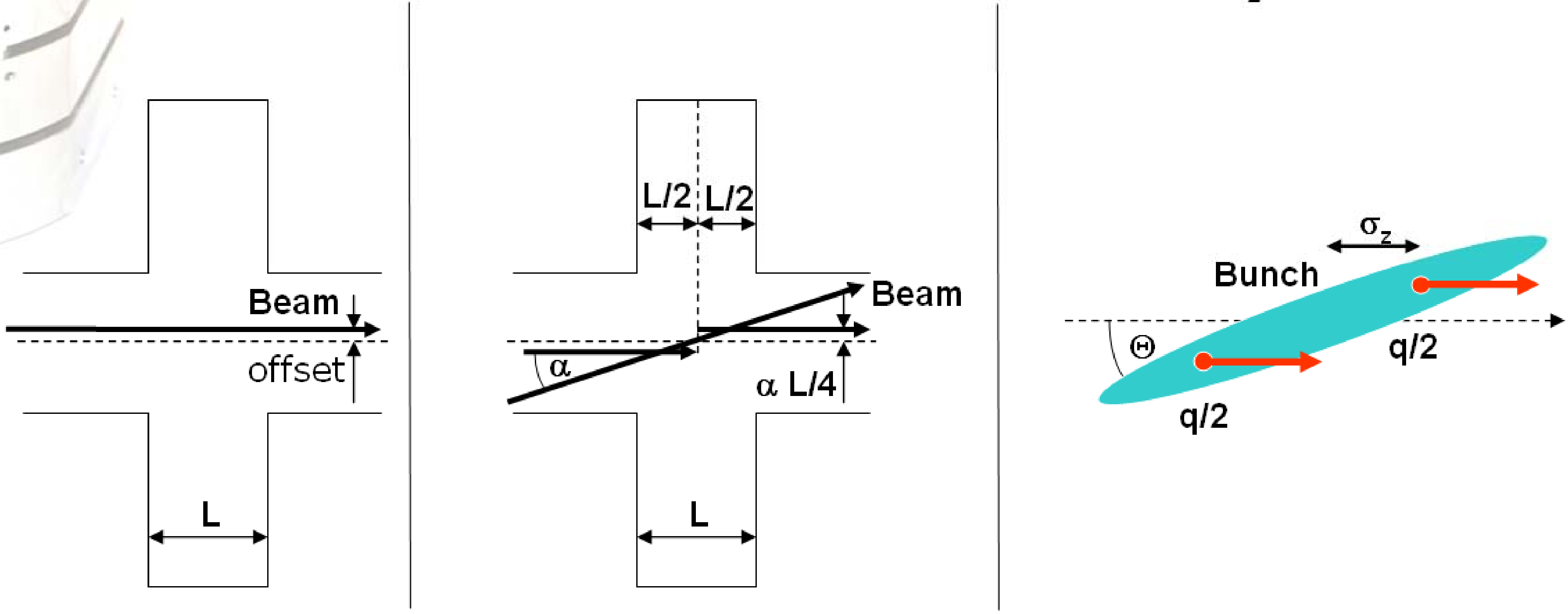


Simulation to show

- propagation of dipole mode in waveguide
- monopole mode no propagation in waveguide

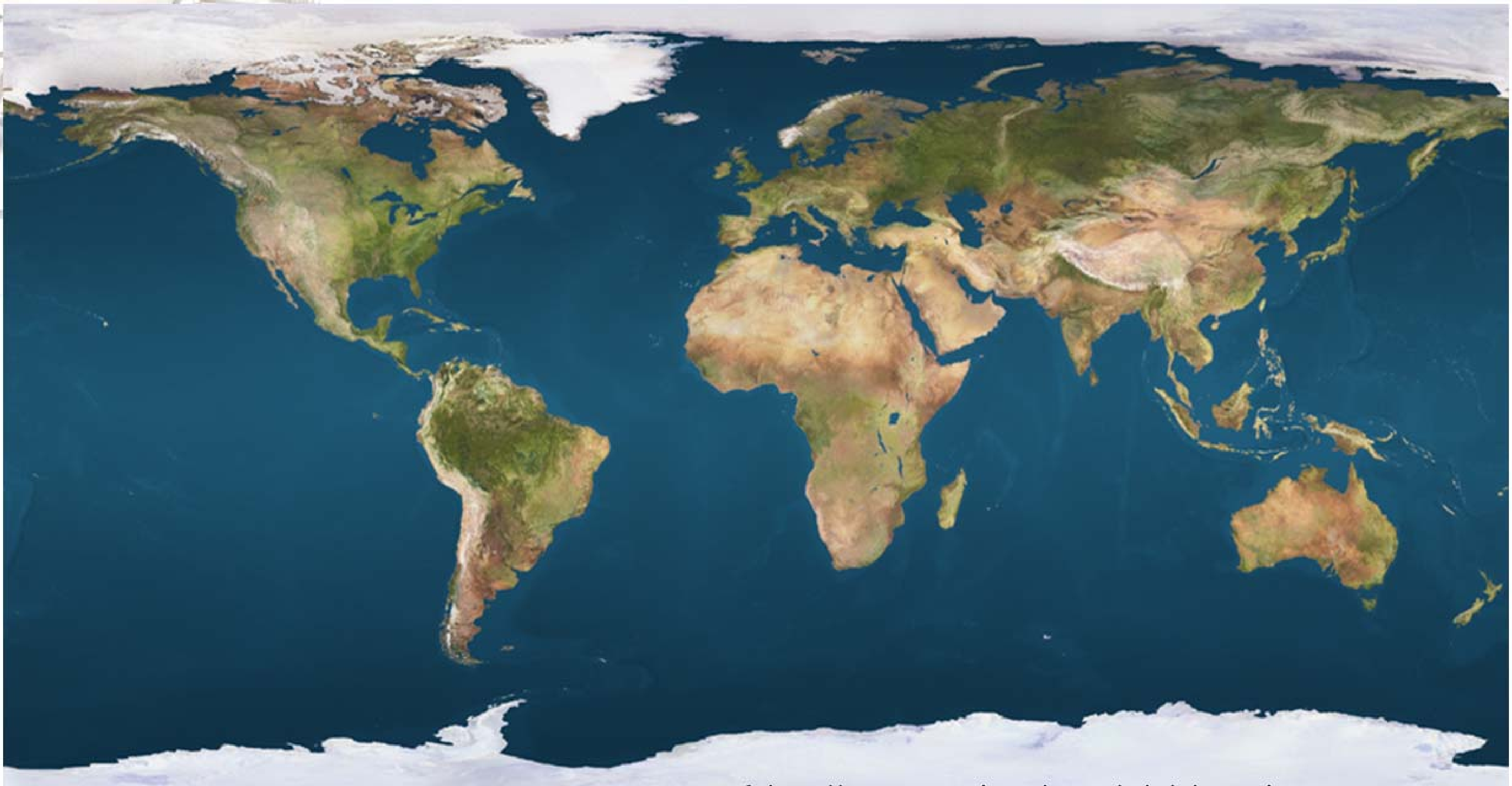
Influence of beam angle and bunch tilt

$$U=C\sin(\omega t) + C^{*}\sin(\omega L/(4c))\cos(\omega t) + C^{**}\sin(\omega\sigma_z/c)\cos(\omega t)$$



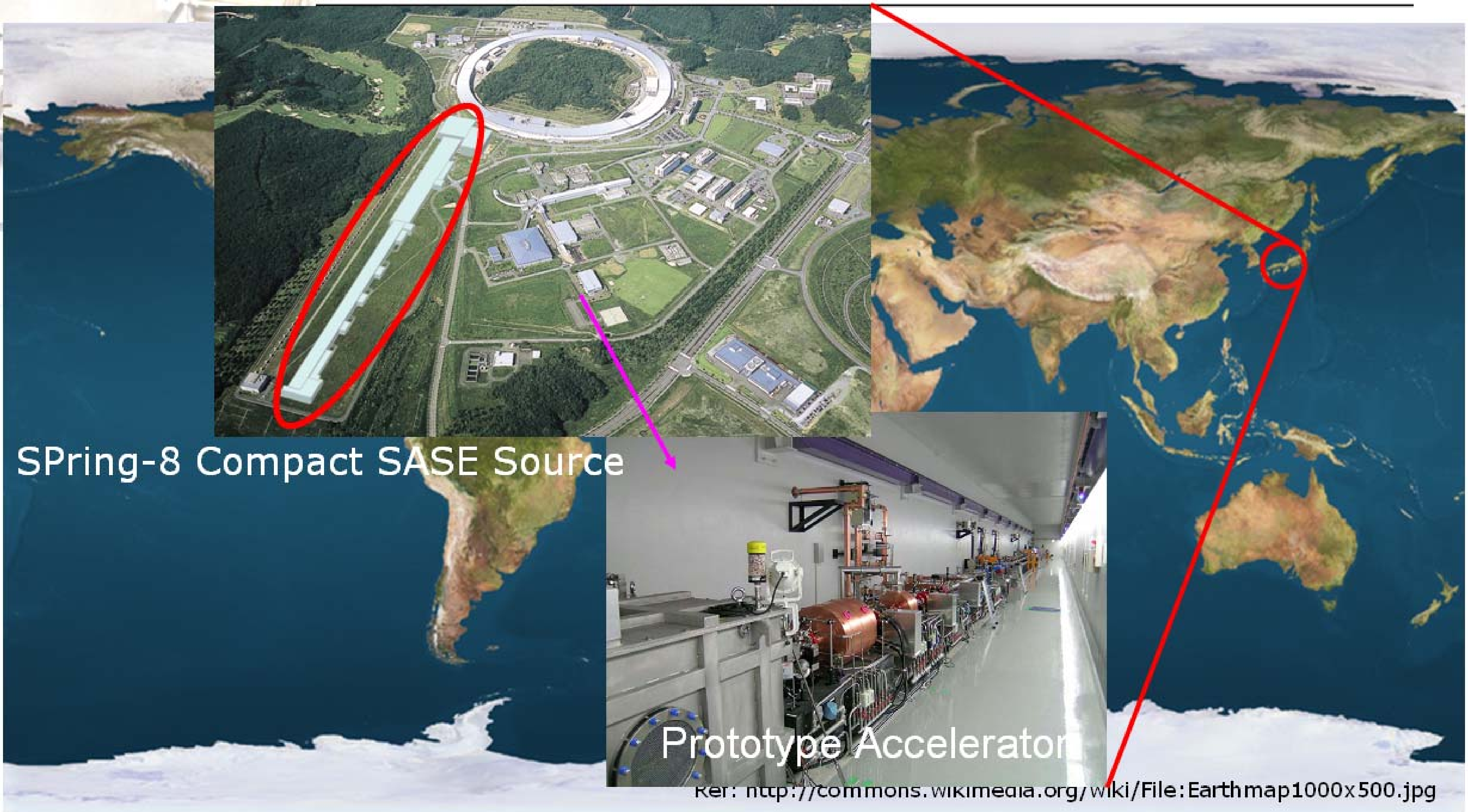
Both parts are shifted by 90° compared to the offset signal

Cavity BPM around the World



Ref: http://commons.wikimedia.org/wiki/File:Earthmap1000x500.jpg

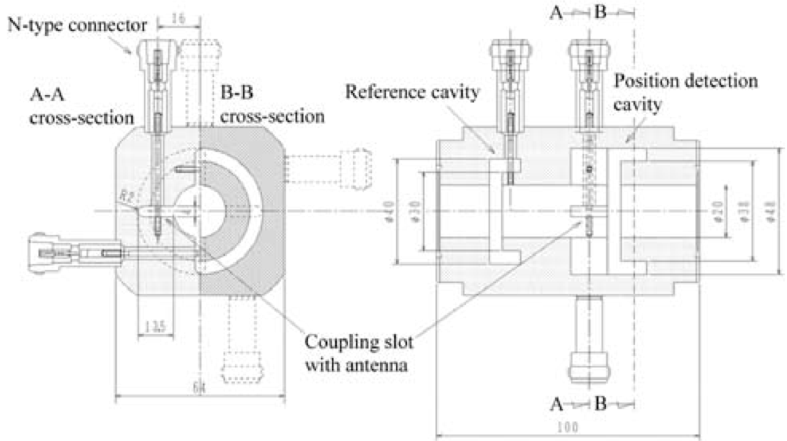
Cavity BPM around the World

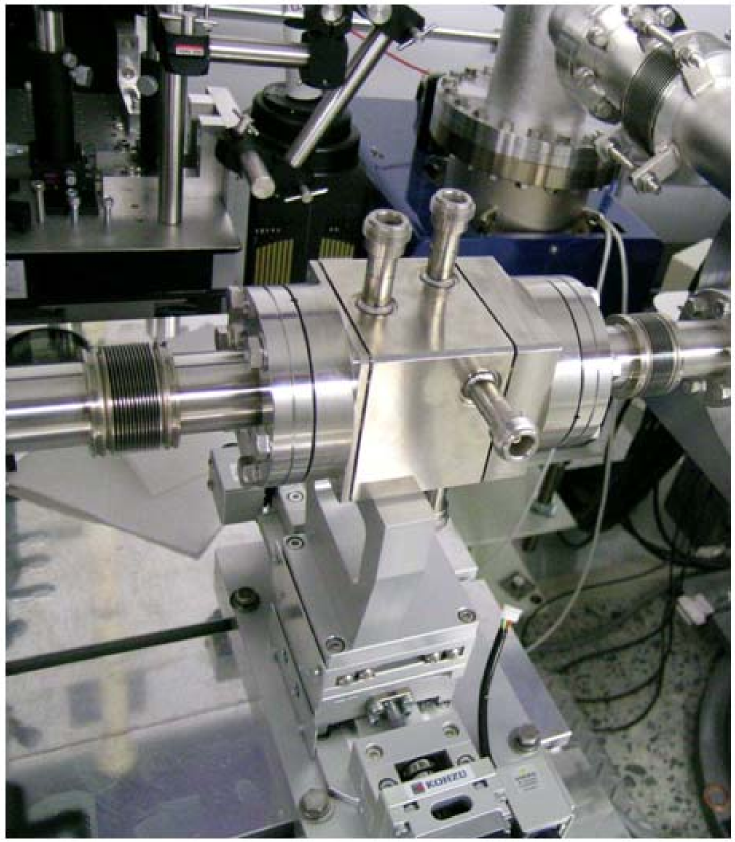


Courtesy: H. Maesaka

Cavity BPM at SCSS Prototype Accelerator

Required resolution: < 0.5 μm



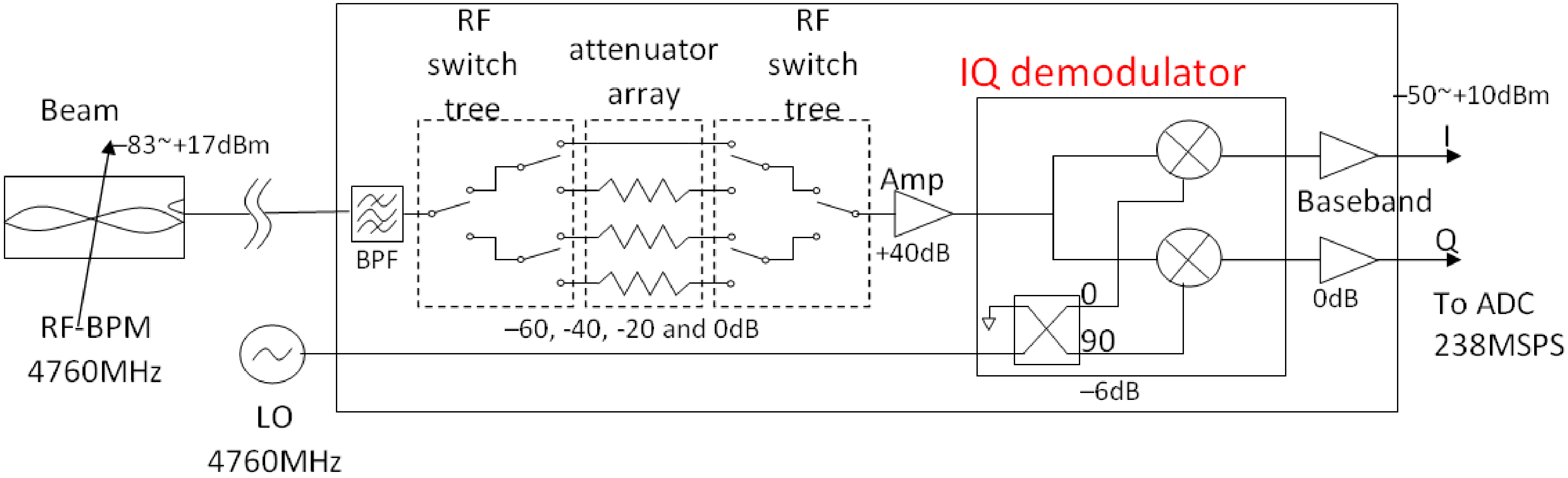


Material: Stainless Steel
Pipe diam.: 20 mm

Courtesy: H. Maesaka

Cavity BPM at SCSS Prototype Accelerator

- Developed circuit with IQ demodulators.
  - IQ demodulator can detect all phase angles.
  - Amplitude is linear.
  - The 90 deg. signal is easily distinguished.
  - The dynamic range is expanded with rf switches and attenuators.



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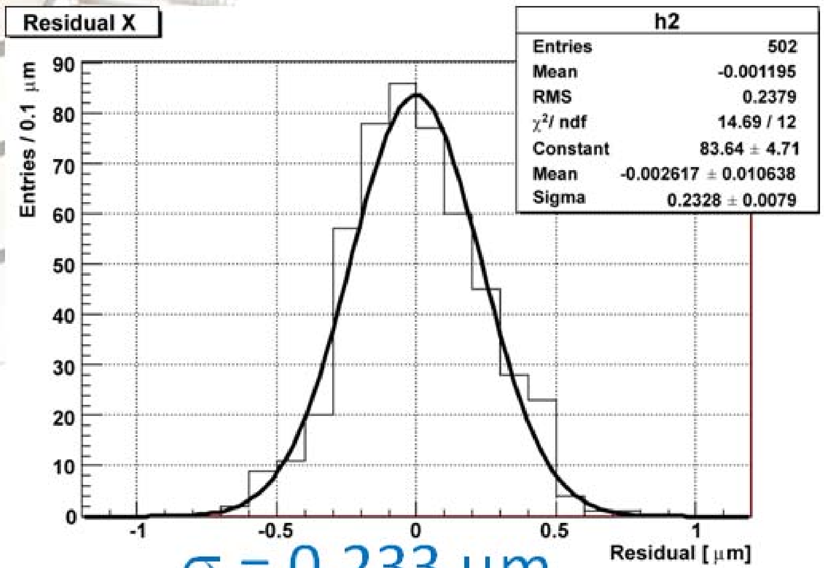
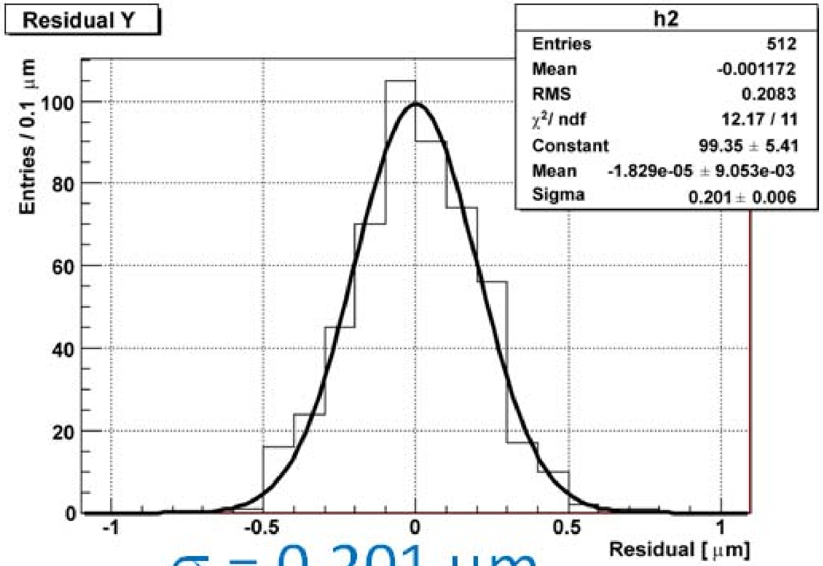


$\sigma = 0.233\ \mu m$

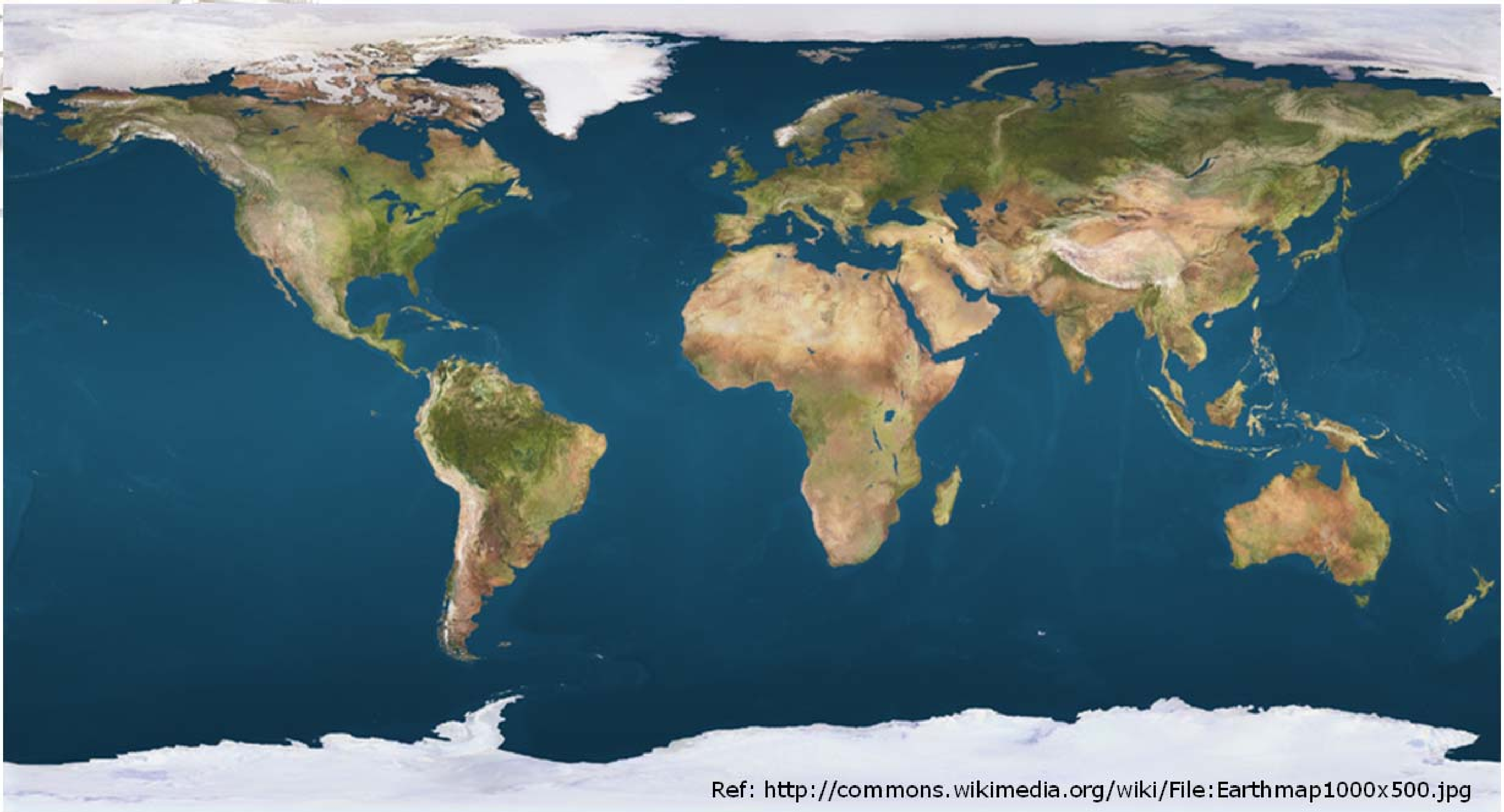


$\sigma = 0.201\ \mu m$

- Assuming the three BPMs have the same resolutions, we obtained at 0.3 nC:
  - X resolution: 0.198 µm
  - Y resolution: 0.171 µm
- XFEL requirement, < 0.5 µm, is satisfied.

See poster H. Maesaka: MOPD07

Cavity BPM around the World



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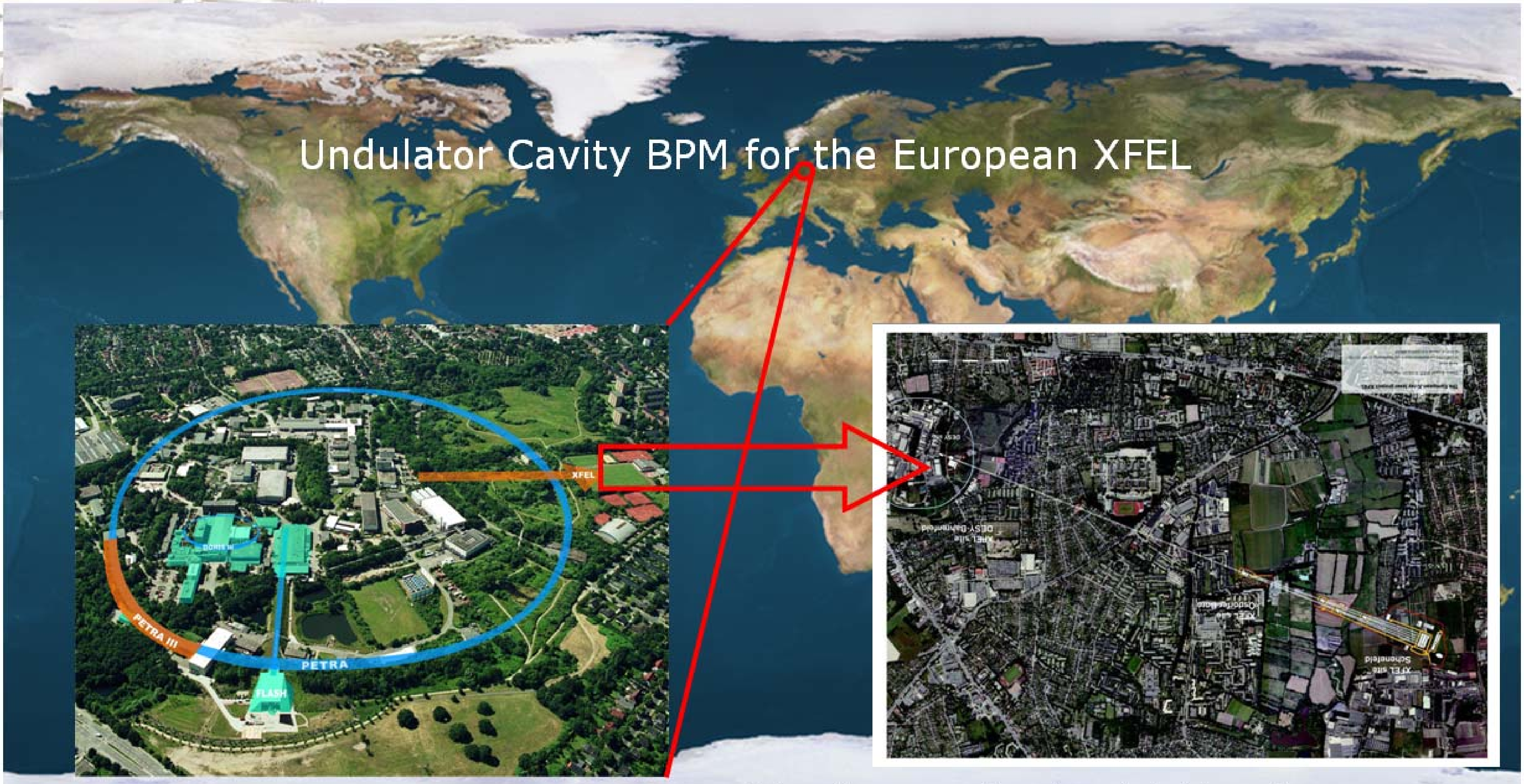

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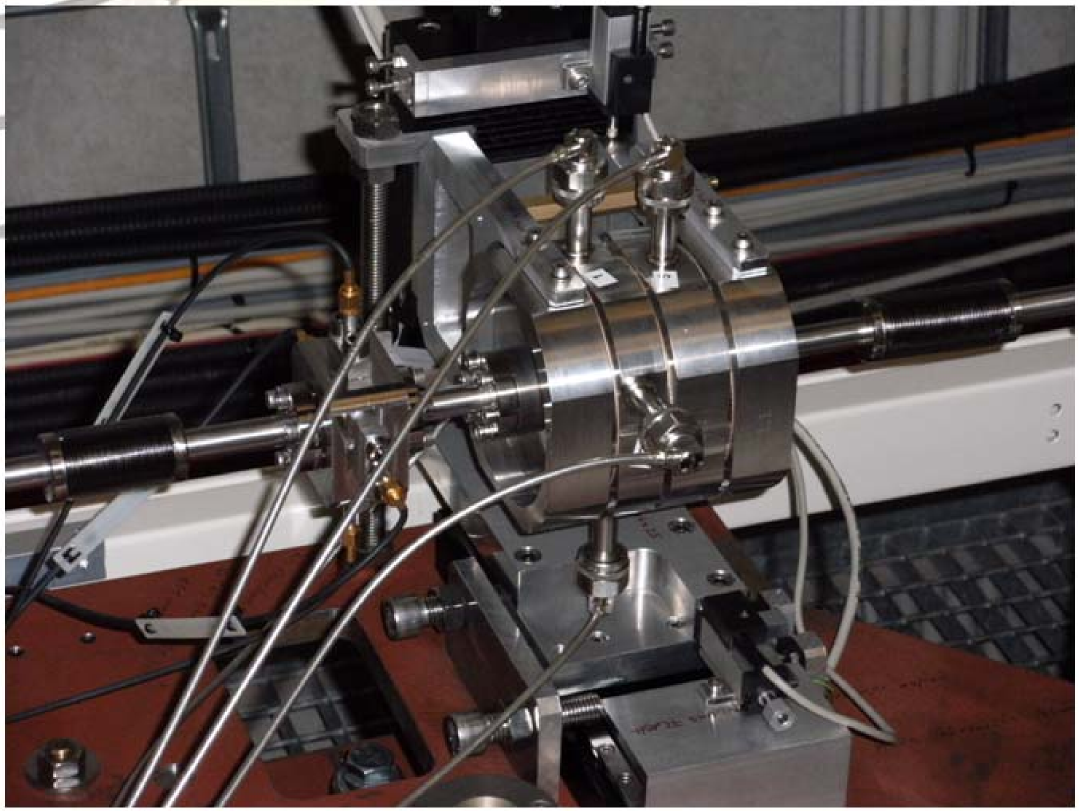
Undulator Cavity BPM for the European XFEL



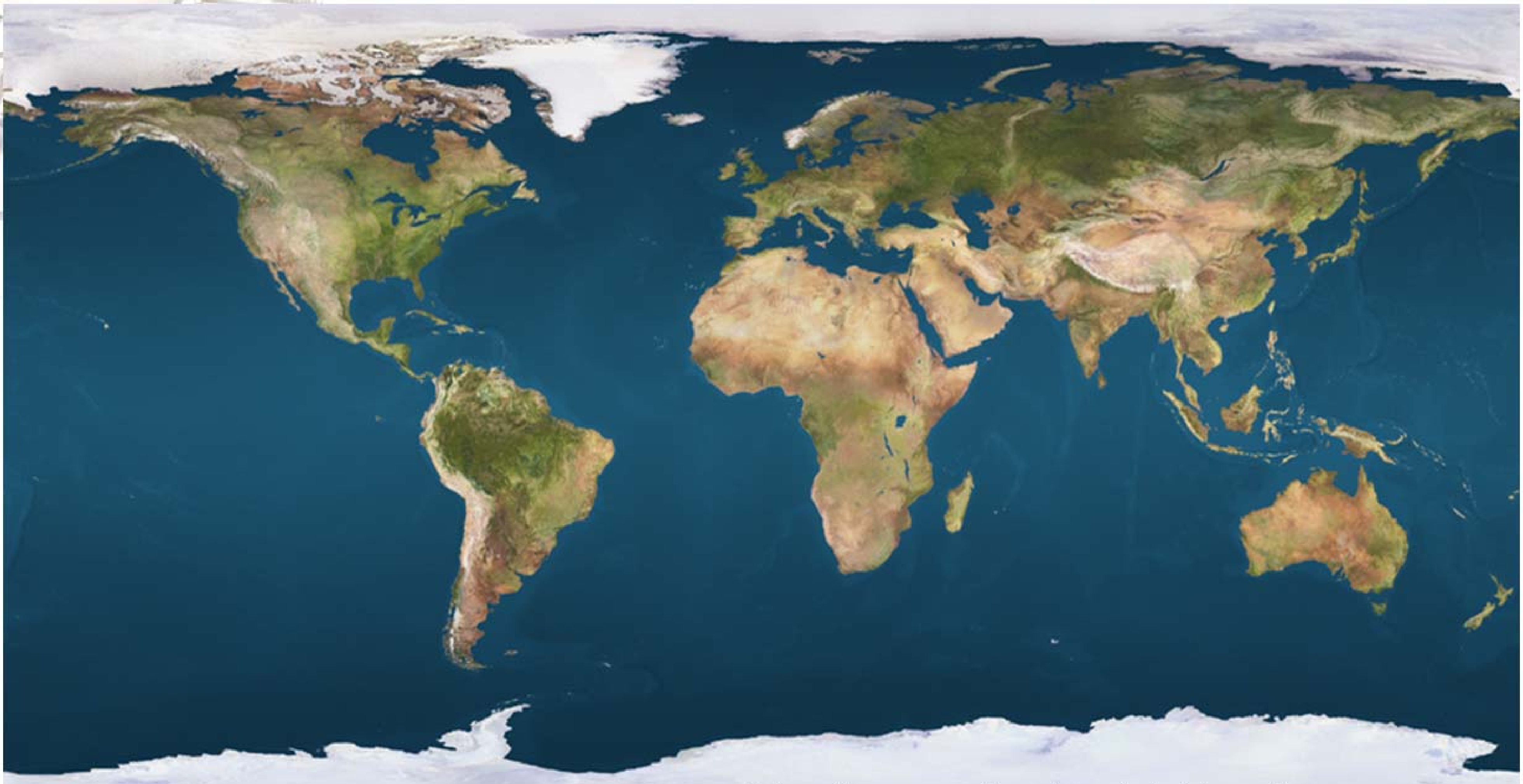
- Design from SPring-8 (T. Shintake)
- Produced six prototypes

  f = 3.3 GHz (for larger pipe possible too)

  Q_L = 70

  Pipe diameter = 10 mm
- One prototype included at FLASH
- Orthogonal coupling: see contribution: MOPD02
- Next steps: 3 BPM in beamline with electronics

Cavity BPM around the World



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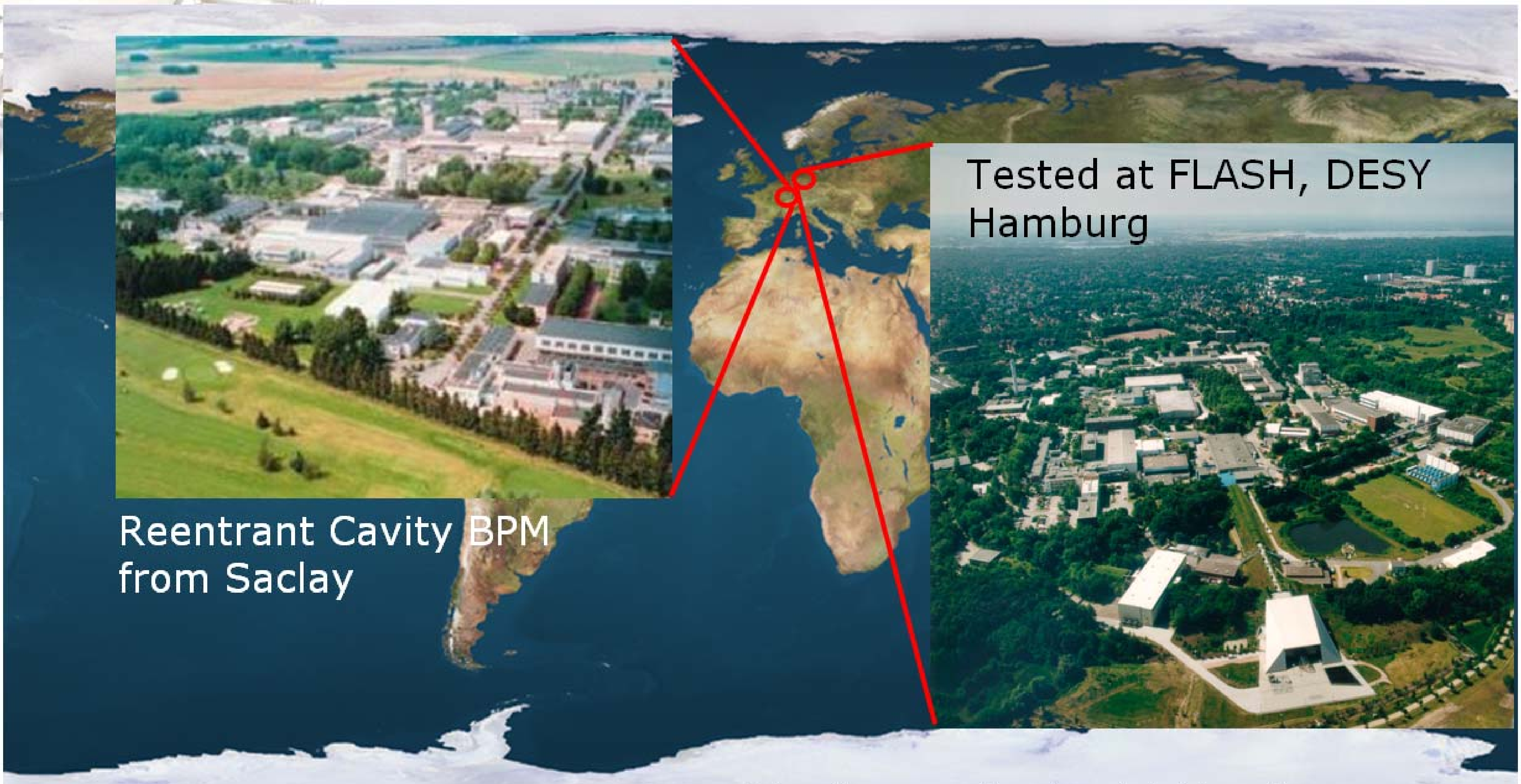


Ref: http://commons.wikimedia.org/wiki/File:Earthmap1000x500.jpg

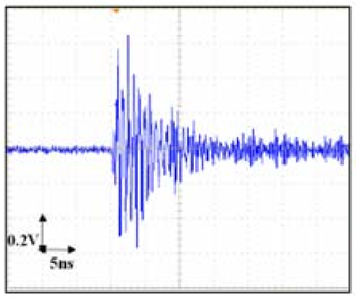
Courtesy: C. Simon

Reentrant Cavity BPM

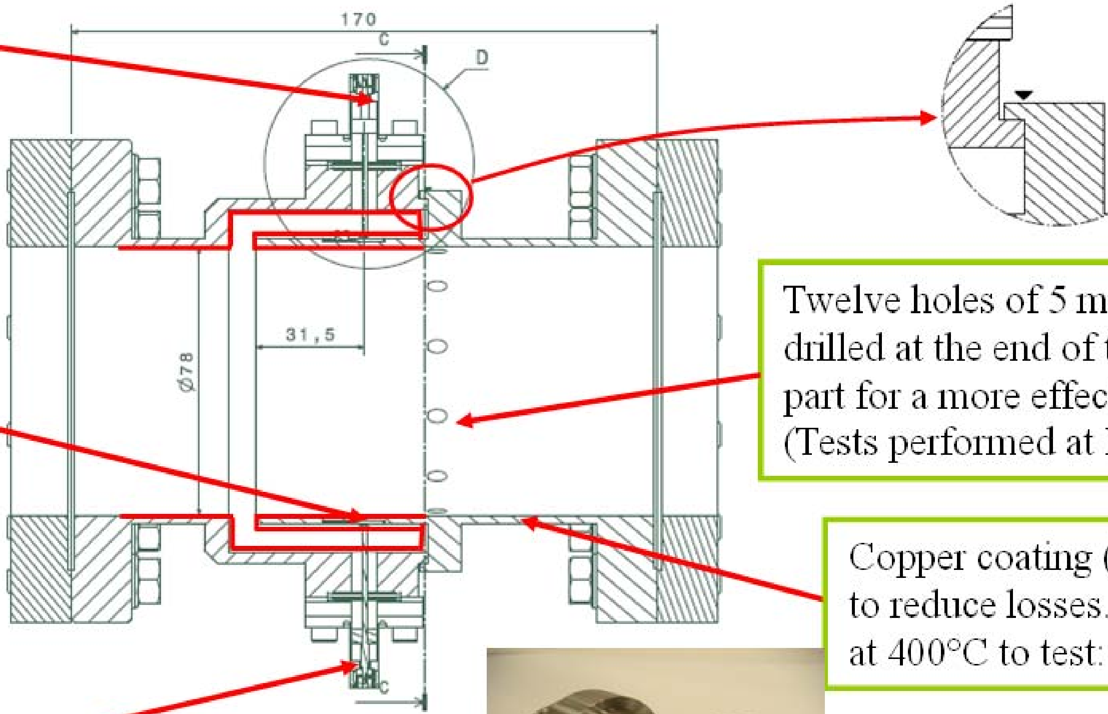
For cold accelerator of European XFEL, Resolution < 50 μm

Cryogenics tests at 4 K on feedthroughs is OK

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



Signal from one pickup



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

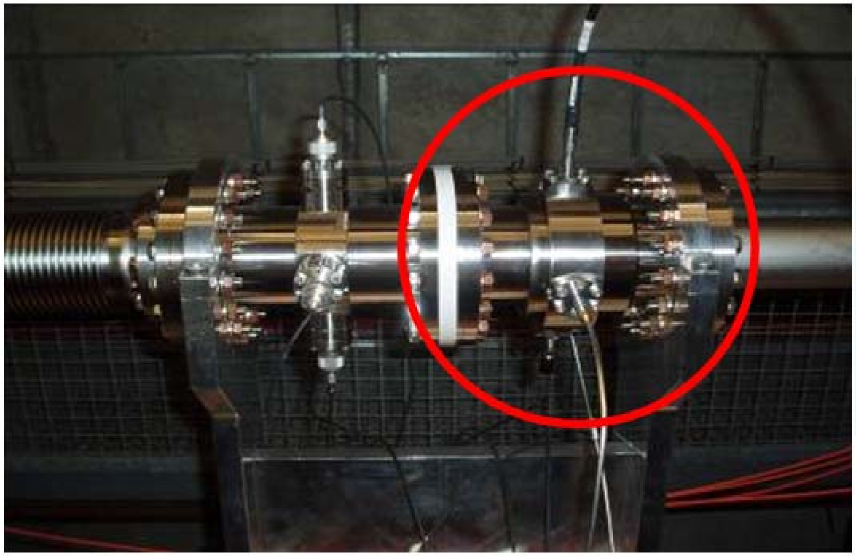
Copper coating (depth: 12 μm) to reduce losses. Heat treatment at 400°C to test: OK

Pipe diam.: 78 mm

Courtesy: C. Simon

Reentrant Cavity BPM

Eigen modes	F (MHz)		Q_l		$(R/Q)_l$ (Ω) at 5 mm	$(R/Q)_l$ (Ω) at 10 mm
	Calculated with HFSS in eigen mode	Measured in the tunnel	Calculated with HFSS in eigen mode	Measured in the tunnel	Calculated	Calculated
Monopole mode	1250	1255	22.95	23.8	12.9	12.9
Dipole mode	1719	1724	50.96	59	0.27	1.15

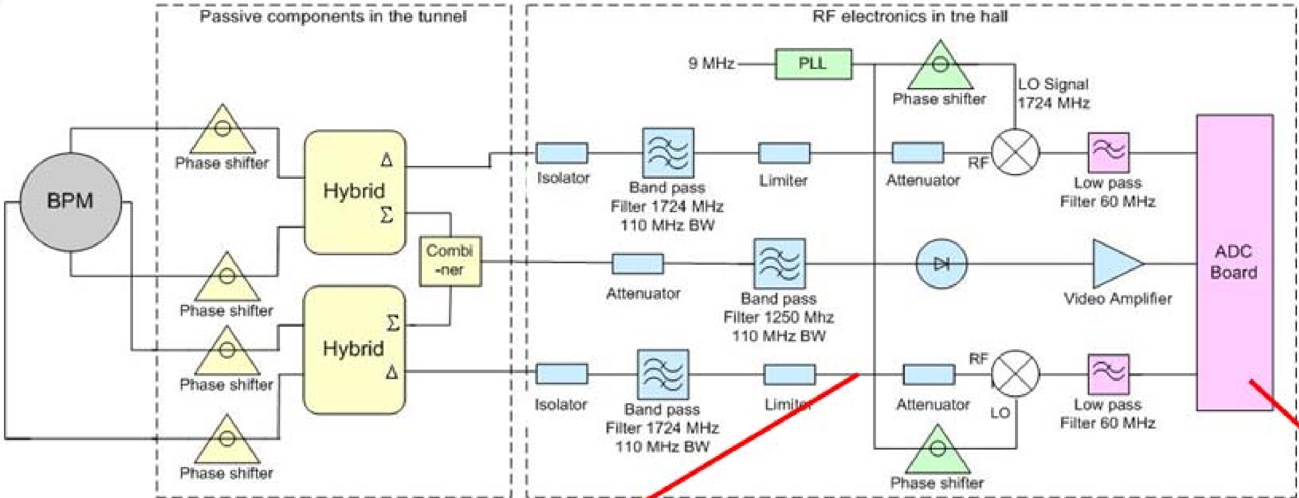


Re-entrant cavity BPM installed in a warm section on the FLASH linac

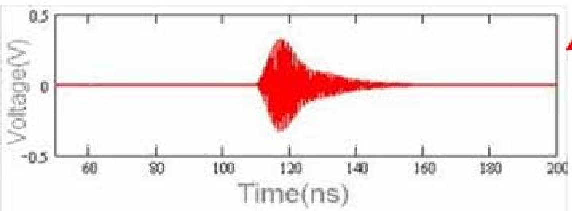
Reentrant Cavity BPM

The rejection of the monopole mode, on the Δ channel, proceeds in **three steps** :

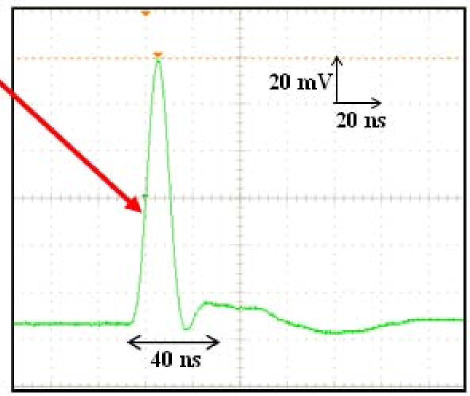
- a rejection based on a hybrid coupler having isolation higher than 20 dB in the range of 1 to 2 GHz.
- a frequency domain rejection with a band pass filter centered at the dipole mode frequency. Its bandwidth of 110 MHz also provides a noise reduction.
- a synchronous detection.



RF signal

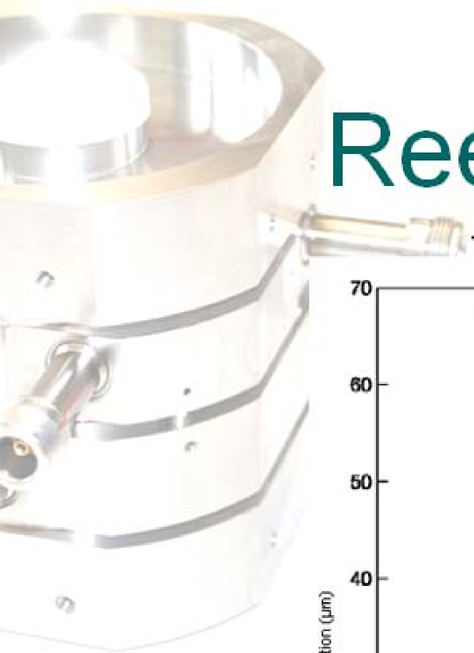


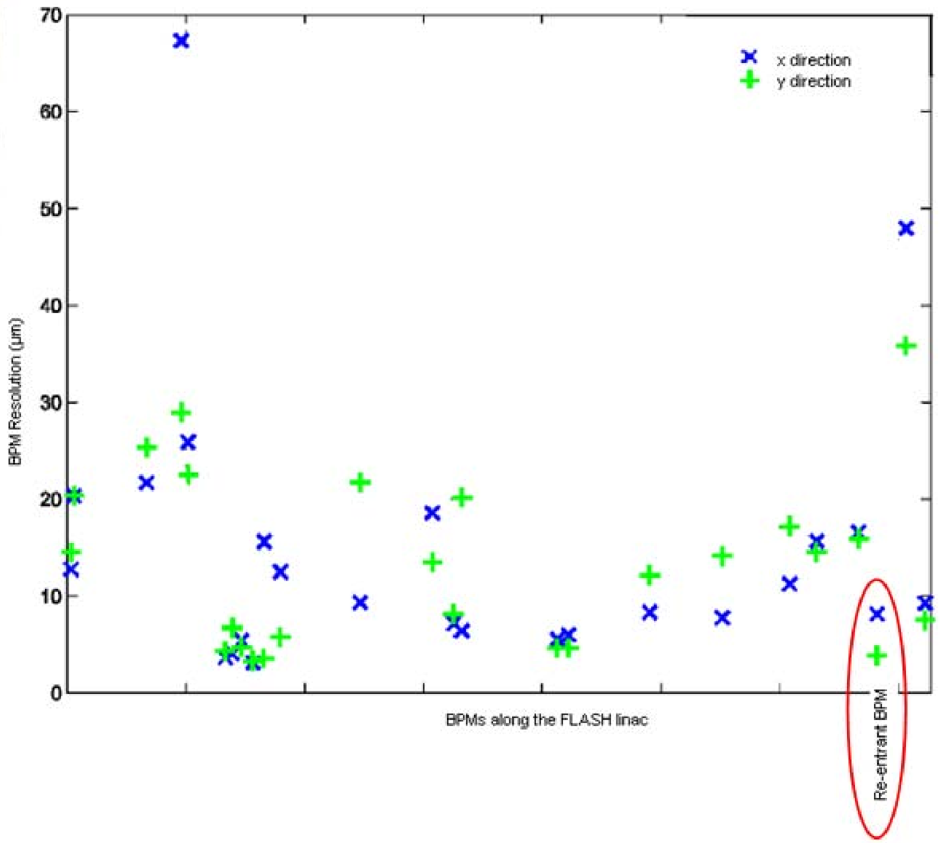
IF signal behind Lowpass Filter on channel Δ



Courtesy: C. Simon

Reentrant Cavity BPM





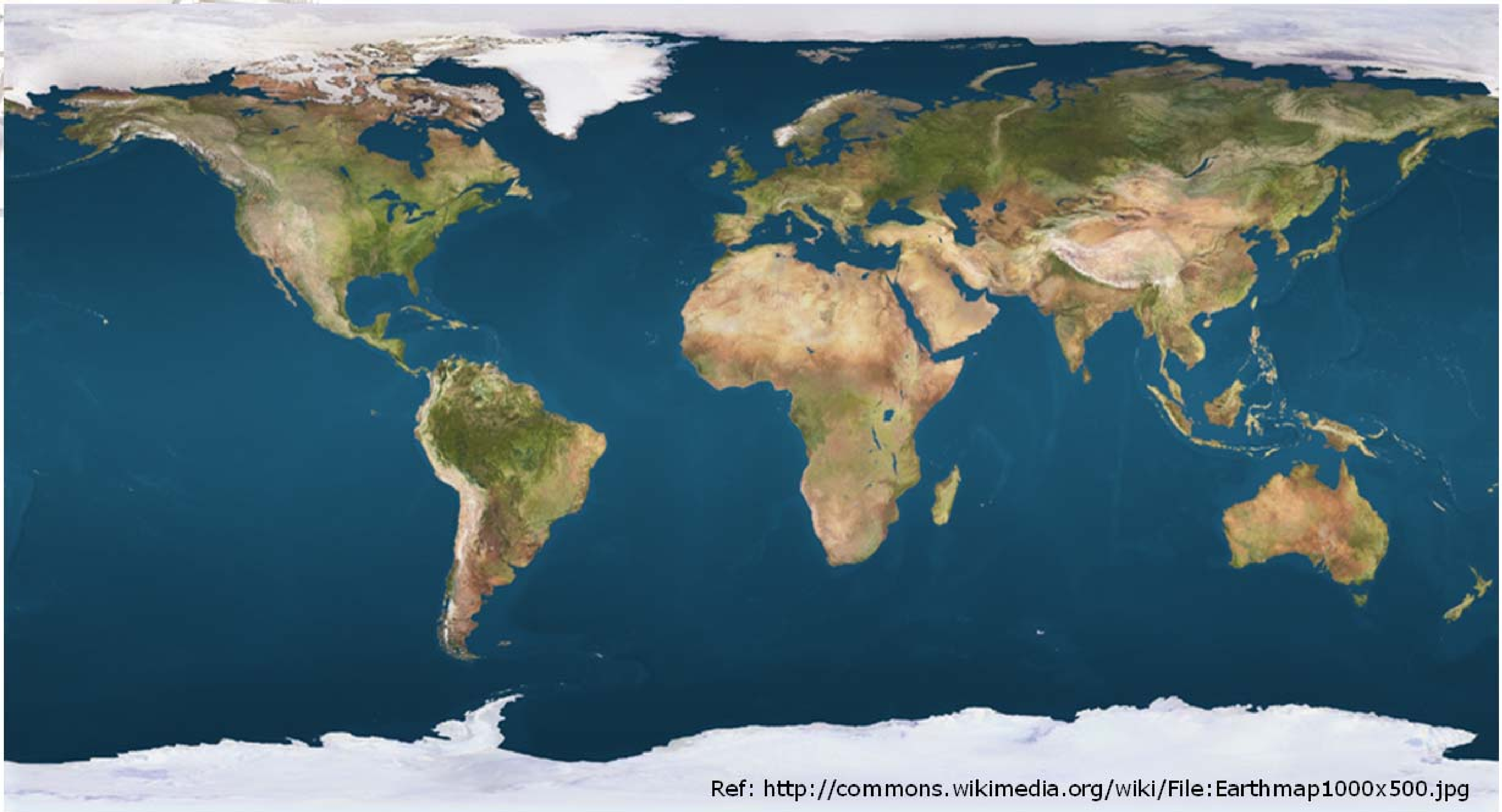
- Bunch to bunch measurements (**time resolution ~40 ns**)
- **30 reentrant cavity BPMs will be installed in the XFEL cryomodules**

RMS resolution:

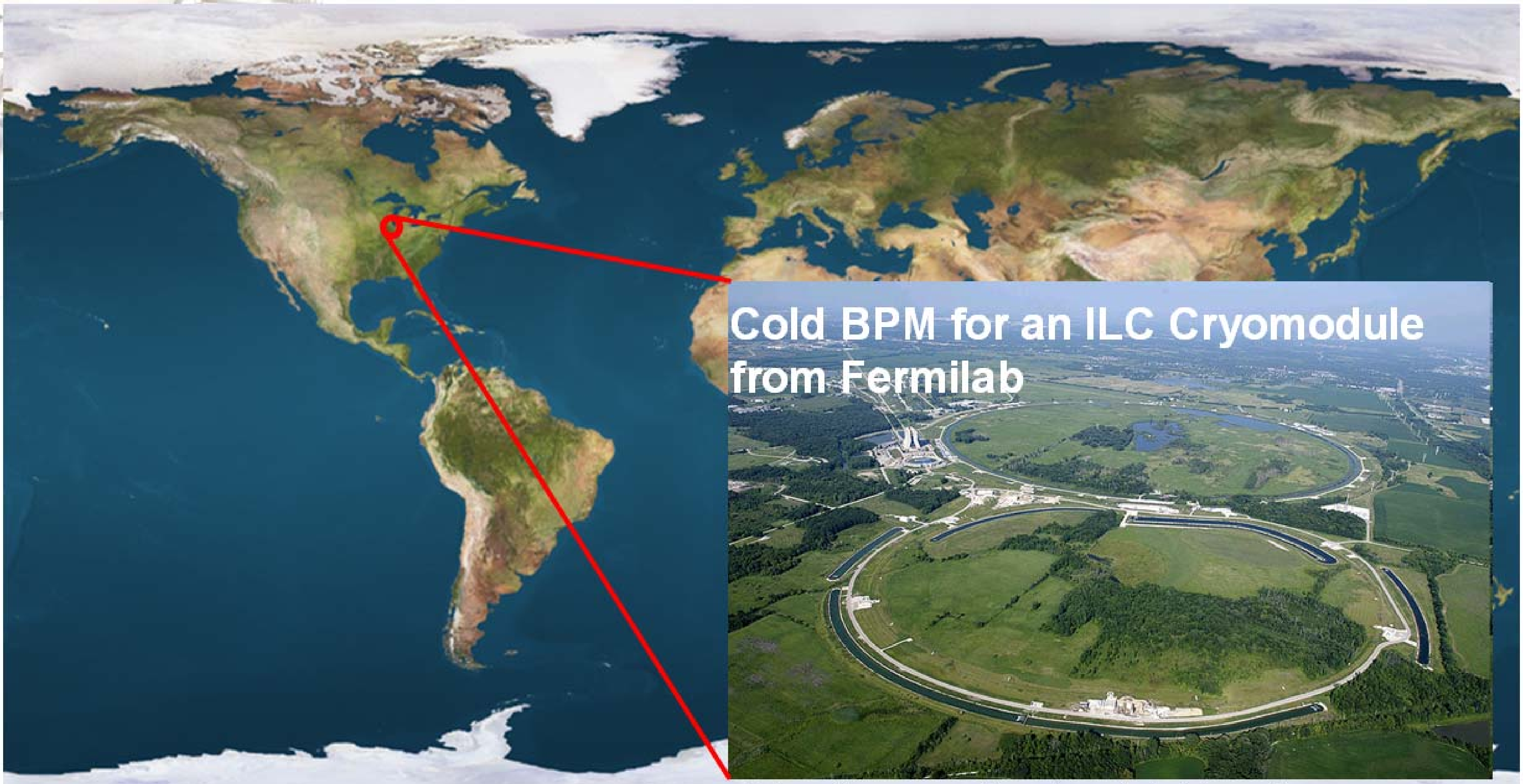
~4 µm on the Y channel
~8 µm on the X channel

with 1 nC and dynamic range +/- 5 mm

Cavity BPM around the World



Cavity BPM around the World

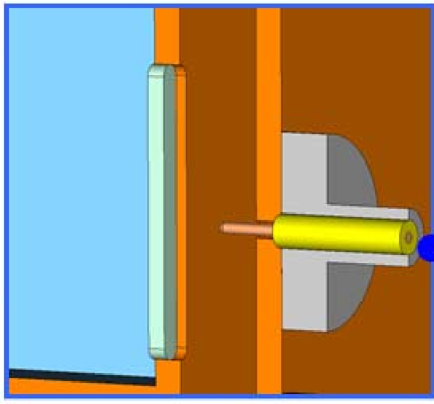


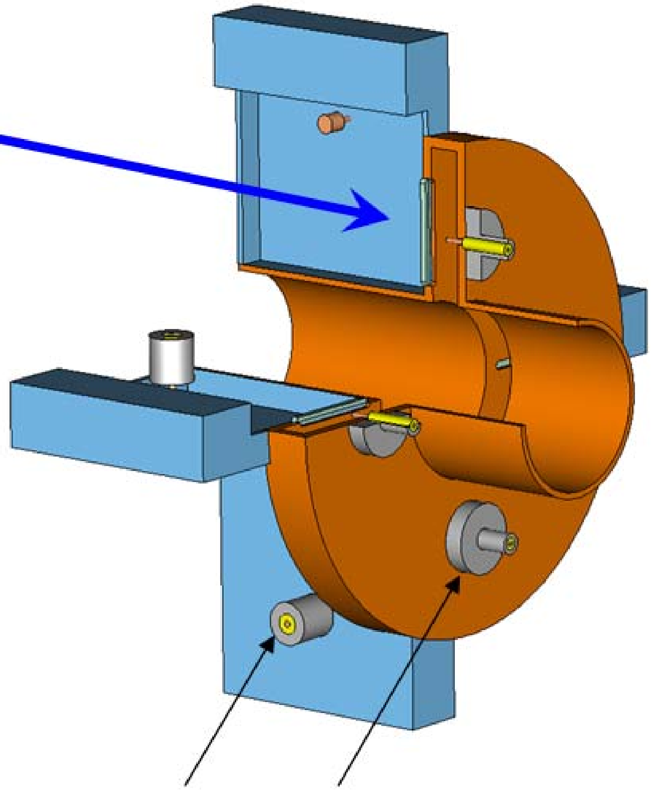
Ref: http://commons.wikimedia.org/wiki/File:Earthmap1000x500.jpg

Courtesy: M. Wendt

Cold BPM for an ILC Cryomodule

Window –
Ceramic brick
to simplify the
cleaning procedure



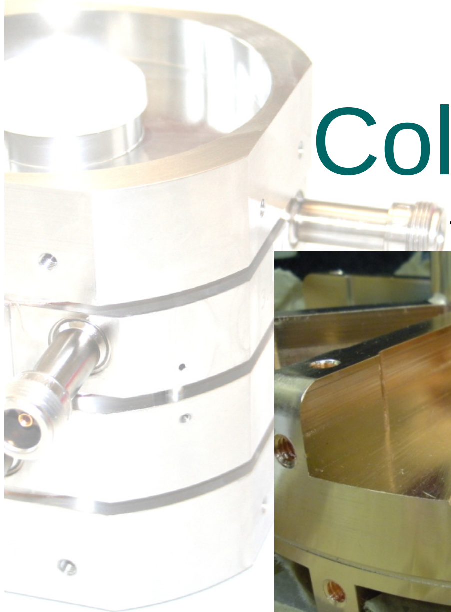


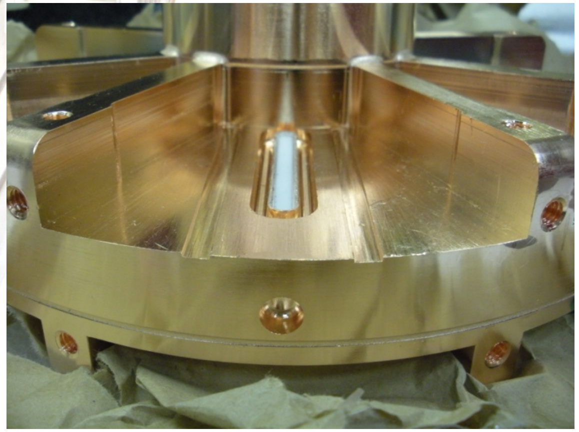
N type receptacles,
50 Ohm

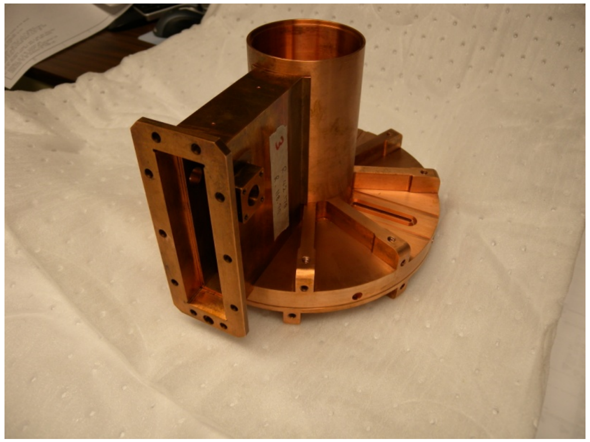
Frequency, GHz, dipole	1.468
monopole	1.125
Loaded Q (**both monopole and dipole**)	~ 600
Beam pipe radius, mm	39
Cell radius, mm	113
Cell gap, mm	15
Waveguide, mm	122x110x25
Coupling slot, mm	51x4x3

Courtesy: M. Wendt

Cold BPM for an ILC Cryomodule

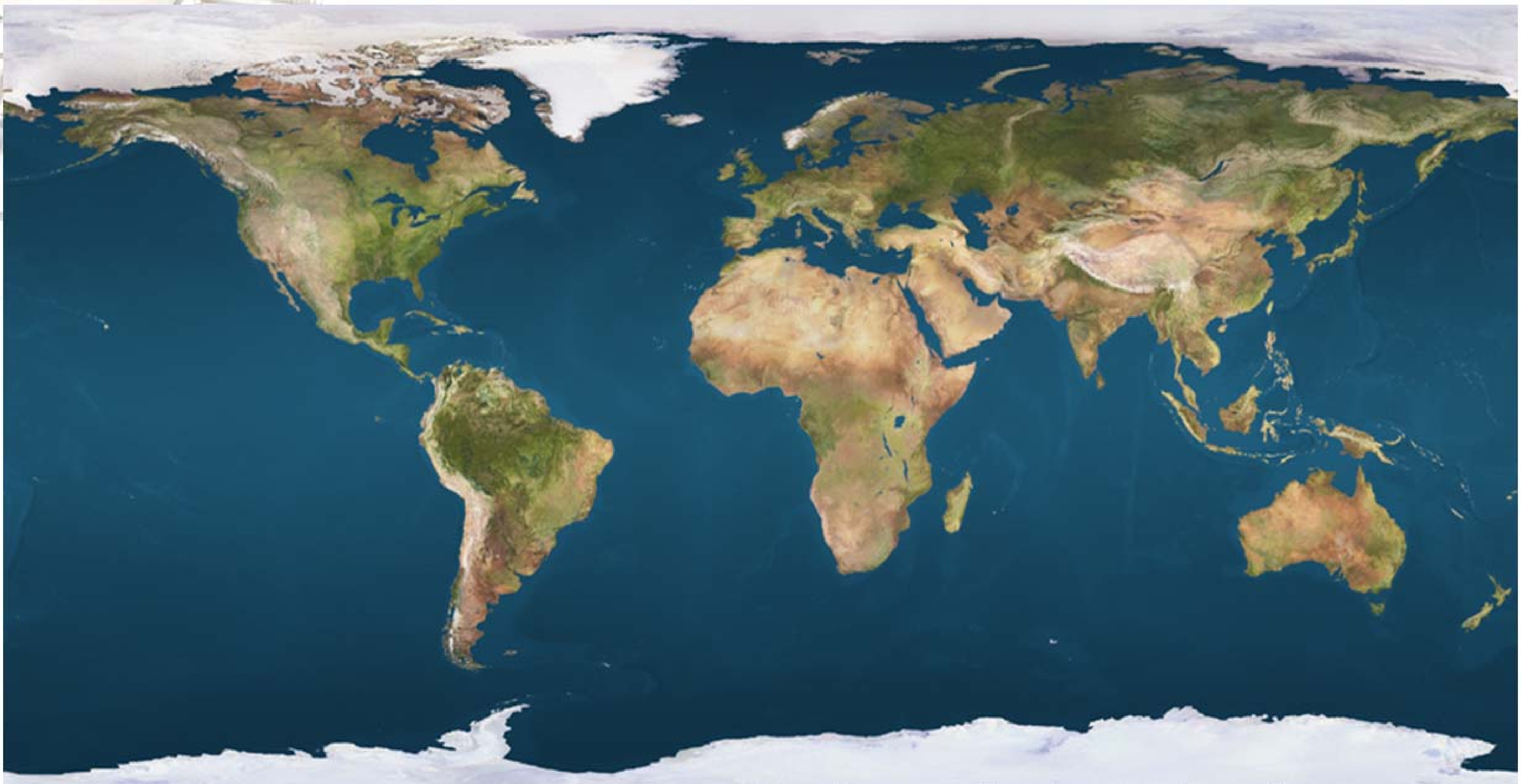






- Prototype status:
  - EM simulations & construction finalized
  - All parts are manufactured, brazing is underway
  - Prototype has “warm” dimensions
- Successful tests of the ceramic slot windows,
  i.e. several thermal cycles 300 K -> 77 K -> 300 K
- Next Steps:
  - Warm prototype finalization (brazing), RF measurements, tuning, beam tests (at the A0-Photoinjector).

Cavity BPM around the World



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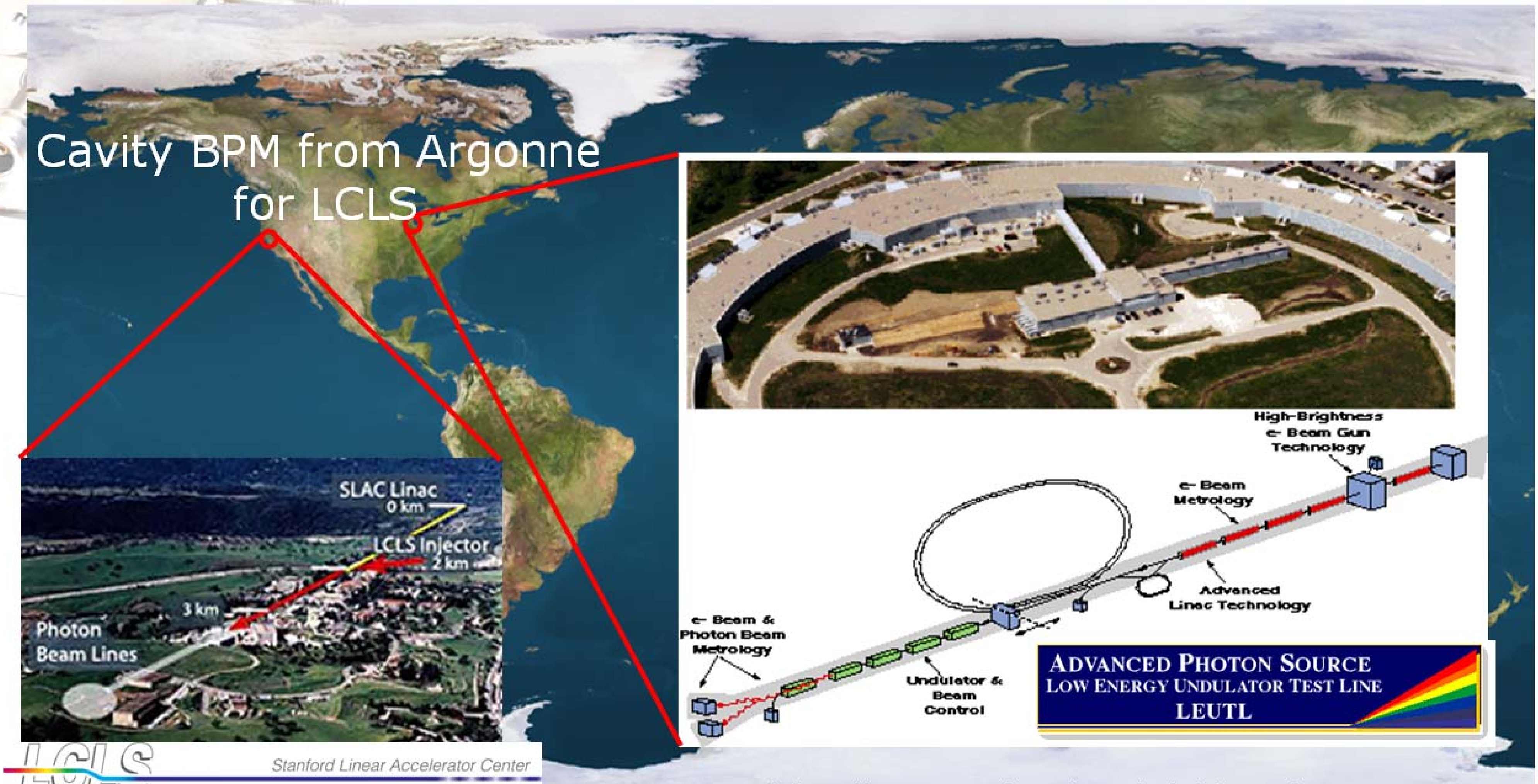
Cavity BPM around the World



Ref: http://commons.wikimedia.org/wiki/File:Earthmap1000x500.jpg

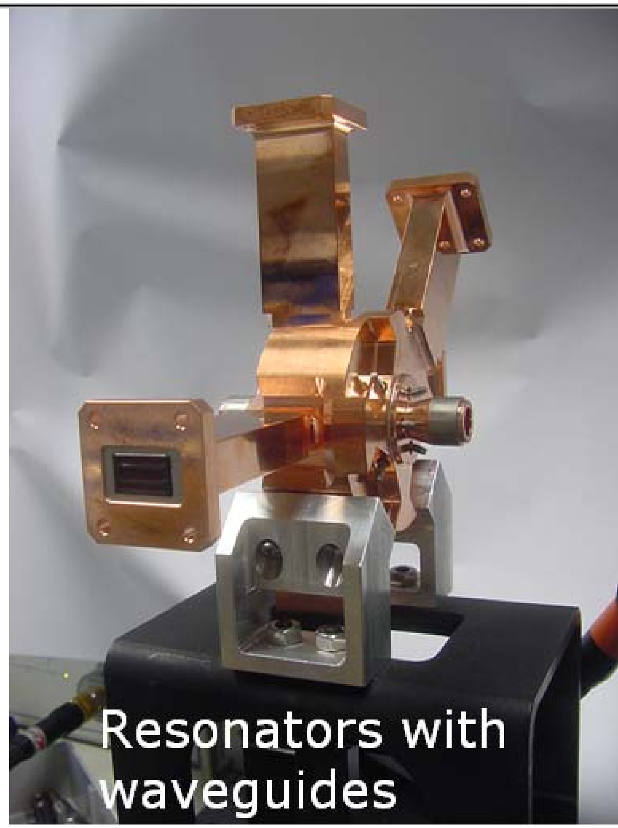
Courtesy: B. Lill

Cavity BPM for LCLS

Requirement: < $1\mu m$

for 0.2 – 1 nC

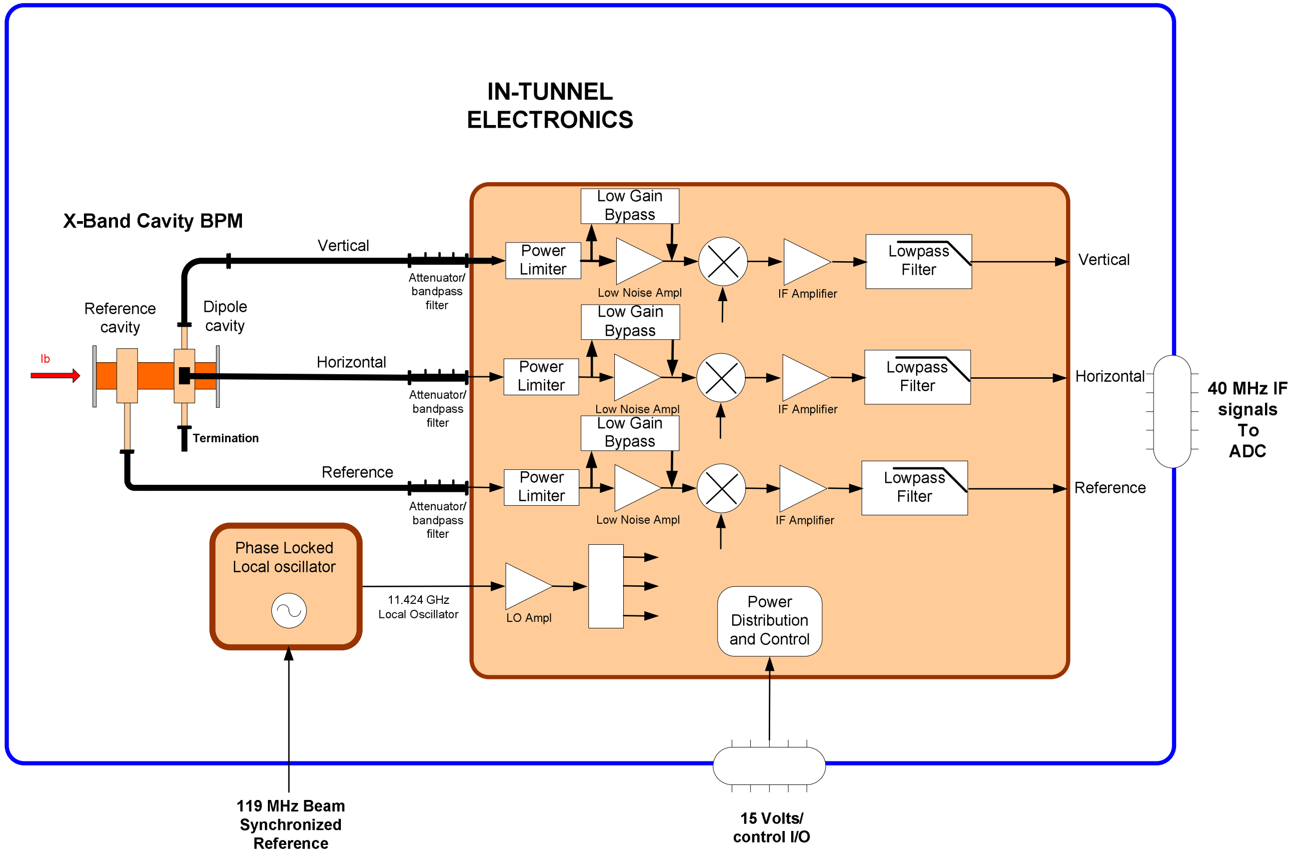
Test of 3 Cavity BPM at APS LEUTL



BPM material: copper
Resonance frequency: 11.384 GHz
Loaded quality factor: 3550
Pipe diameter: 10 mm

Courtesy: B. Lill

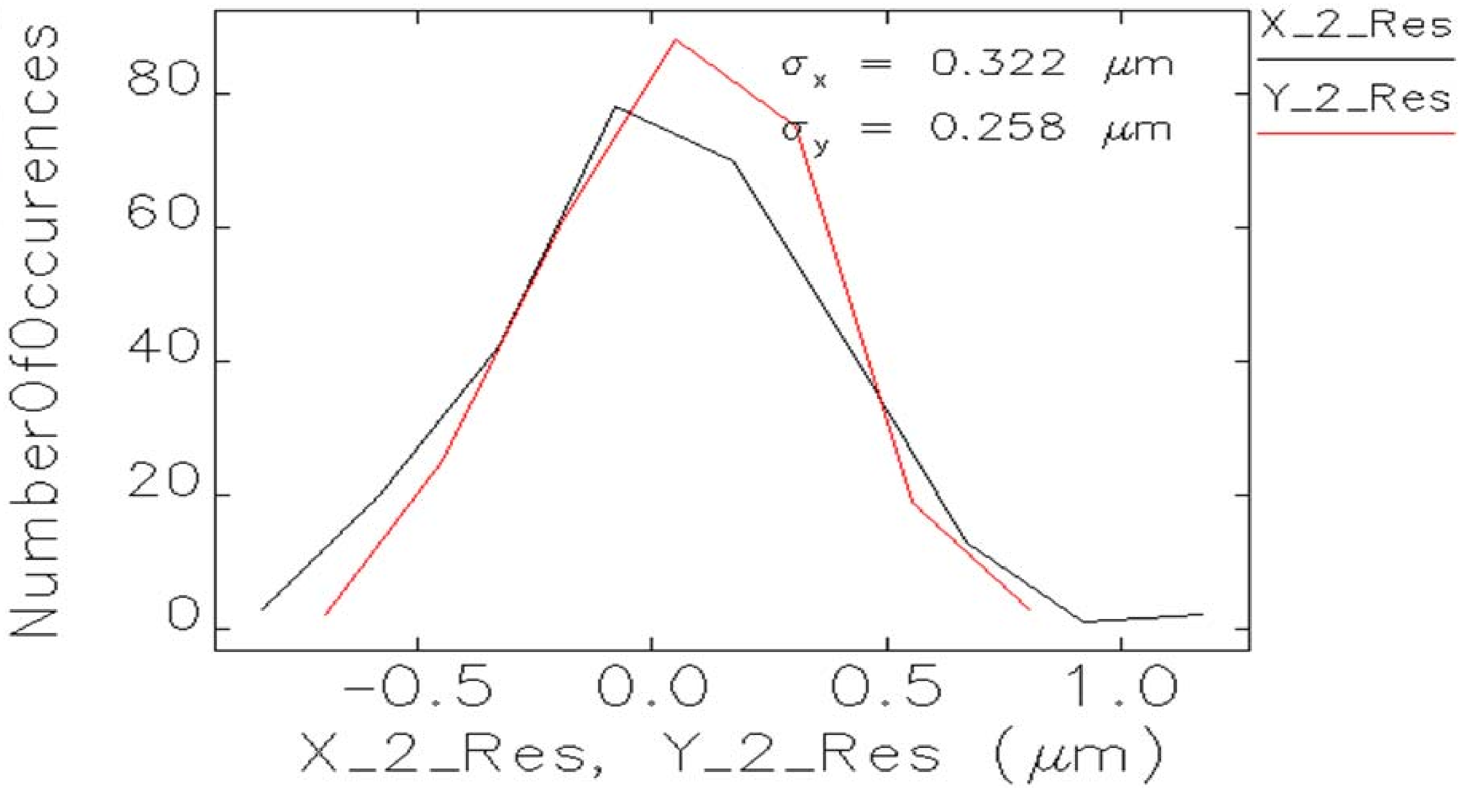
Cavity BPM for LCLS: Electronics



Waveguides connected to electronics board

Courtesy: B. Lill

Cavity BPM for LCLS: Results



Beam Charge/pulse: 0.2 to 0.5 nC

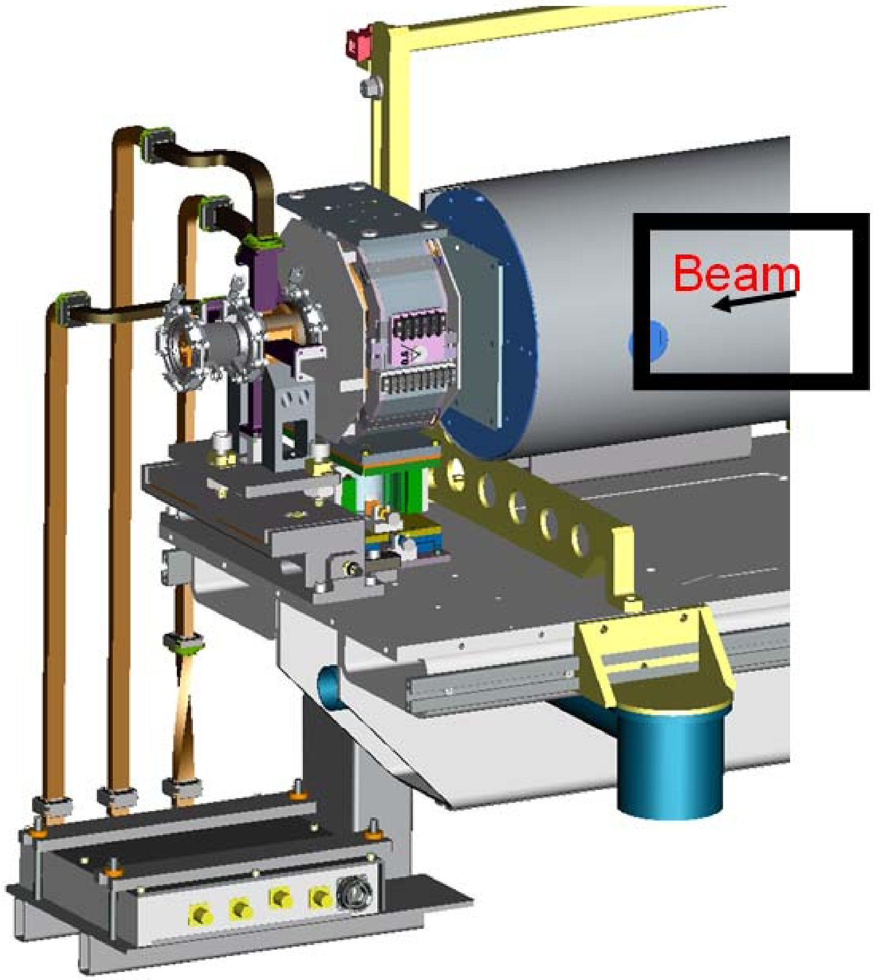
Resolution below Requirement

Courtesy Nick Sereno

Courtesy: B. Lill

Cavity BPM for LCLS

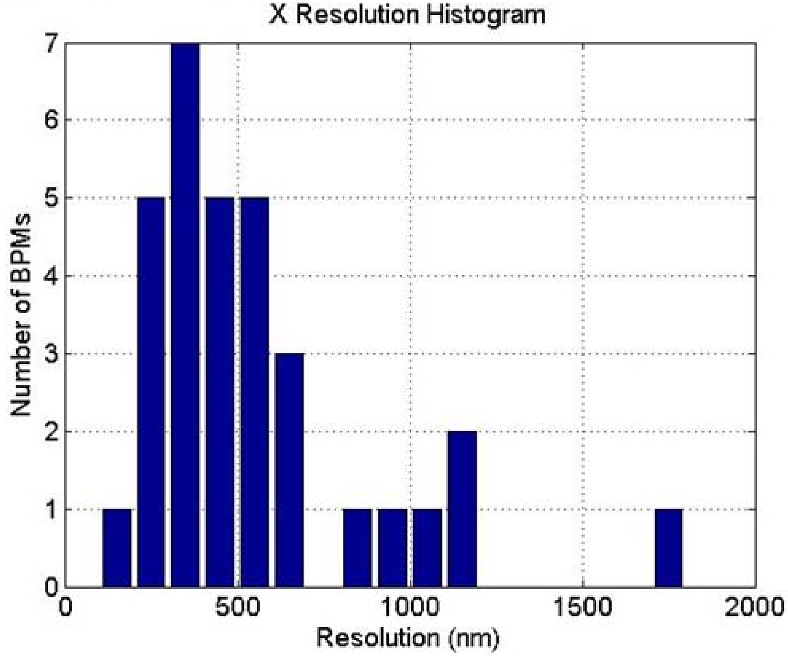
Undulator System Layout

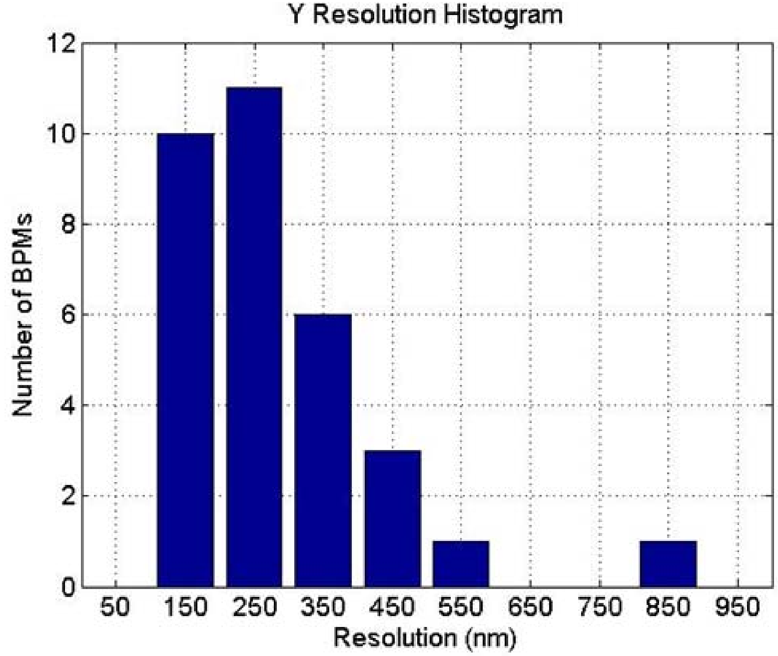


Courtesy: S. Smith

Cavity BPM at LCLS

Distribution of measured resolution:

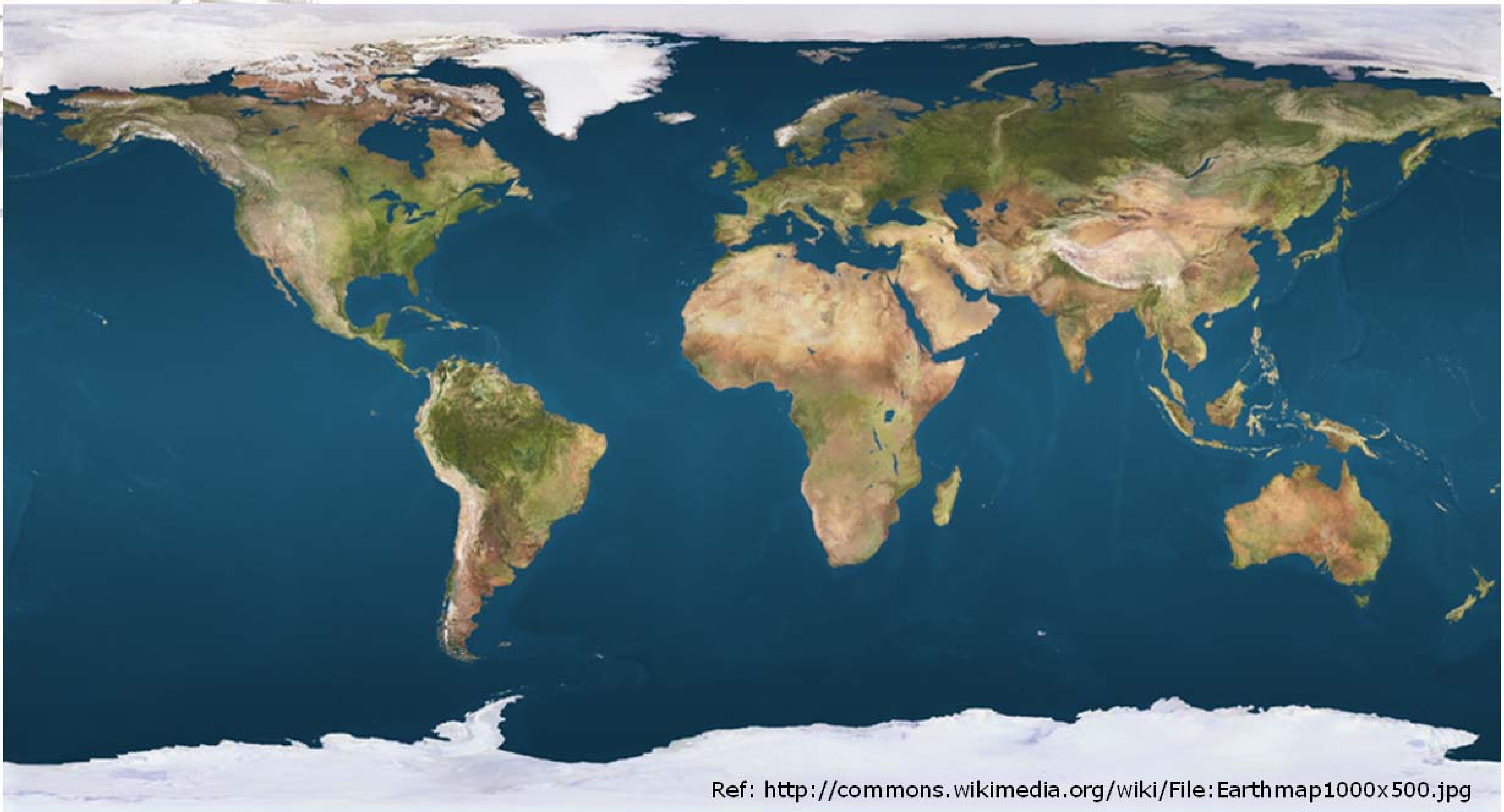




- Typical (median) resolutions:
  - σ_x ~ 440 nm with a few > 1 micron
  - σ_y ~ 230 nm, none > 1 micron
- Why the difference? Jitter? Energy variation?

See next talk TUOC03: Stephen Smith 'LCLS Cavity BPM'

Cavity BPM around the World



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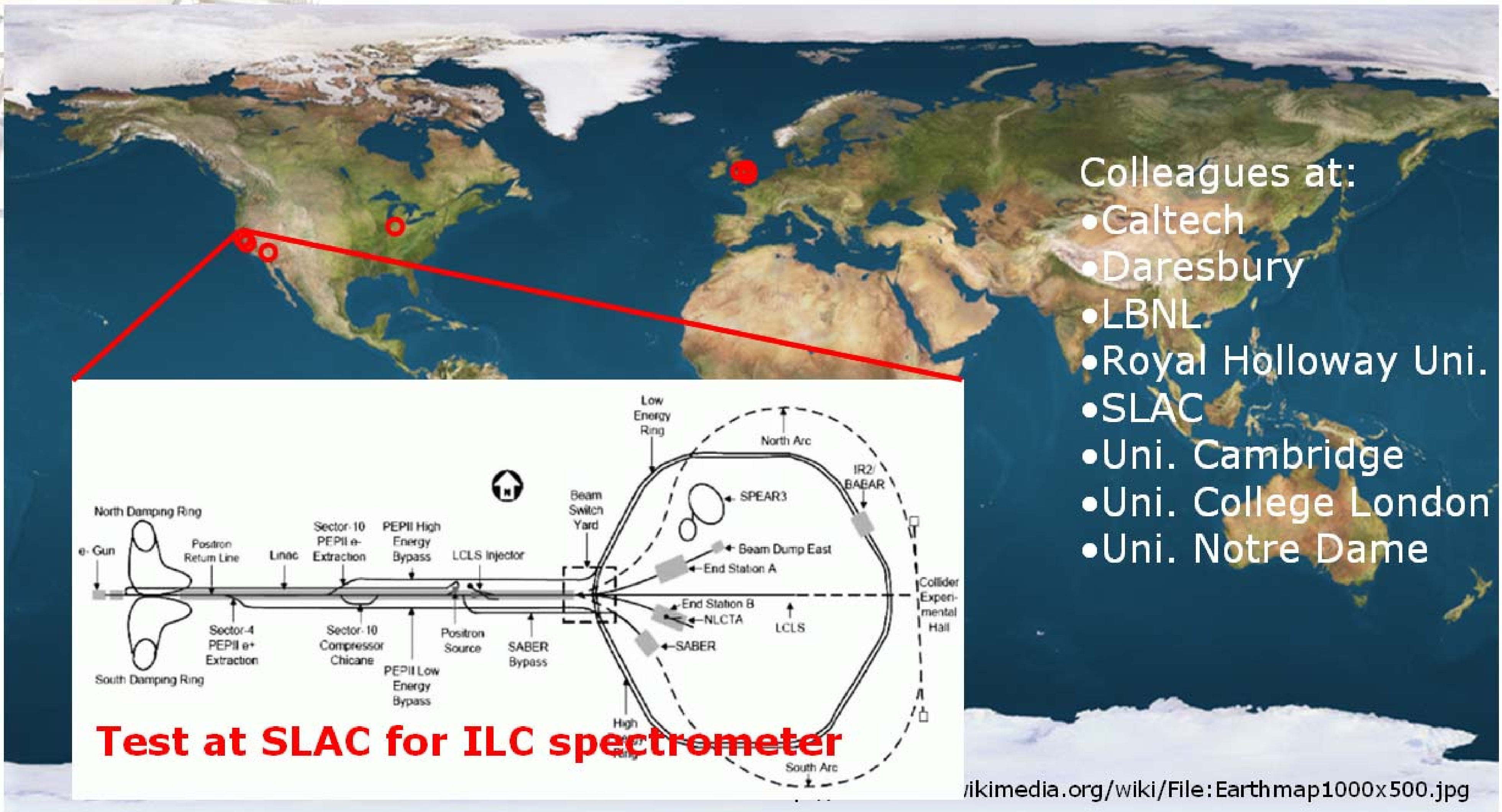
Cavity BPM around the World



Test at SLAC for ILC spectrometer

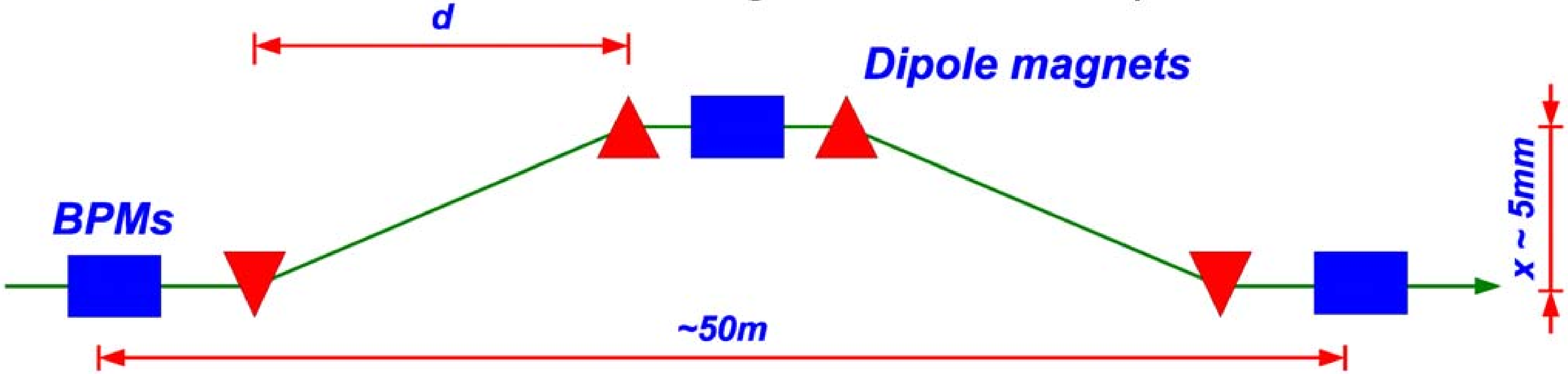
Colleagues at:
- Caltech
- Daresbury
- LBNL
- Royal Holloway Uni.
- SLAC
- Uni. Cambridge
- Uni. College London
- Uni. Notre Dame

…ikimedia.org/wiki/File:Earthmap1000x500.jpg

Courtesy: M. Slater

Cavity BPM for ILC spectrometer

Schematic of baseline design for the ILC spectrometer



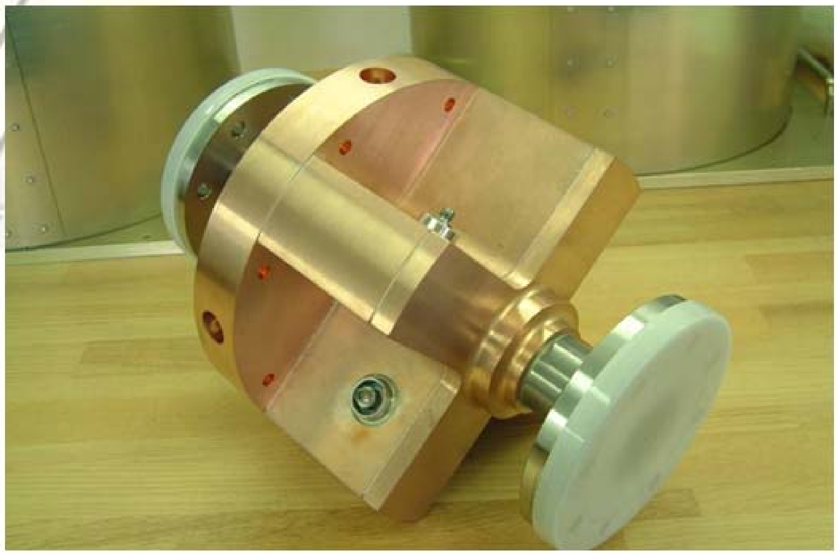
Required fractional energy measurement resolution: 10^{-4}

This results in a BPM resolution of < 500 nm

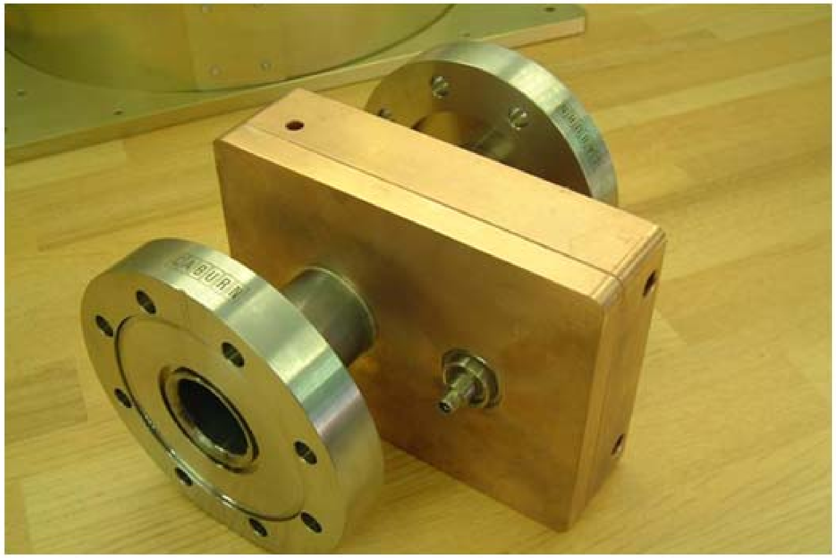
For better resolution the deflection can be smaller: smaller emittance growth

Courtesy: M. Slater

Cavity BPM for ILC spectrometer



Dipole cavity



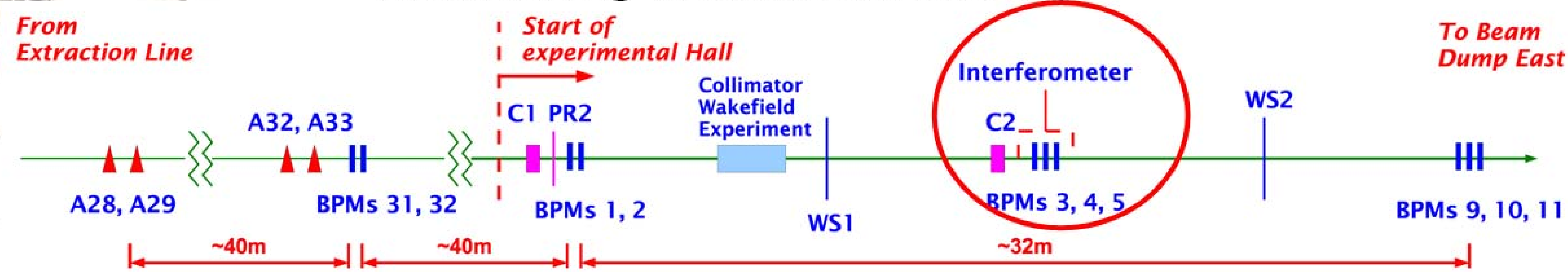
Reference cavity

BPM material: copper
Resonance frequency: 2.859 GHz
Loaded quality factor: ~500
Pipe diameter: 36 mm

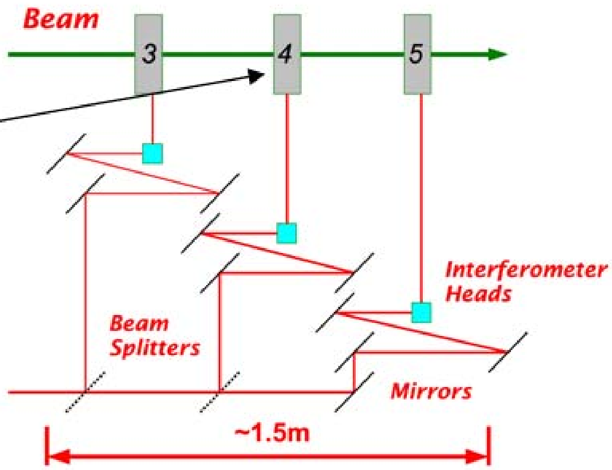
Courtesy: M. Slater

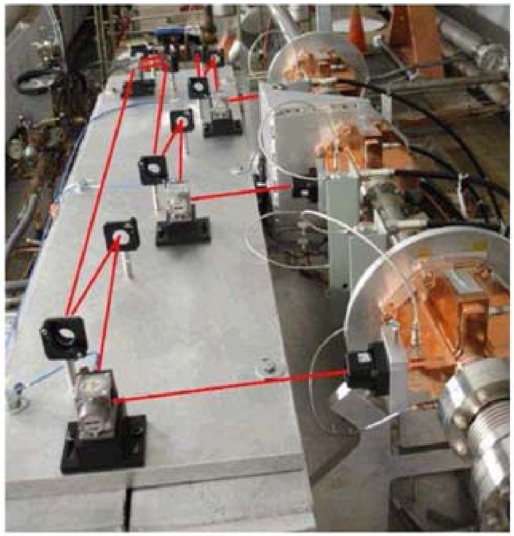
Cavity BPM for ILC spectrometer

Measurement with 3 cylindrical Cavity BPM and monitoring vibrational motion



BPM 4 is mounted on dual axis mover for position calibration

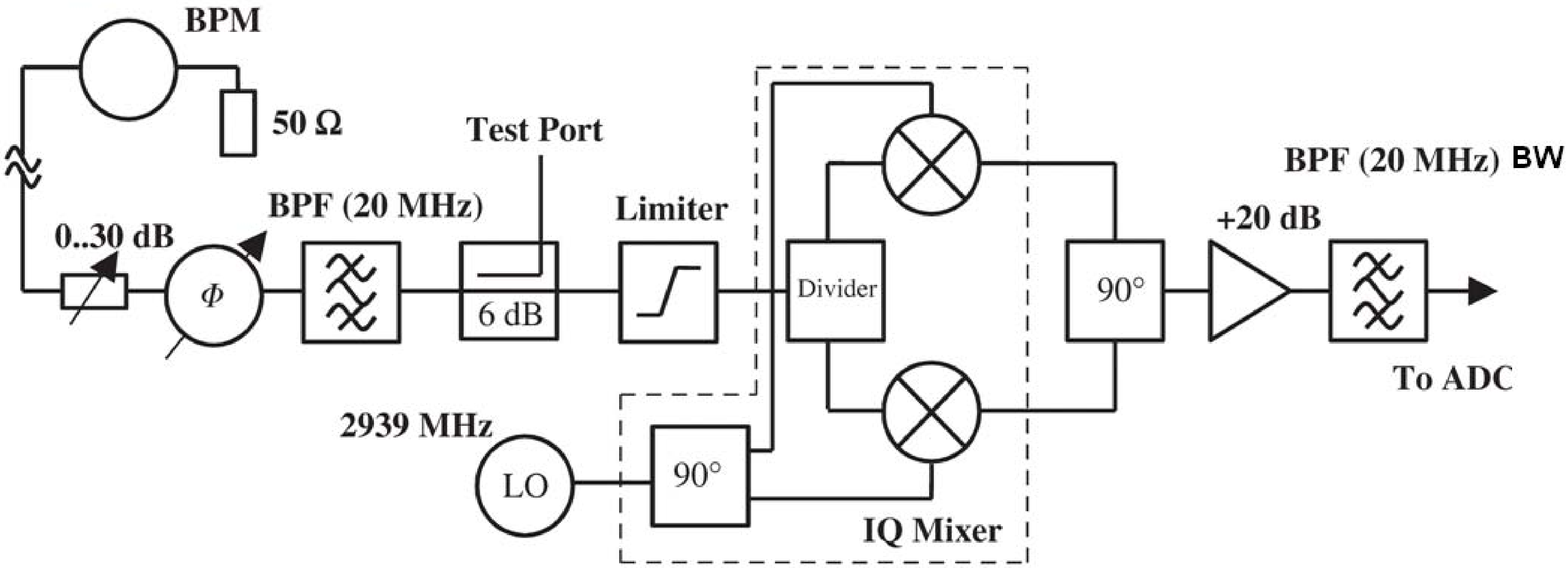




Includes horizontal rigid motion of entire system and non-rigid motion of each BPM with respect to each other

Courtesy: M. Slater

Cavity BPM for ILC spectrometer



Here already an I-Q-Demodulation is applied

Courtesy: M. Slater

Cavity BPM for ILC spectrometer

Results

Resolution measured by taking into account that all 3 BPM are identical (charge about 2.6 nC):

horizontal = 0.53 ± 0.05 μm,

vertical = 0.46 ± 0.02 μm

Vibrational motion:

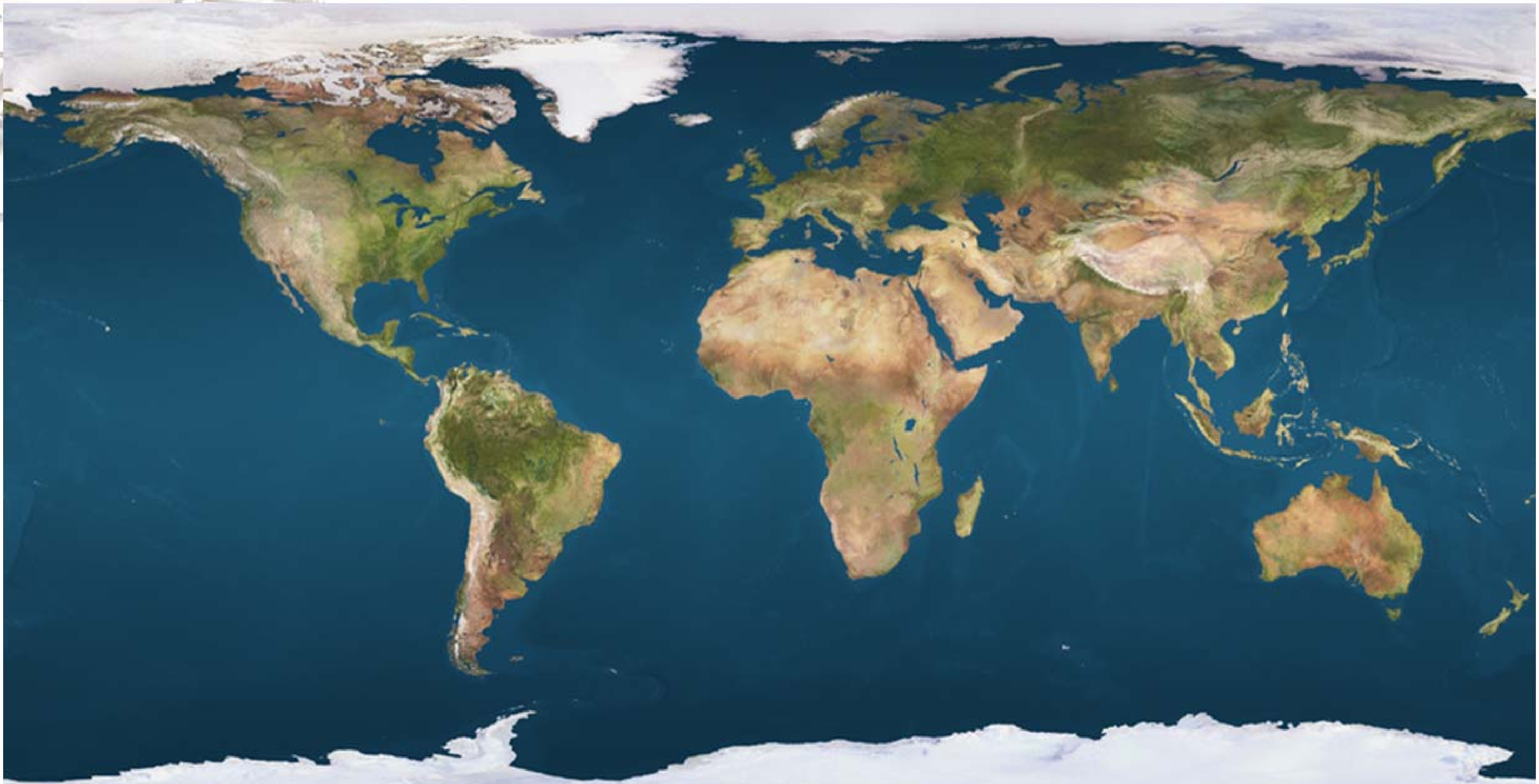
BPM 3: Total = 170 nm, non-rigid motion = 94 nm

BPM 4: Total = 680 nm, non-rigid motion = 620 nm

BPM 5: Total = 130 nm, non-rigid motion = 72 nm

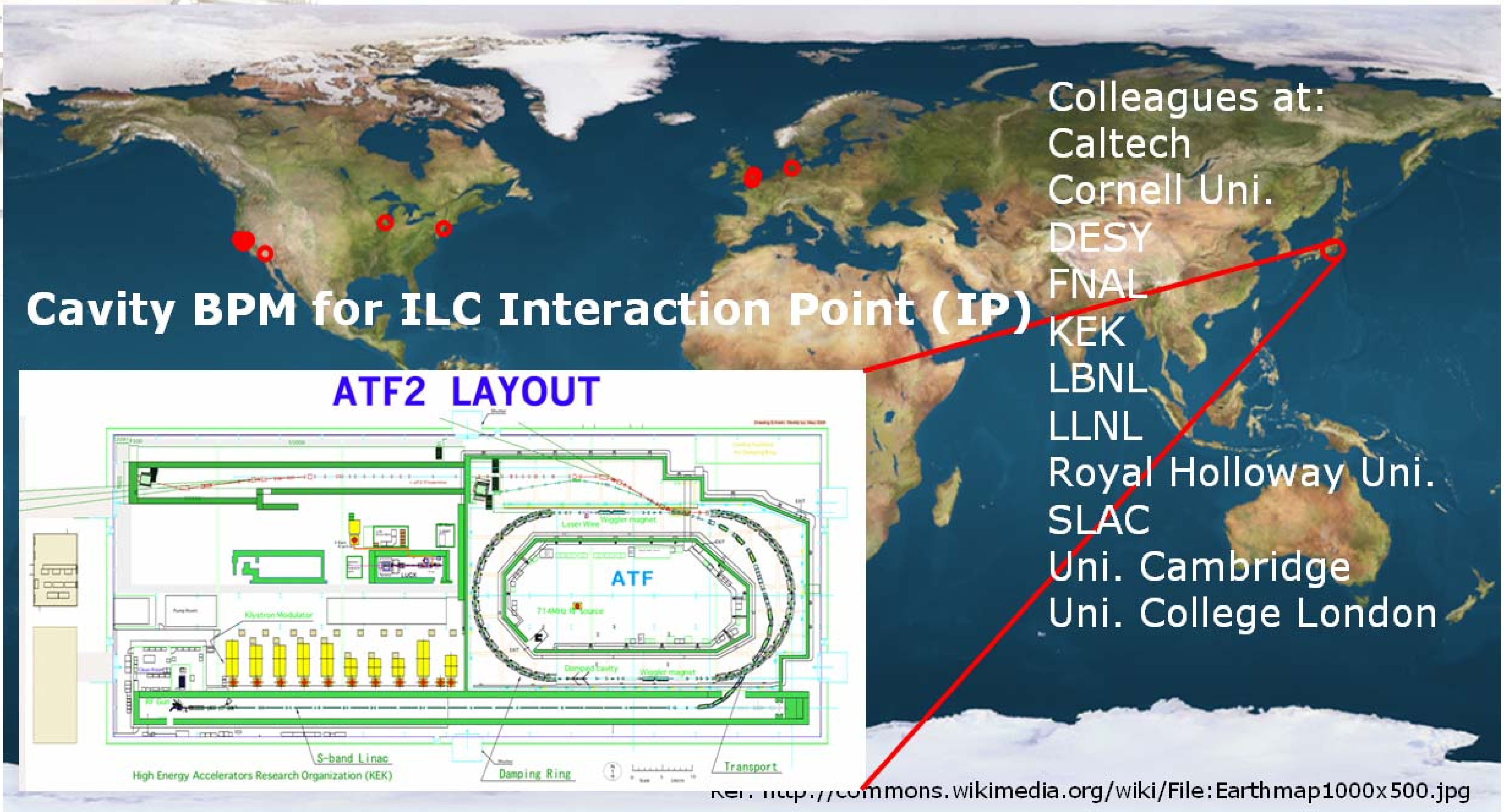
Latency between interferometer and BPM observed therefore vibrations can not be corrected completely, will be improved

Cavity BPM around the World



Ref: http://commons.wikimedia.org/wiki/File:Earthmap1000x500.jpg

Cavity BPM around the World



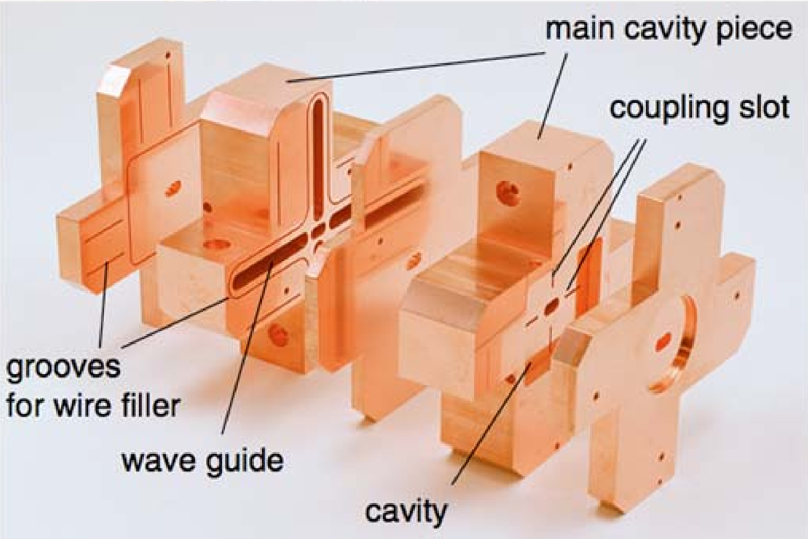
Cavity BPM for ILC Interaction Point (IP)

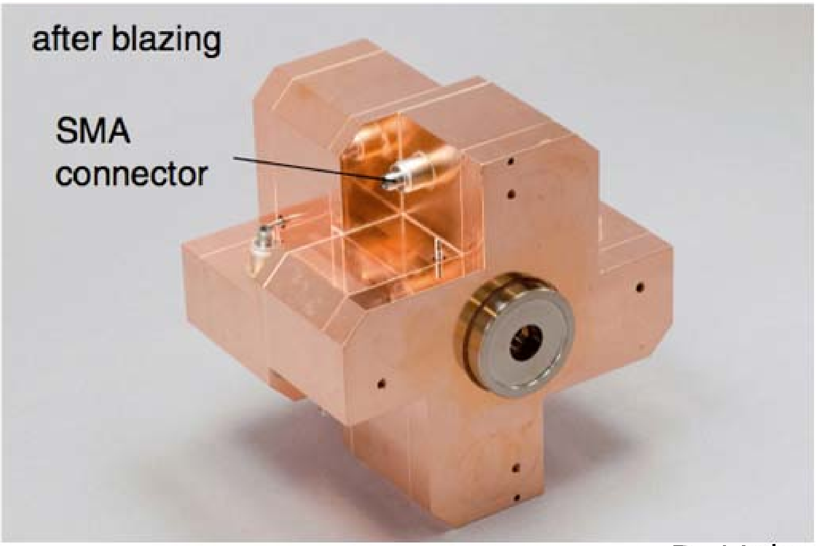
Colleagues at:
Caltech
Cornell Uni.
DESY
FNAL
KEK
LBNL
LLNL
Royal Holloway Uni.
SLAC
Uni. Cambridge
Uni. College London

Ref: http://commons.wikimedia.org/wiki/File:Earthmap1000x500.jpg

Courtesy: Y. Honda

Cavity BPM for ILC IP





- Special BPM to monitor beam stability at the virtual IP of ATF2 final focus test line. Required resolution: 2nm
- Design points
  - ➢ minimize X-Y contamination by a rectangular cavity design.
  - ➢ suppress beam angle effect (special need for the strong focus optics) by a thin cavity gap.
- bench test result
  - ➢ X-port
    f: 5707.4MHz, Q_L: 2182
  - ➢ Y-port
    f: 6420.8MHz, Q_L: 1308

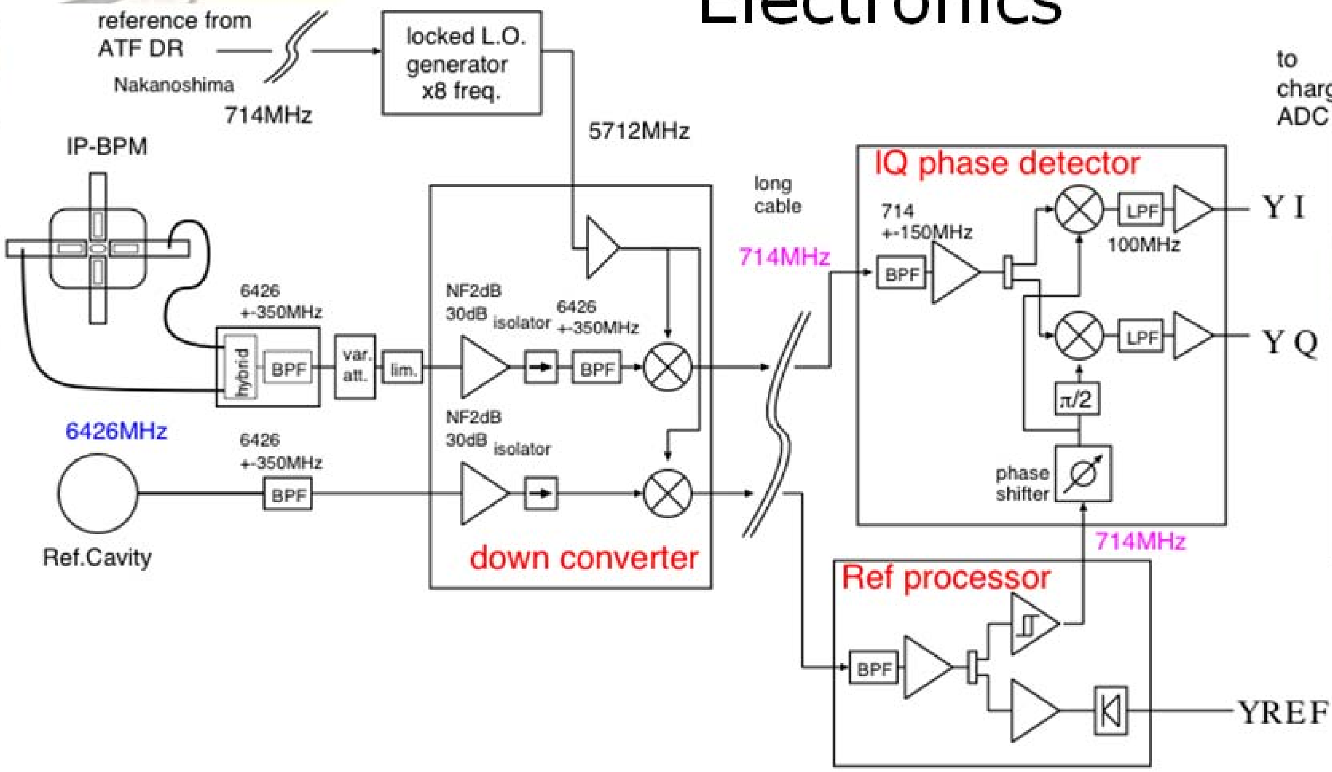
➢ Pipe shape: 6 and 12 mm aperture

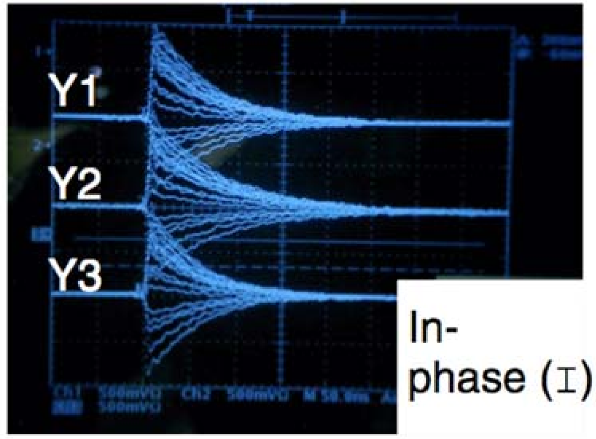
Mounted in beamline without mover on heavy granit table (Δt limit variation 10 mK)

Courtesy: Y. Honda

Cavity BPM for ILC IP

Electronics

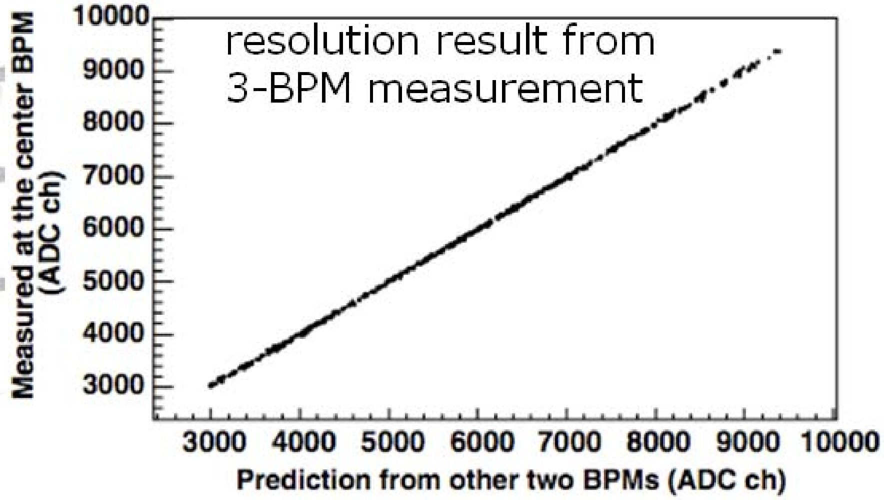


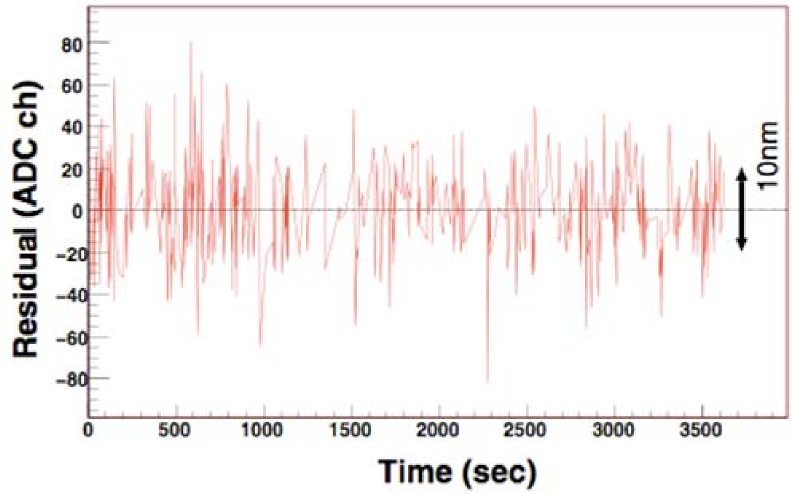


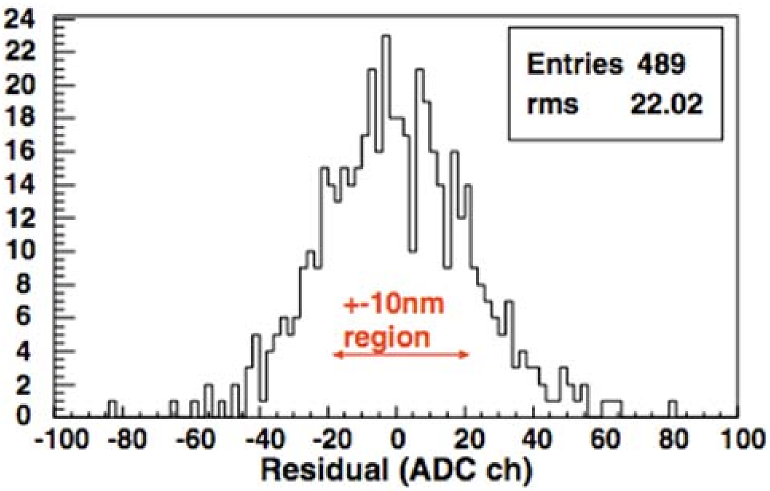
- detection BW: 20MHz (gate width 50nsec)
- noise limit: -95dBm at input of down-converter
- expected signal: -97dBm (1nm position, 1.6nC/bunch)

Courtesy: Y. Honda

Cavity BPM for ILC IP







Measured resolution:
8.72 +- 0.28(stat.) +- 0.35(sys) nm
(at 0.68x10^10 e/bunch)
intrinsic noise of the system was estimated to be 3.8nm
(unknown resolution source: 7.9nm)

Summary

- Influence of monopole mode decreased due to wave guide
- Influence of beam angle and bunch tilt filtered with I-Q demodulator
- Resolution depends on effort for mechanical production, electronics and non-rigid motion compensation
- Best resolution so far 8.72 nm at KEK