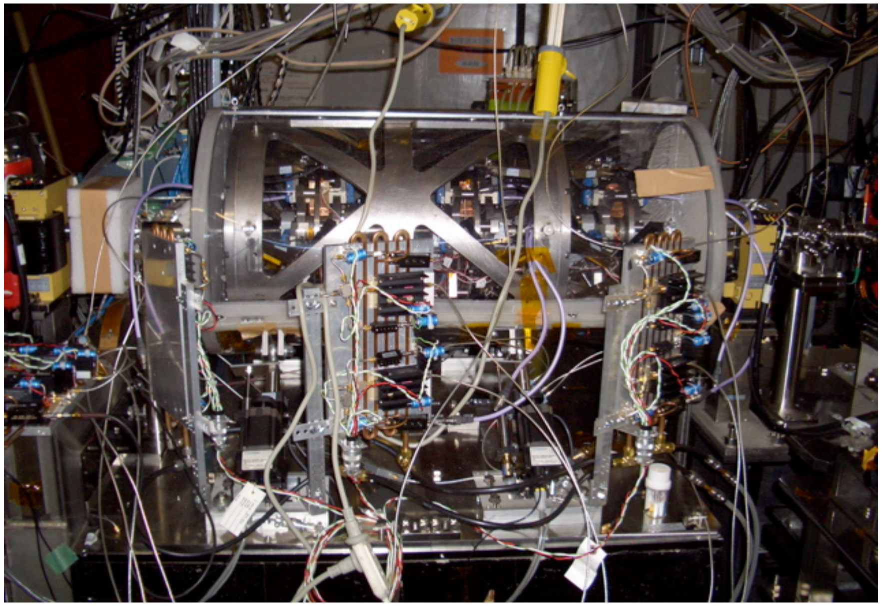
The NanoBPM Project:
Nanometer Resolution Beam Position Monitors for the International Linear Collider



Toyoko Orimoto
Caltech

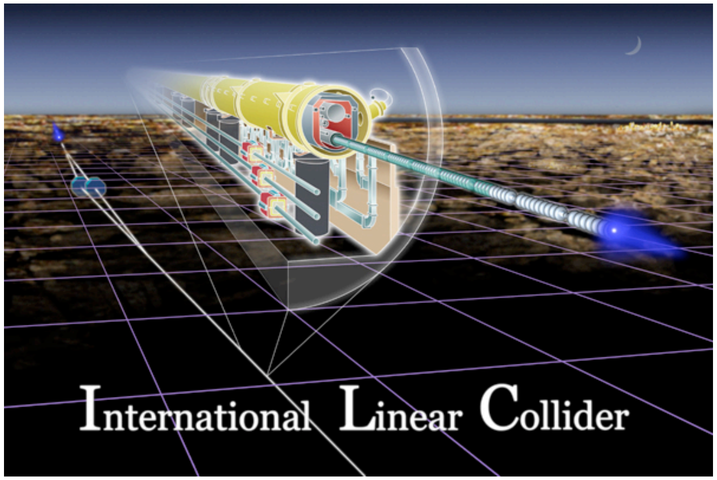
DPF+JPS06, 1 Nov 2006

Overview

1. Nanometer resolution BPMs for the ILC
2. The NanoBPM Collaboration
   - How do cavity BPMs work?
   - Our BPMs and experimental setup
   - Signal processing and analysis
   - Resolution studies
   - Comparison with simulations & limitations
3. Related Activities
4. Summary & Future Plans

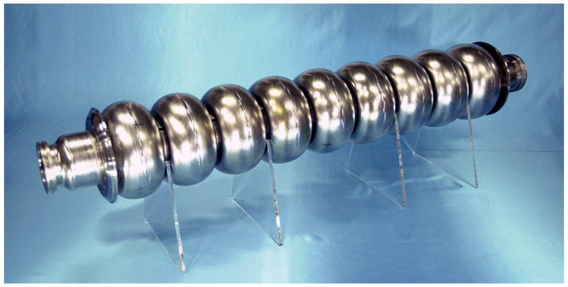
Introduction

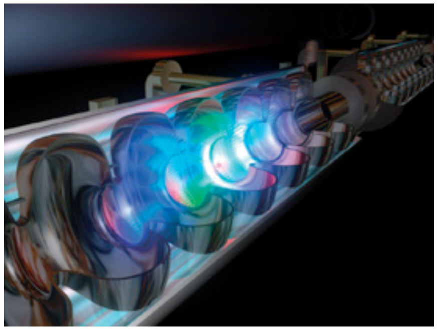
- R&D project for the **International Linear Collider**

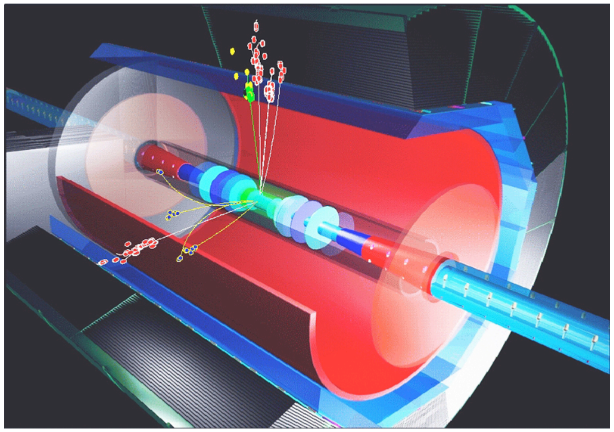


- Collaborators from US (LBNL, LLNL, SLAC, Cornell, Caltech), UK (Cambridge, Oxford, Queen Mary, Royal Holloway, University College London), Japan (KEK)...

- **High resolution BPMs for the ILC**







Why Nanometer Resolution BPMs?

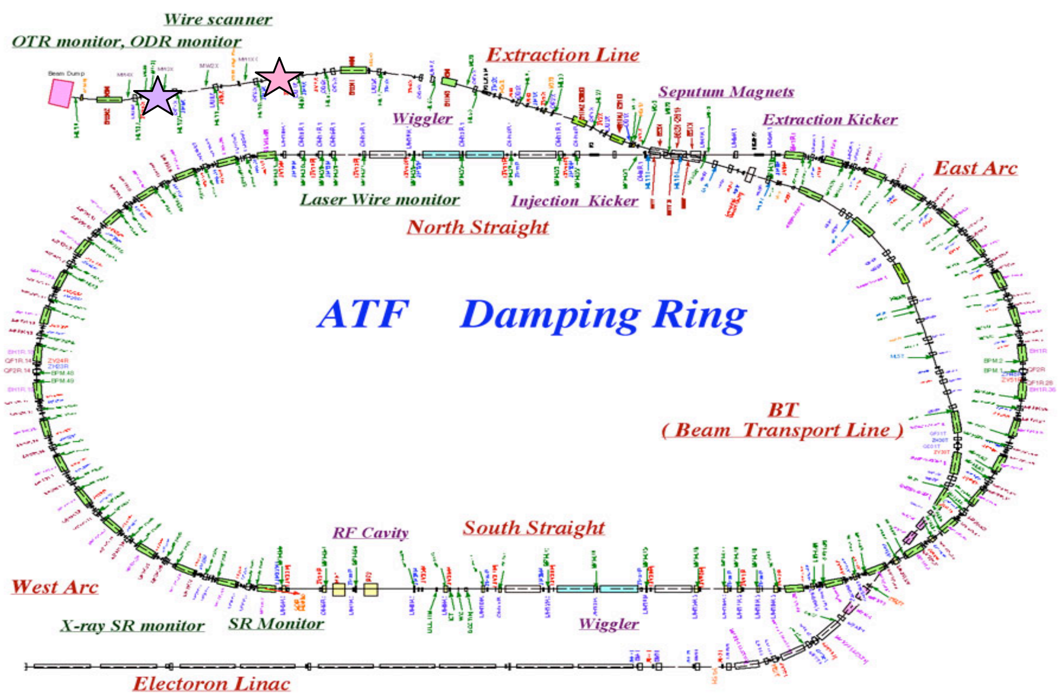
- Beam size at ILC 300 nm (x) by 3 nm (y)
- Focusing magnets near the ILC interaction region must be stabilized wrt one another at the level of a few nanometers
- Beam diagnostics
  - < 100nm for the ILC
  - Near the IP, ~few nm required!
  - **Very high resolution beam position monitors**
- Resolution limited by signal/noise ratio
  - Thermal & electronics noise
  - **Theoretical resolution O(1 nm)**

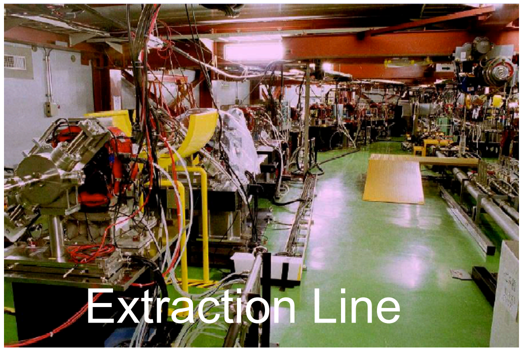
The NanoBPM Collaboration

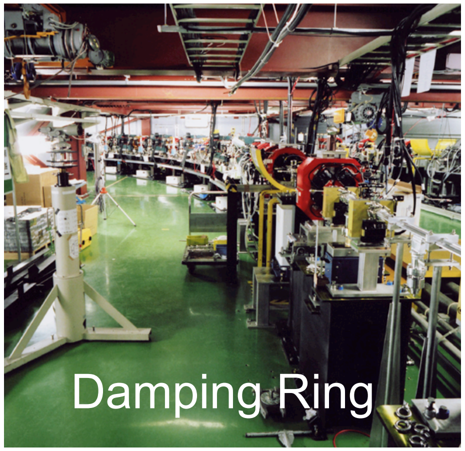
Collaborators from labs all over the world…

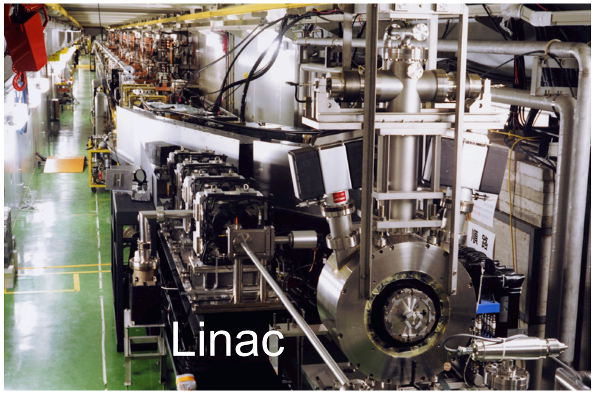
- BPMs were constructed at BINP in Novosibirsk, Russia
- Mechanical support system developed at Livermore
- Electronics and software developed at SLAC
- Online monitoring and analysis by Berkeley
- Simulation, DAQ and data analysis from UK contributors
- Experiments conducted at KEK, Japan

Accelerator Test Facility at KEK





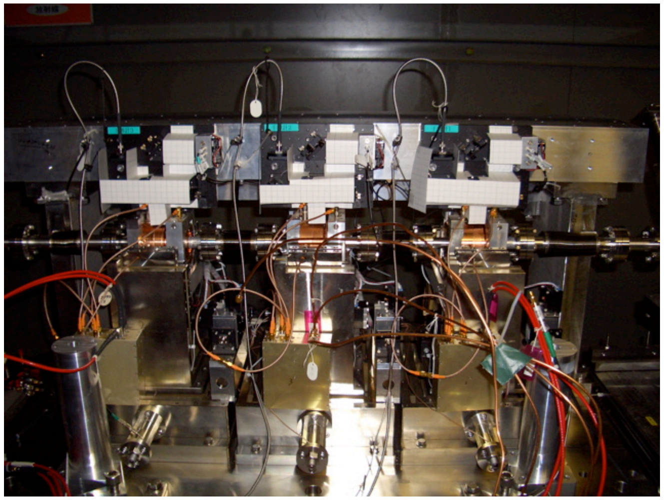




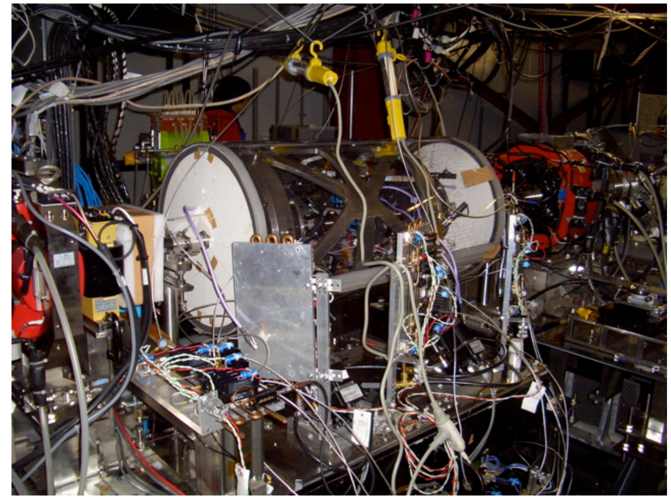
Ultra low emittance beam

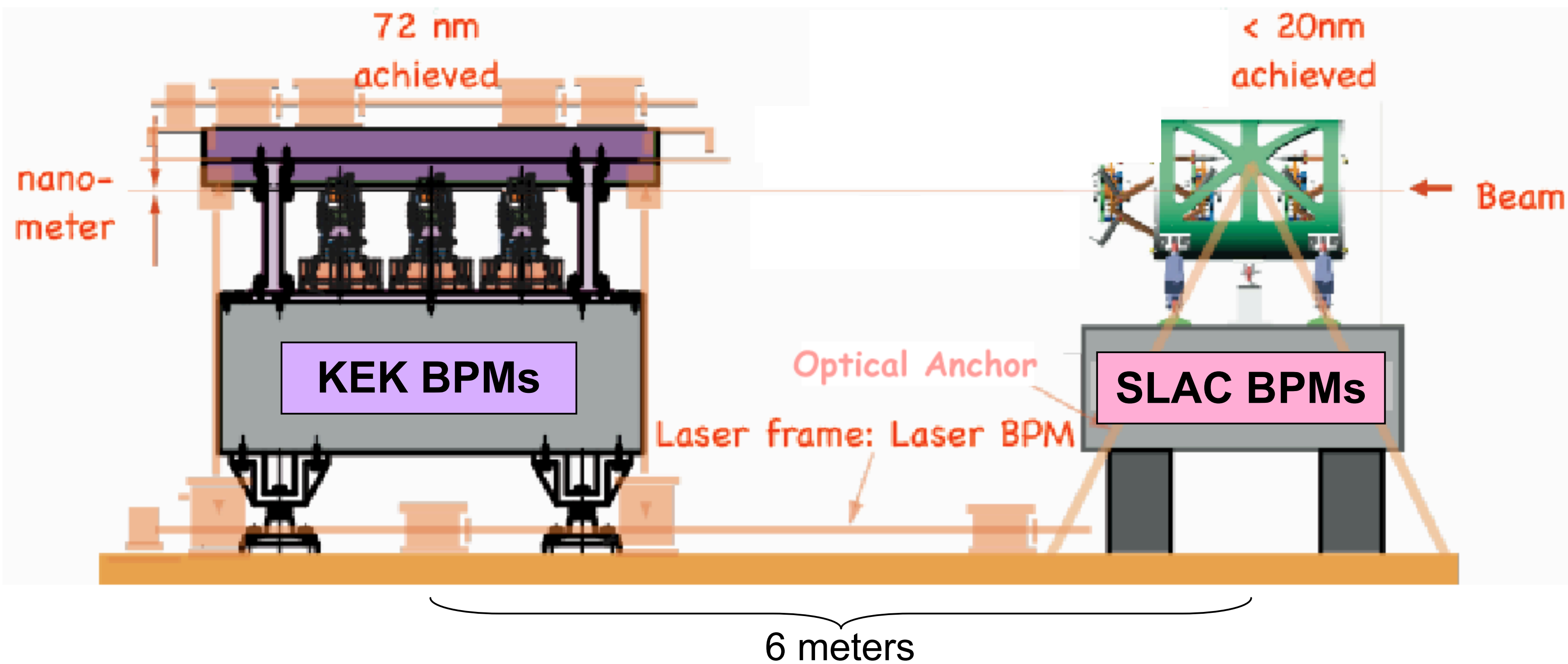
- **Energy: 1.3 GeV**
- **Intensity: 1e10 electrons/bunch**
- **Beam Size: 70µm x 7µm RMS**

SLAC-BINP & KEK BPMs at ATF

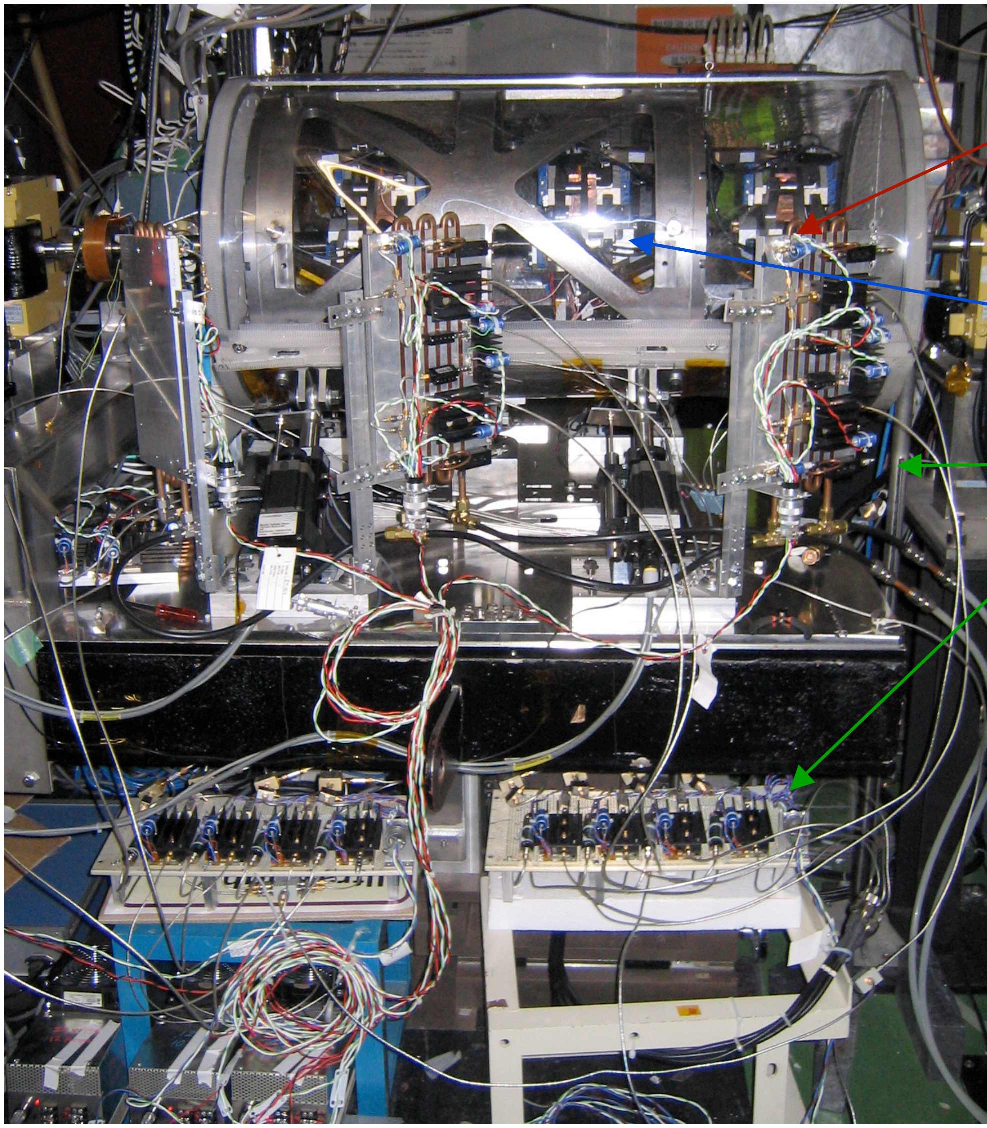


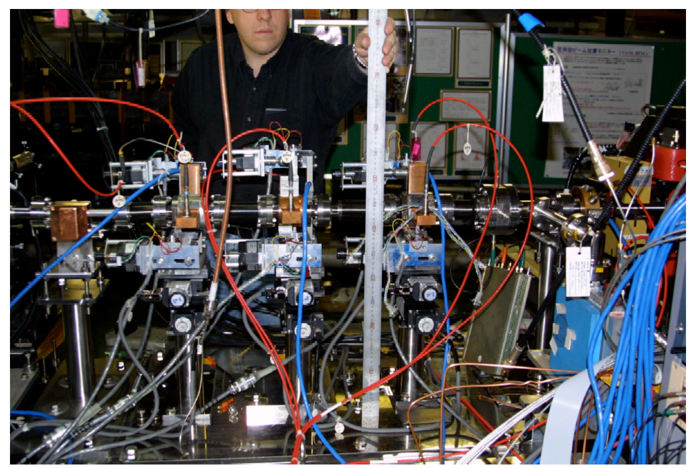
Two BPM experiments at ATF extraction line



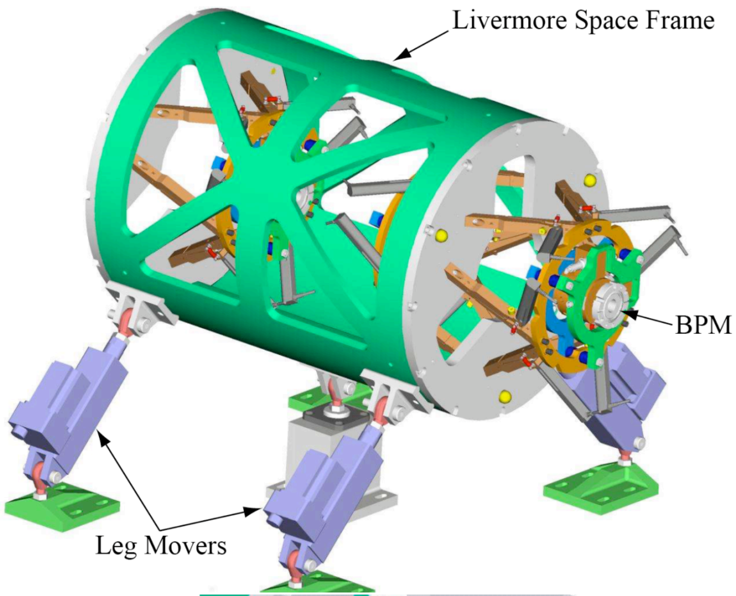


NanoBPM Experiment

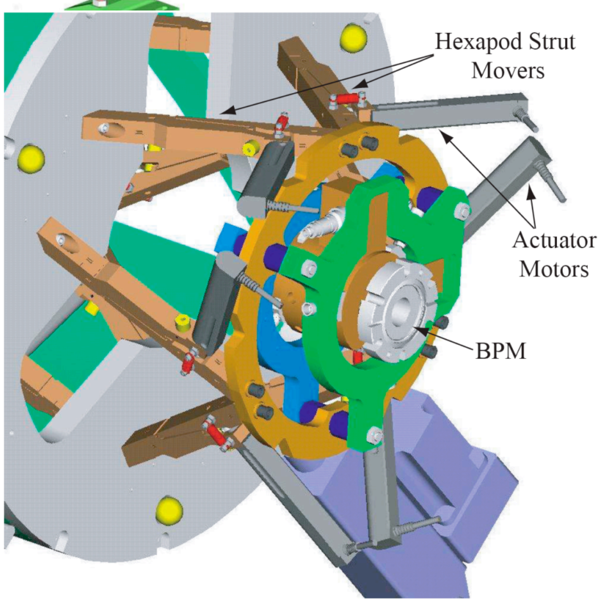


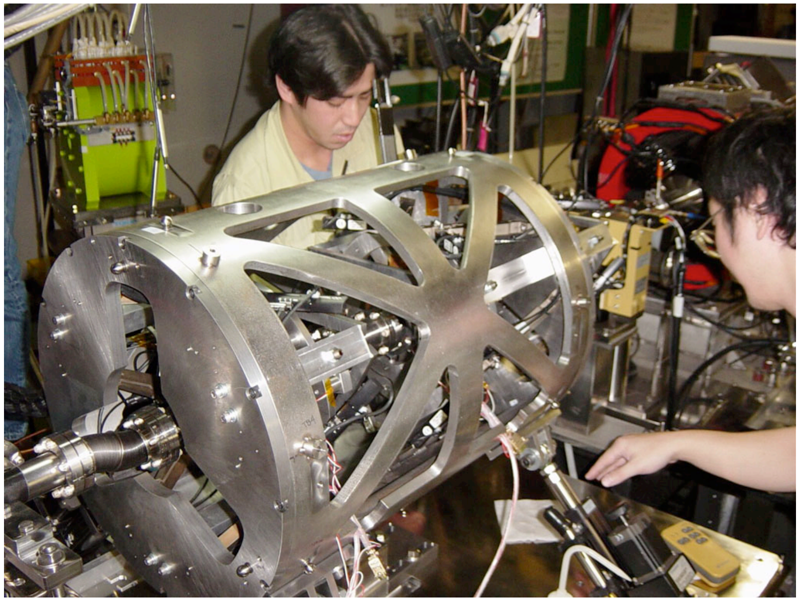


Stabilization-Mover Structure (LLNL)



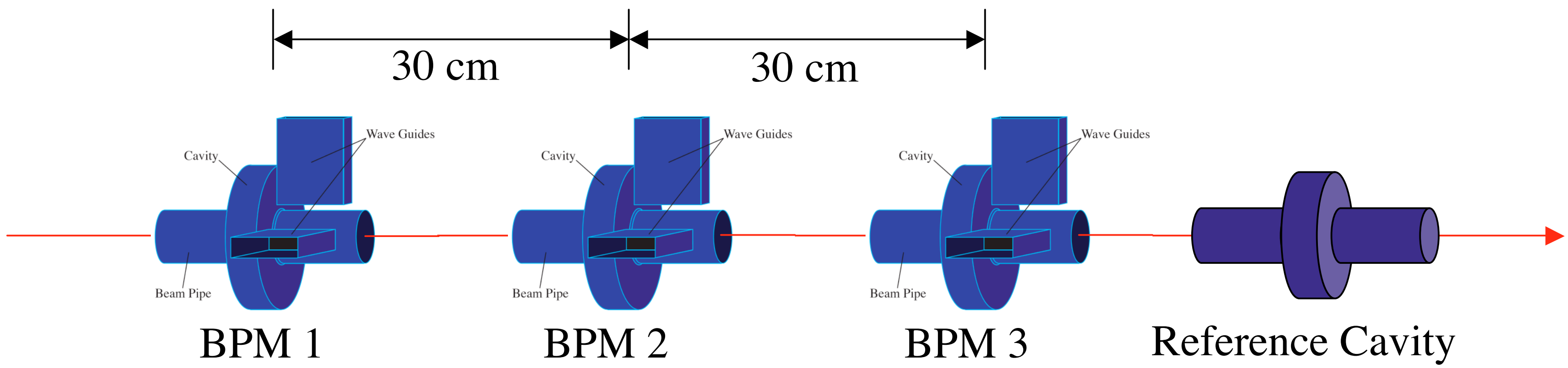
- BPMs mounted on rigid space frame with *x*, *y*, *x'*, *y'* movers
  - Entire frame can also move in *x*, *y*, *x'*, *y'*
  - Aligning BPMs with beam
  - Calibration
- Developed at Livermore (LLNL)

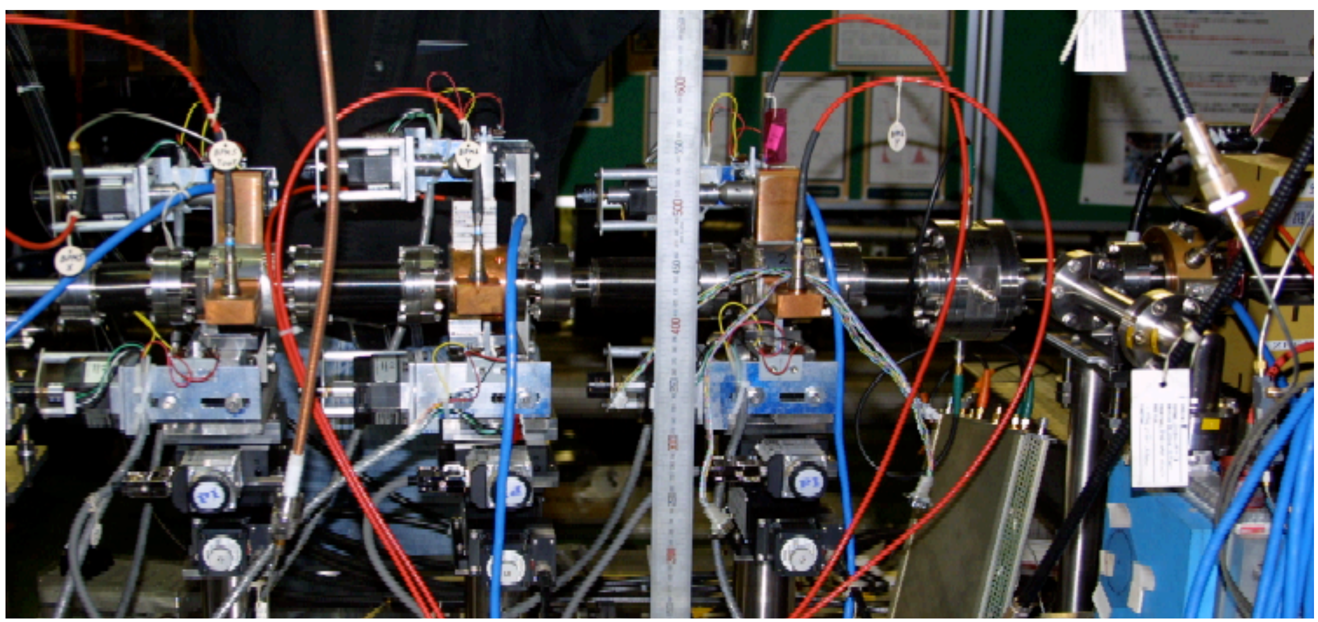




BINP BPMs

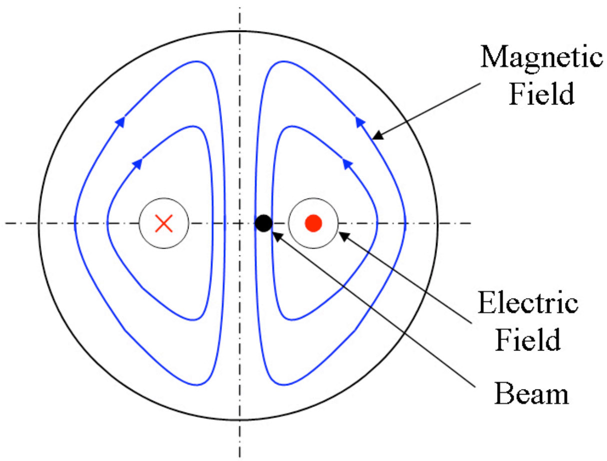
- 3 position cavity BPMs with dipole mode couplers
- 1 reference cavity for phase and charge normalization

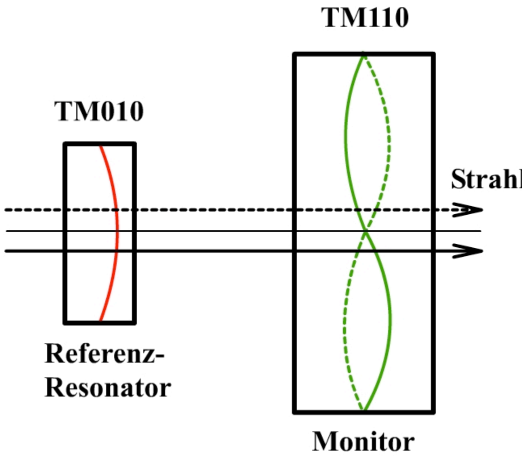




How Do Cavity BPMs work?

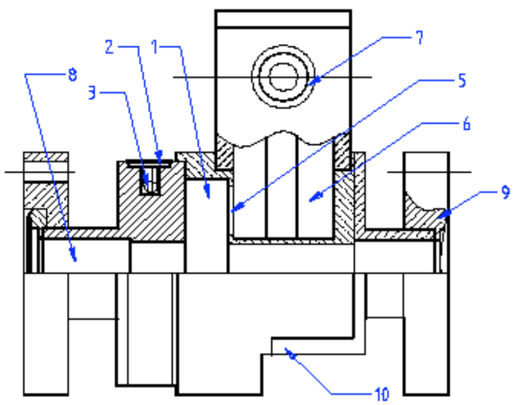
- Beam induces **displacement-dependent** current inside cavity
- A bunch moving through the cavity excites EM standing waves
- Excitation dependent on beam offset
- Dipole excitation mode (TM110) is used because it has strongest dependence on position
- Radio frequency signal read out via waveguide

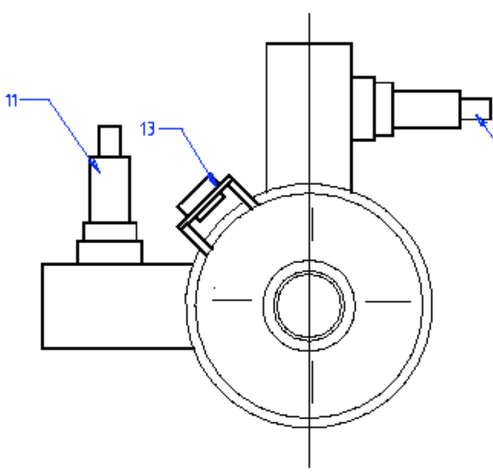




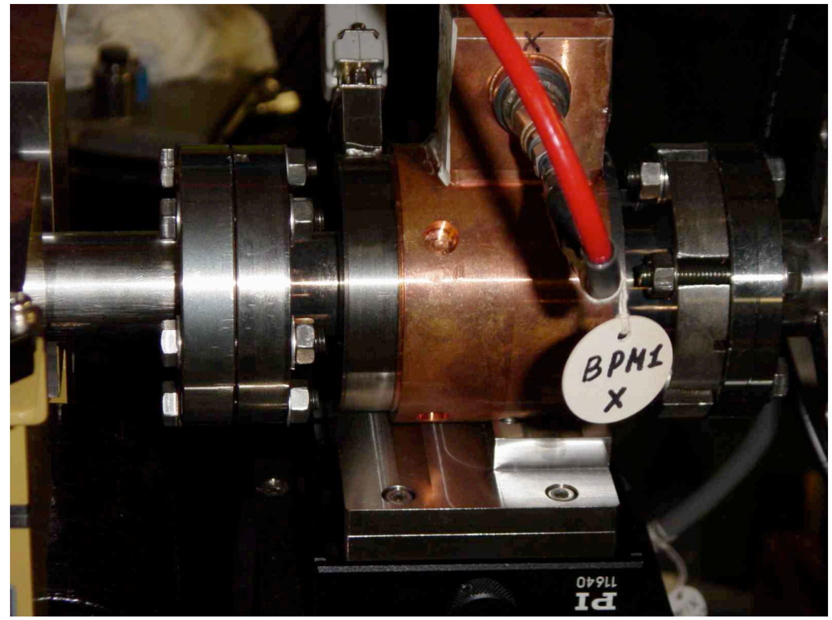
BINP Cavity BPMs

- Made at BINP (Vogel, et al.)
- Copper cavities
- Design freq 6426 MHz (C-Band)
- Dipole-mode selective couplers

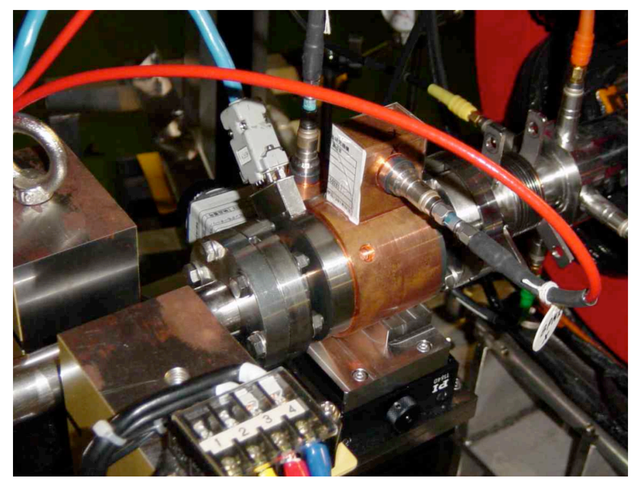




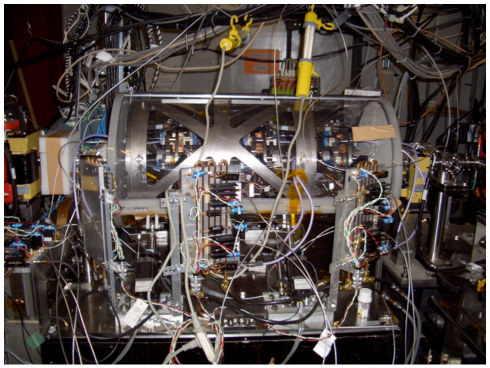
1.- Cavity sensor .
2- Heater.
3 – Temperature sensor.
5 – Coupling slot.
6 – Output waveguide.
7 – Output feedthrough.
8 – Beam pipe.
9 – Vacuum flange.
10 – Support plate.
11 – Y position output.
12 - X position output.
13 – Heater control connector.

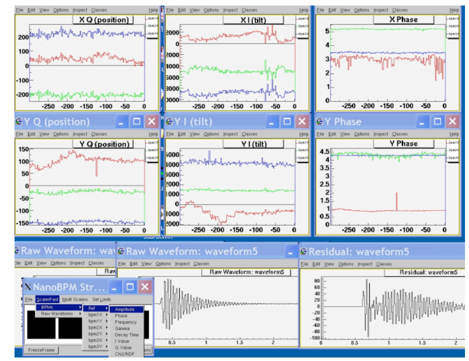


Length of cavity	12.00 mm
Radius of cavity	27.06 mm
Radius of beampipe	9.00 mm
Coupling slot dimensions	1.50 mm × 12.00 mm



Beam to Analysis





BPMs → Electronics → DAQ → Online Monitoring

EPICS

ROOT

Offline Analysis

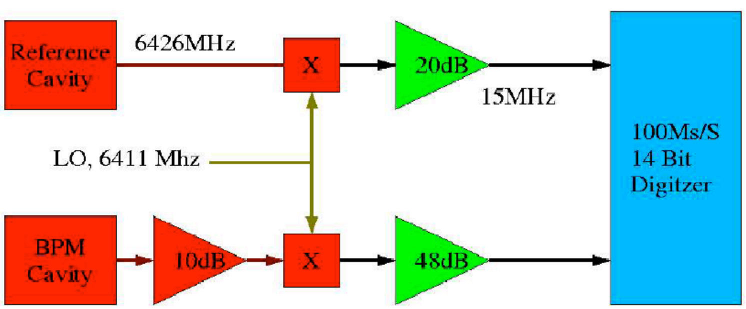
calibration

resolution studies

stability

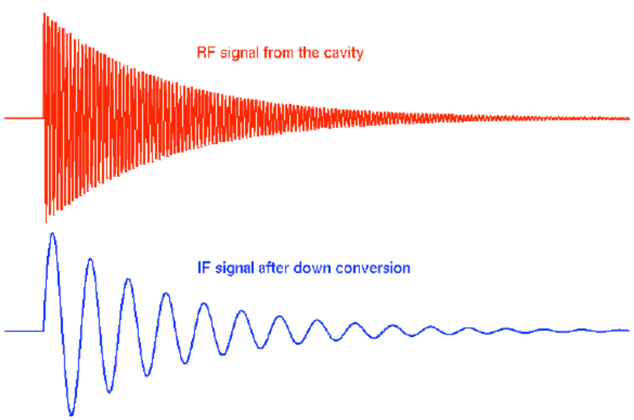
noise studies

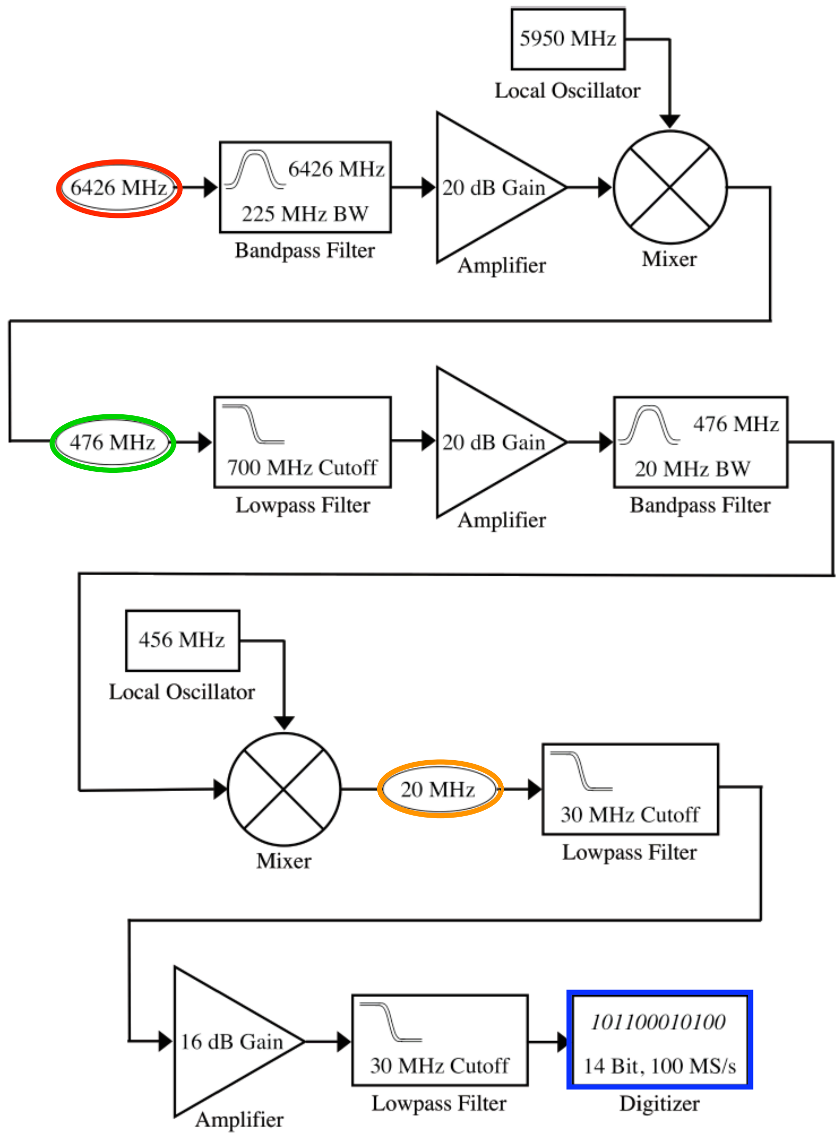
ROOT, MatLab



Signal Processing – Electronics (SLAC)

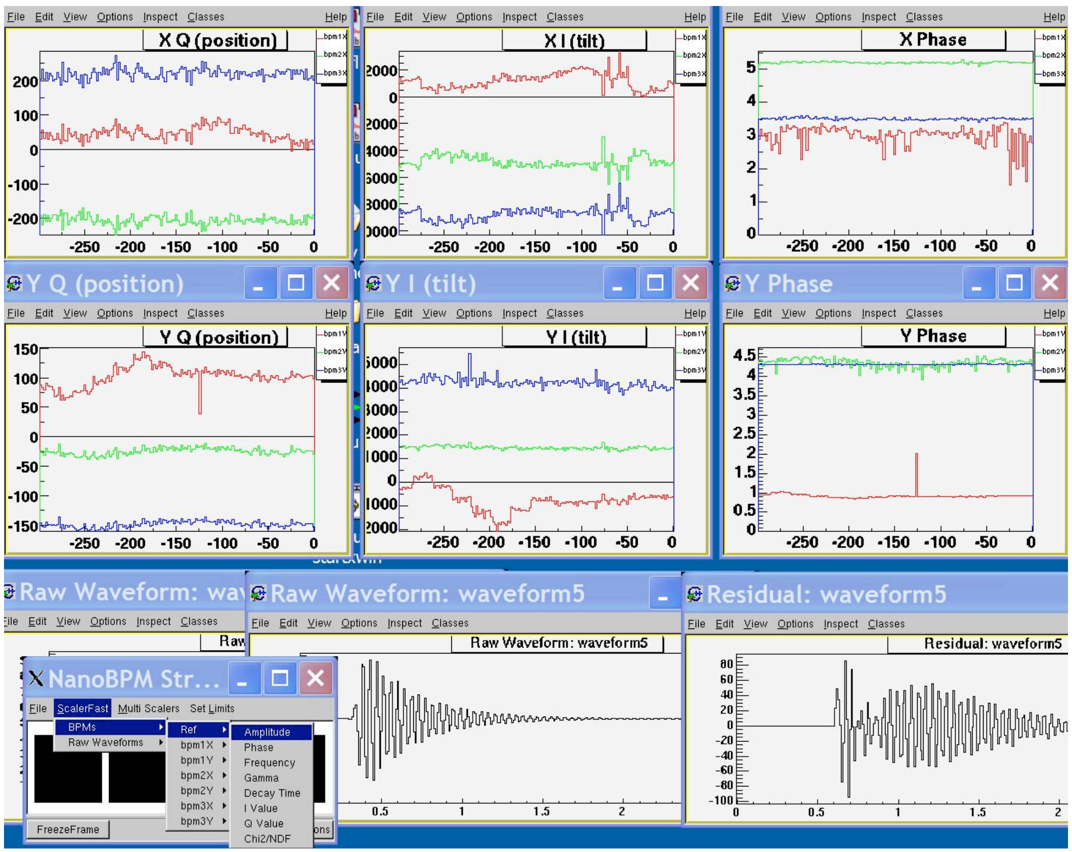
- Cavity design 6426MHz
- Two stage mix down:
  - First IF 476 MHz
  - Second IF 20 MHz
- Bandpass filters to remove out of band noise
- Lowpass filters to remove residual LO
- Digitize 14 bit at 100 MSamples/sec





Online Monitoring

- ROOT based strip charts (LBNL)

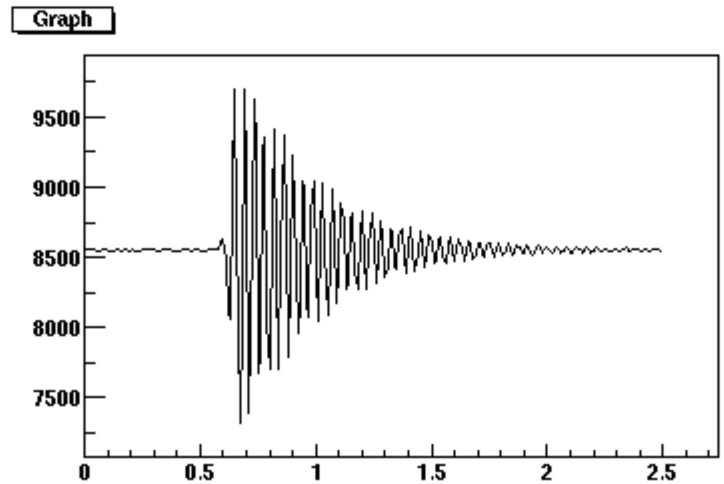


- Reads in data via EPICS and processes signals to give us bunch position and tilt
- One of our main diagnostic/trouble-shooting tools

Cavity BPM Signals

- Decaying sinusoids…like a damped harmonic oscillator

$$\hat{V}(t) = A\, e^{j(\omega t+\phi)}\, e^{-\Gamma t}$$
$$= c_x x + j\, c_{x'} x'$$
$$\sim Q + j\, I$$
$\sim$ Position & Tilt



- *I & Q* normalized by reference cavity *A* and φ

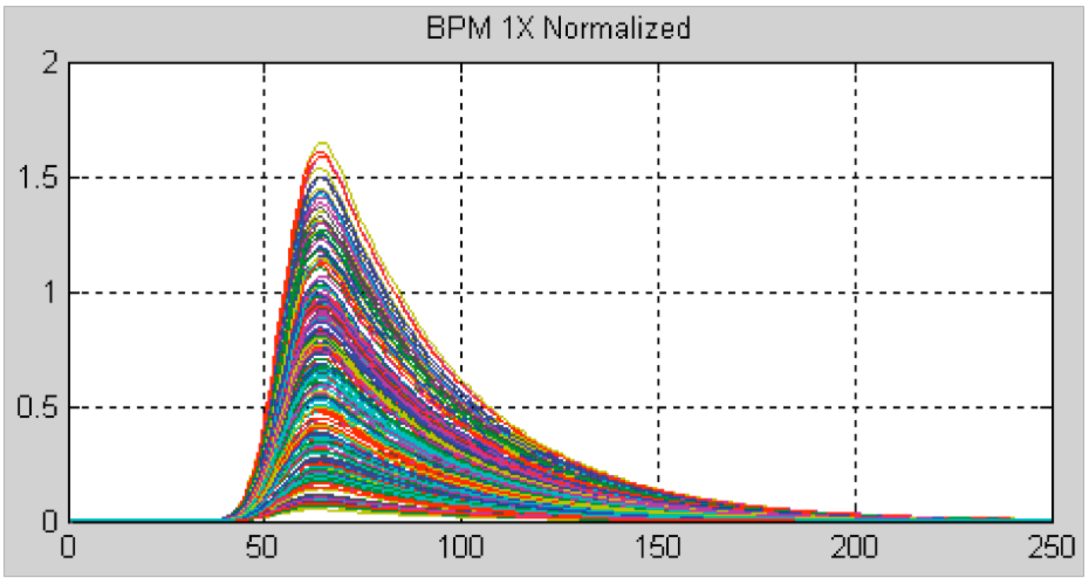
$$I = \frac{A}{A_{\mathrm{Ref}}}\cos(\varphi - \varphi_{\mathrm{Ref}}) \qquad Q = \frac{A}{A_{\mathrm{Ref}}}\sin(\varphi - \varphi_{\mathrm{Ref}})$$

- Amplitude and phase info are extracted from signals
- Then, calibration to get real positions and tilts

Waveform Processing

- Fit Method
  - Fit waveform to exponentially decaying sine wave
  - $V(t) = A \sin(\omega t+\phi)\, e^{-\Gamma t}$
- Digital Down Conversion
  - Multiply by complex LO and then apply a low pass filter in software

Demodulated waveforms from DDC



Sample

Calibration

- Must convert basis set from I & Qs and calibrate scale to have positions and tilts in μm and μrad

$$\begin{pmatrix} P \\ T \end{pmatrix} = \begin{pmatrix} \cos\Theta & \sin\Theta \\ -\sin\Theta & \cos\Theta \end{pmatrix} \begin{pmatrix} I \\ Q \end{pmatrix}$$

- Calibration implemented to eliminate effects of beam jitter, using the fact that I & Q for one of the BPMs is related in a linear way to the I & Qs in the other two BPMs:

$$I_i = a_{ij} I_j + b_{ij} Q_j + a_{ik} I_k + b_{ik} Q_k + c_i$$
$$Q_i = f_{ij} I_j + g_{ij} Q_j + f_{ik} I_k + g_{ik} Q_k + h_i$$

- Use many extractions to get a set of simultaneous equations to be solved, using singular value decomposition (SVD)

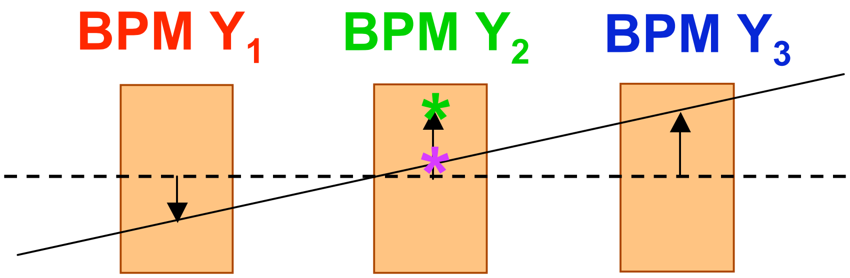
- Then by moving the BPMs one at a time, we can get Θ

$$\Delta I_i = I_i - (a_{ij} I_j + b_{ij} Q_j + a_{ik} I_k + b_{ik} Q_k + c_i)$$
$$\Delta Q_i = Q_i - (f_{ij} I_j + g_{ij} Q_{lj} + f_{ik} I_k + g_{ik} Q_k + h_i)$$

$$\Delta Q_i = A_i \Delta I_i + B_i$$
$$\tan\Theta = A_i$$

Resolution Studies

- **Residual** = Difference between position read from the middle BPM and the extrapolation from outer 2 BPMs = $y_2 - k(y_3 - y_1)$



- **Resolution** ~ RMS of the distribution of the residual

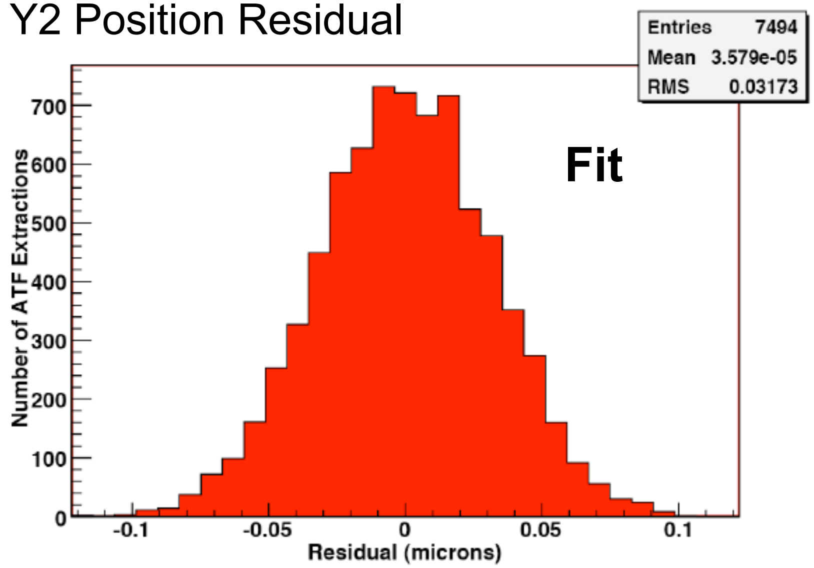
- **Regression** against other variables

$$\delta y_i = y_i - (a_i + b_{ij}x_j + c_{ij}y_j + b_{ik}x_k + c_{ik}y_k + \cdots)$$

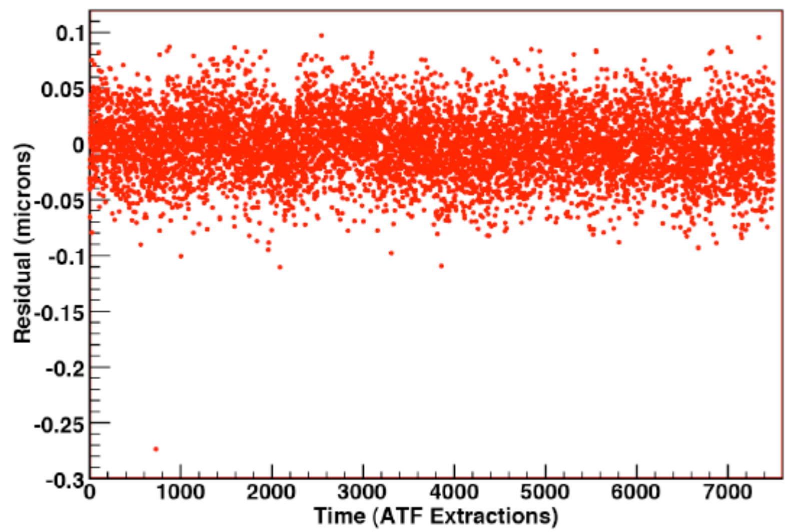
Can use multiple ATF extractions with SVD to get residual, similarly to what is done for calibration

Resolution (Results from 2005)

Y2 Position Residual



Y2 Position Residual vs Time

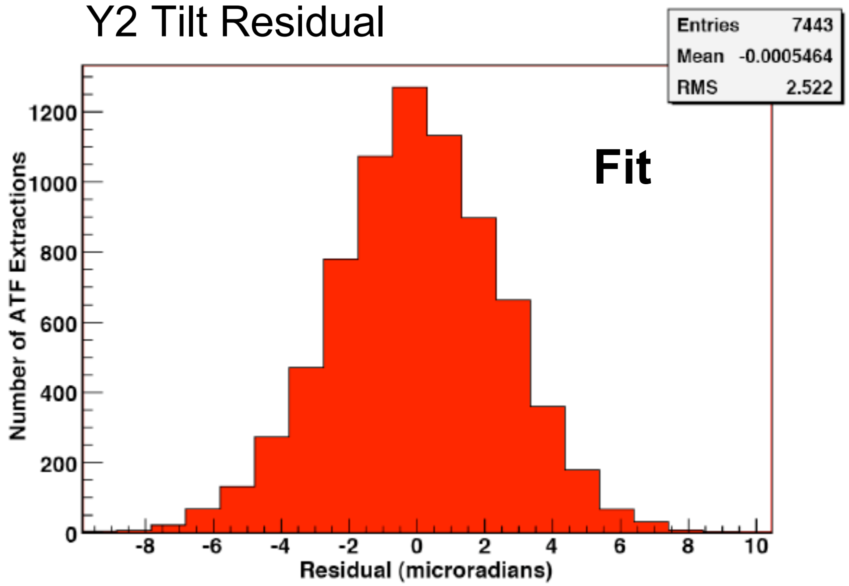


11 March 2005	Position Resolution
Fit	24 nm
DDC	38 nm

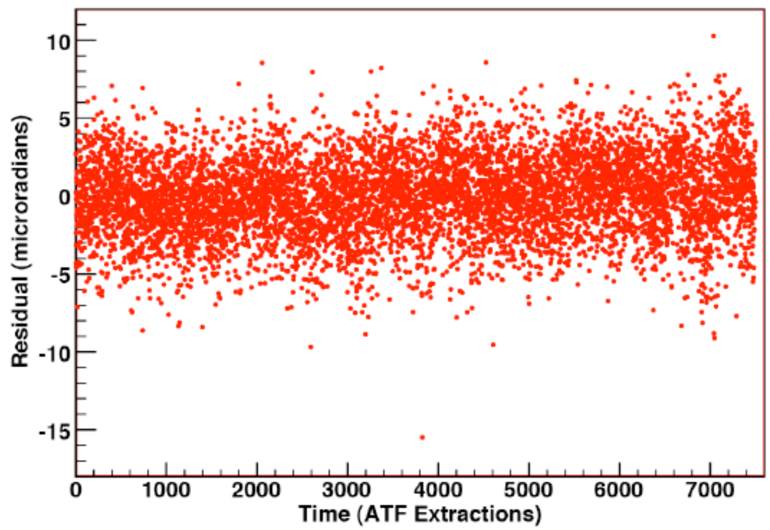
~7500 events

Tilt Resolution (Results from 2005)

Y2 Tilt Residual



Y2 Tilt Residual vs Time

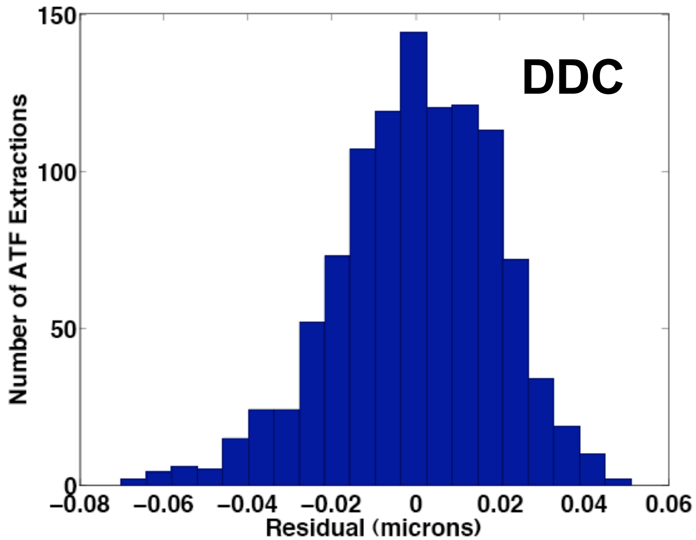


11 March 2005	Tilt Resolution
Fit	2.5 urad
DDC	3.8 urad

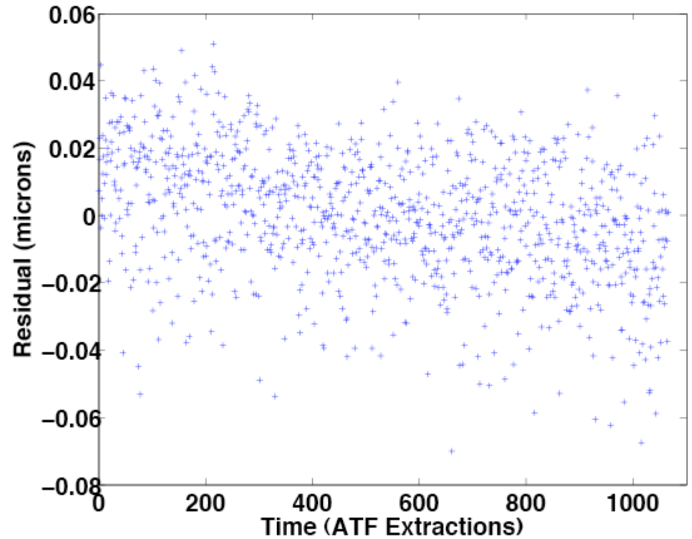
~7500 events

Resolution (Results from 2006)

Y2 Position Residual



Y2 Position Residual vs Time



12 April 2006	Position Resolution
Fit	18 nm
DDC	16 nm

~1100 events

12 April 2006	Tilt Resolution
Fit	2.0 urad
DDC	3.9 urad

~1100 events

Simulation

- Studies with GdfidL
- Comparison of values from simulation and values using measured inputs

Theoretical resolution
Estimated from simulation
1.8nm

Channel	Sim.	$1x$	$1y$	$2x$	$2y$	$3x$	$3y$
W_{norm} ($\times 10^8$ J/C^2/mm^2)	3.6	2.8 ± 0.2	2.7 ± 1.0	3.6 ± 0.2	6.2 ± 0.5	3.7 ± 0.2	4.4 ± 0.4
Decay time τ (ns)	152	167.1 ± 0.6	133.1 ± 25.3	163.7 ± 0.5	153.5 ± 13.7	153.1 ± 0.9	140.1 ± 2.2
P_{out} for 10^{10} e^- at 1 nm (dBm)	-115.2	-113.6 ± 0.2	-112.9 ± 2.7	-112.5 ± 0.2	-109.8 ± 0.9	-112.1 ± 0.2	-110.9 ± 0.4
Sensitivity for 10^{10} e^- (μV/nm)	0.55	0.47 ± 0.01	0.51 ± 0.15	0.53 ± 0.01	0.72 ± 0.07	0.56 ± 0.02	0.63 ± 0.03
Gain (dB)	39.0	43.7 ± 0.1	44.1 ± 0.1	43.9 ± 0.1	43.4 ± 0.1	44.0 ± 0.1	45.8 ± 0.2
Signal for 10^{10} e^- (ADC Counts/nm)	0.40	0.59 ± 0.02	0.67 ± 0.23	0.68 ± 0.02	0.87 ± 0.09	0.73 ± 0.02	1.01 ± 0.05
P_{Thermal}, $T = 20°$ C, $B = 20$ MHz (dBm)	-100.9	—					
Noise figure (dB)	3.1	—					
Noise (ADC Counts)	2.1	4.1 ± 1.3	4.2 ± 1.3	4.4 ± 1.4	4.0 ± 1.2	4.3 ± 1.3	4.2 ± 1.3
Expected Resolution (nm)	5.2	6.9 ± 2.3	6.4 ± 3.2	6.5 ± 2.1	4.6 ± 1.5	5.9 ± 1.8	4.2 ± 1.3
Signal Bandwidth (MHz)	1.02	1.60 ± 0.02	1.59 ± 0.2	1.21 ± 0.09	1.49 ± 0.16	1.59 ± 0.05	1.54 ± 0.19
Expected noise after DDC (ADC Counts)	0.7	1.4 ± 0.5	1.5 ± 0.4	1.6 ± 0.5	1.4 ± 0.4	1.5 ± 0.5	1.5 ± 0.5
Expected Resolution after DDC (nm)	1.8	2.5 ± 0.8	2.2 ± 1.1	2.3 ± 0.7	1.6 ± 0.5	2.1 ± 0.7	1.5 ± 0.5

Limits on Resolution

- Studied limitations with simulation by:
  - Taking real data and replacing measured position with predicted position (from regression coefficients), and computing amplitude and phase
  - Then decaying sine waves generated using these amplitudes and phases
  - Amplitude and phase noise added to the waveforms

Limits on Resolution

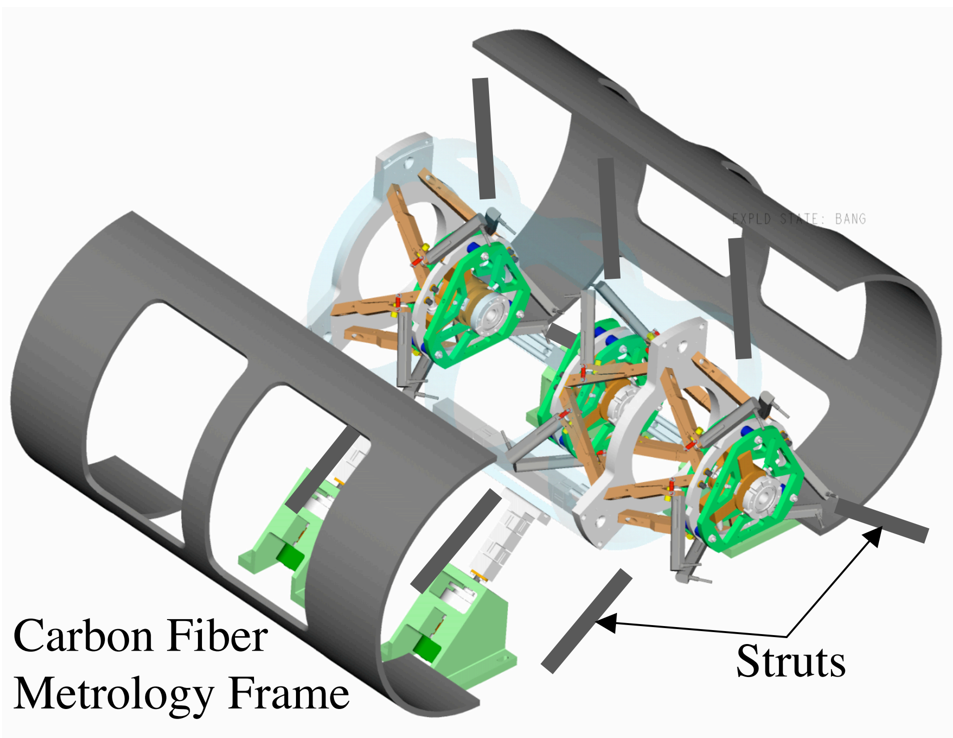
- Resolution studies from simulation, to study effect of amplitude and phase noise

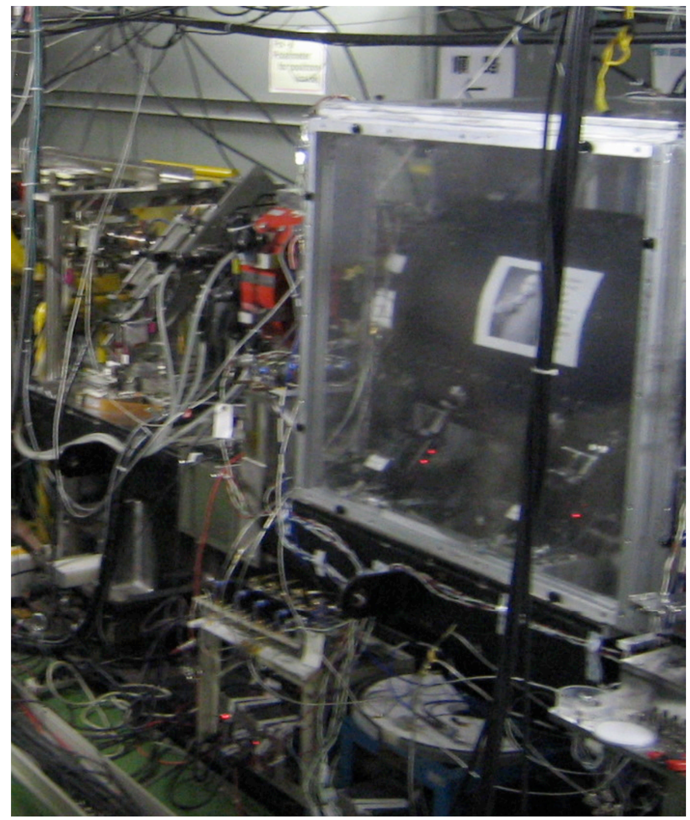
	Resolution (nm)	
Source	11 March 05	12 April 06
Amplitude Noise Only	9.3	2.8
Phase Noise Only	4.2	1.3
Amplitude + Phase Noise	10.0	2.9
Best Measurement	24	16
Contribution from other	22	16

- Improvements in 2006
- Theoretical expectation of 1.8 nm compares well with values with resolution from amplitude and phase noise only

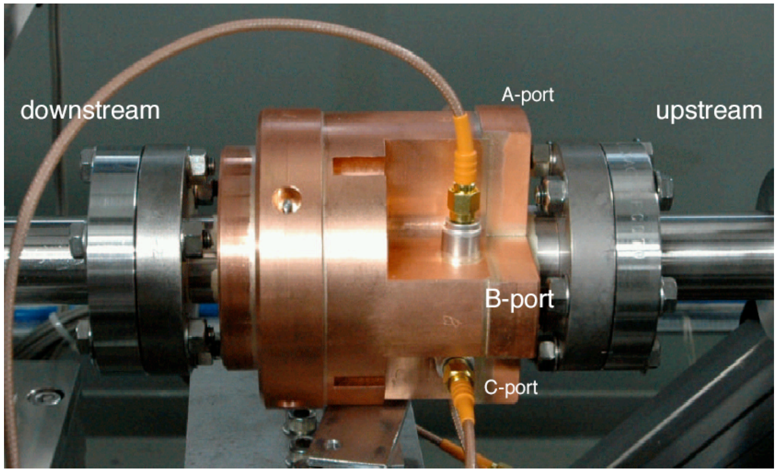
Carbon Reference Frame

- Carbon fiber reference frame with zero coefficient of thermal expansion (LLNL)
  - Laser driven system that measures BPM position wrt reference with great precision
  - Radial struts reach from the metrology frame through the space frame

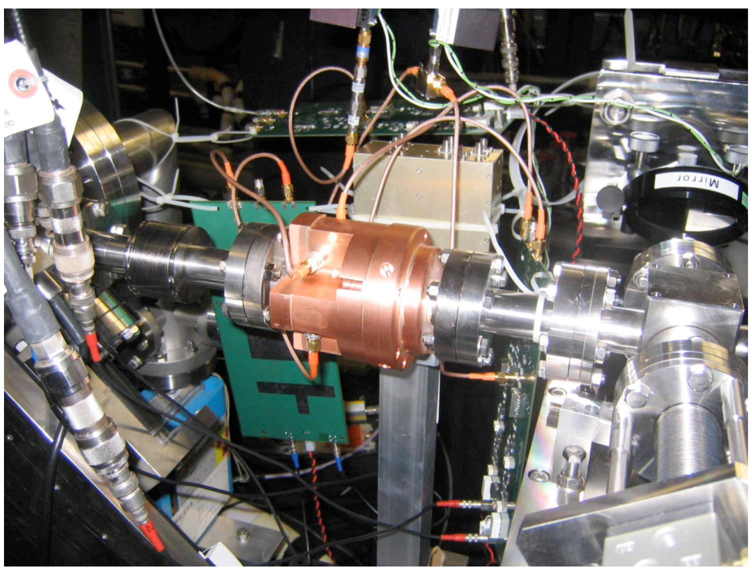


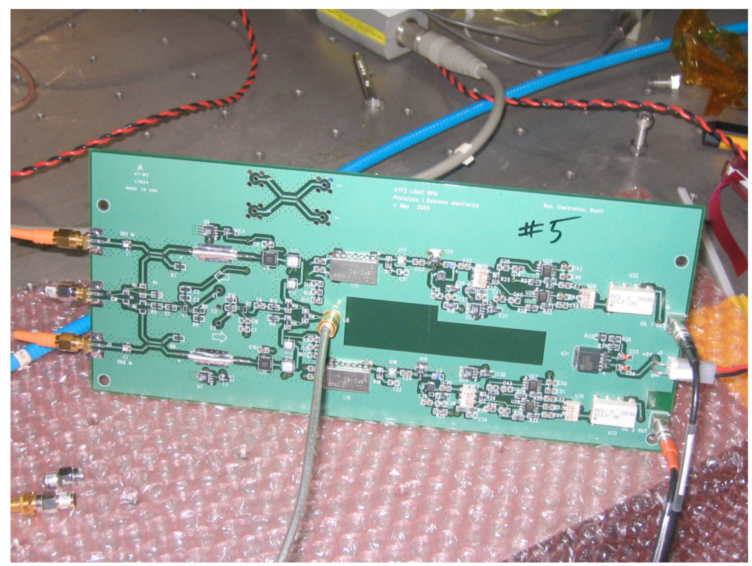


ATF2 BPMs

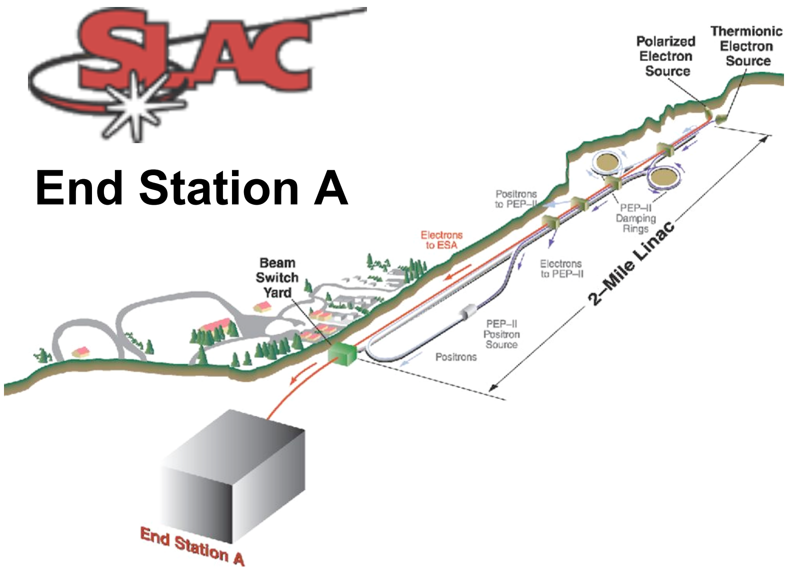


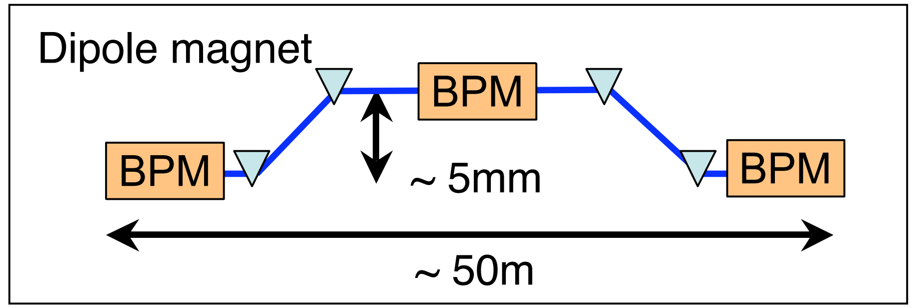
- BPMs for upcoming ATF2
- Designed by NanoBPM colleagues (Y.Honda, A.Liapine)
- Built by Pohang Acc. Lab, Korea
- Electronics developed by SLAC
- Prototype installed in extrac. line between KEK and BINP BPMs



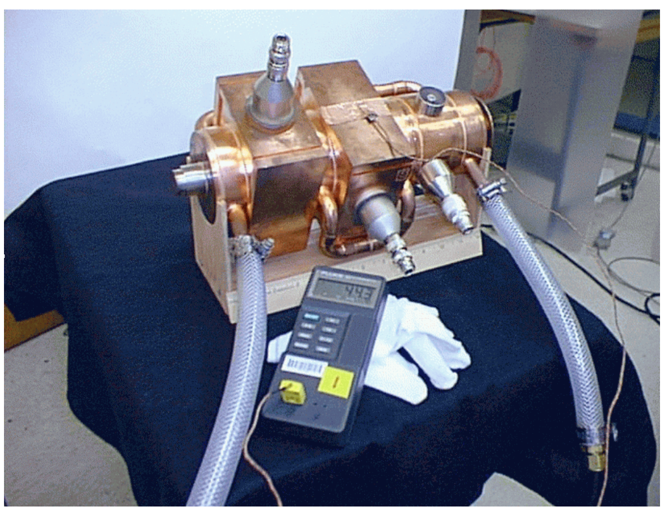


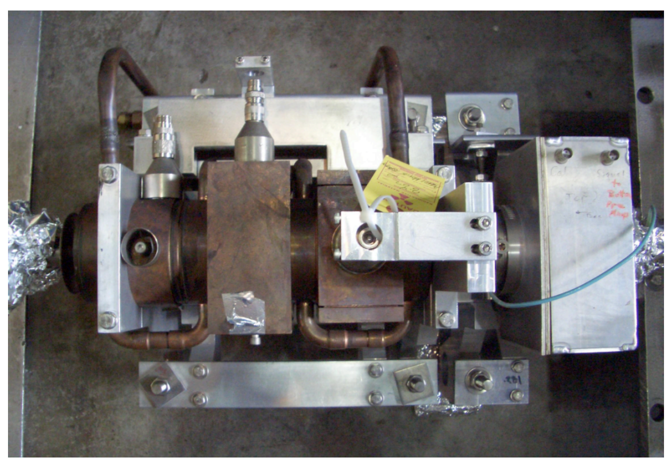
Energy Spectrometer at SLAC ESA

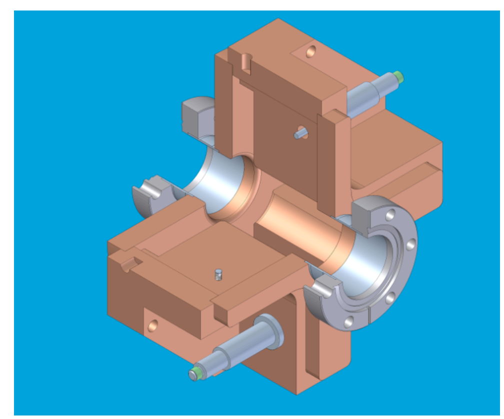




- SLAC Linac BPMs
- ILC Linac BPMs SLAC
- New BPMs designed by UCL





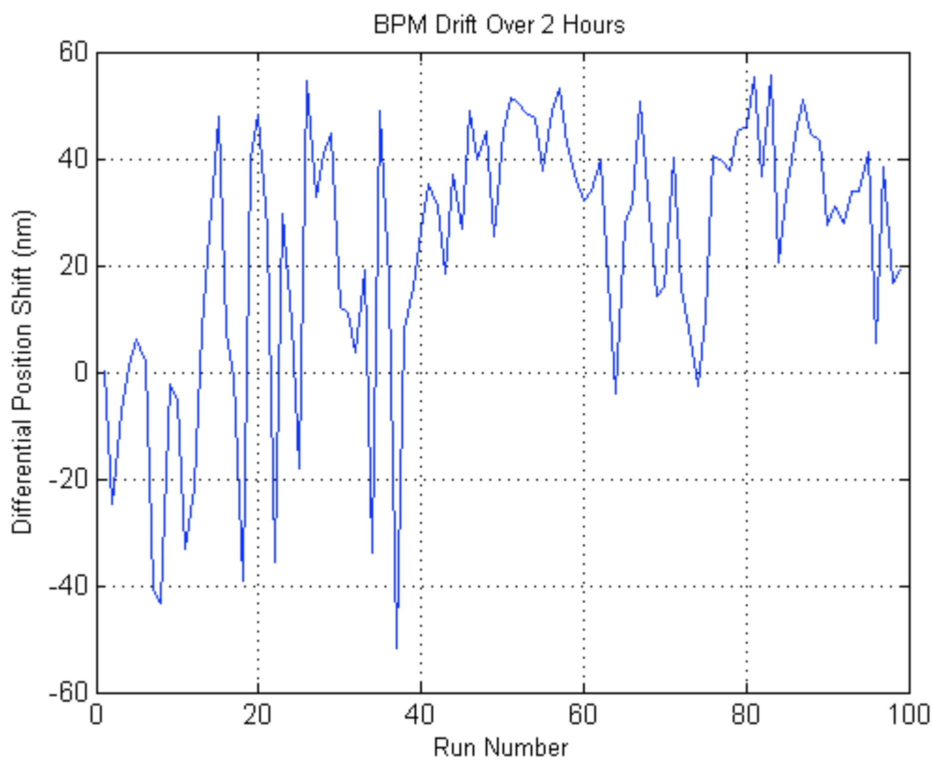


Summary & Plans

- Best resolution achieved
  - 16 nm in position and 2.0 urad in tilt
  - Simulations suggest limitations do not primarily arise from amplitude or phase noise
- Upcoming ATF Trip – 3 week period Nov-Dec
  - Multi-bunch mode
  - Carbon reference frame system
  - ATF2 Electronics
- NIM paper draft in the works…

Stability Studies

- Excellent stability (at least BPM to BPM)
- Drifts look very small over short term (~ 2 hours)
- Good running periods were only a few hours
  - Would like to study long term stability (~several hours)

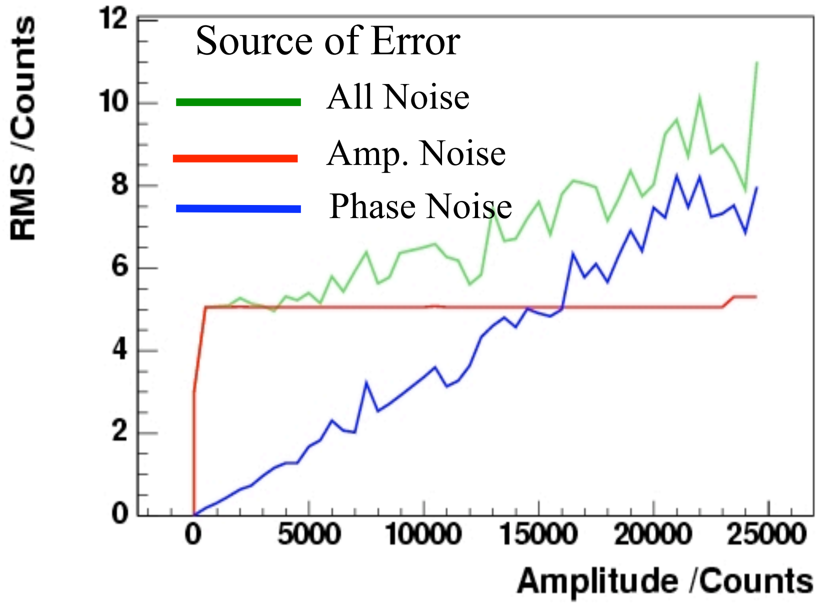


S.Smith, SLAC

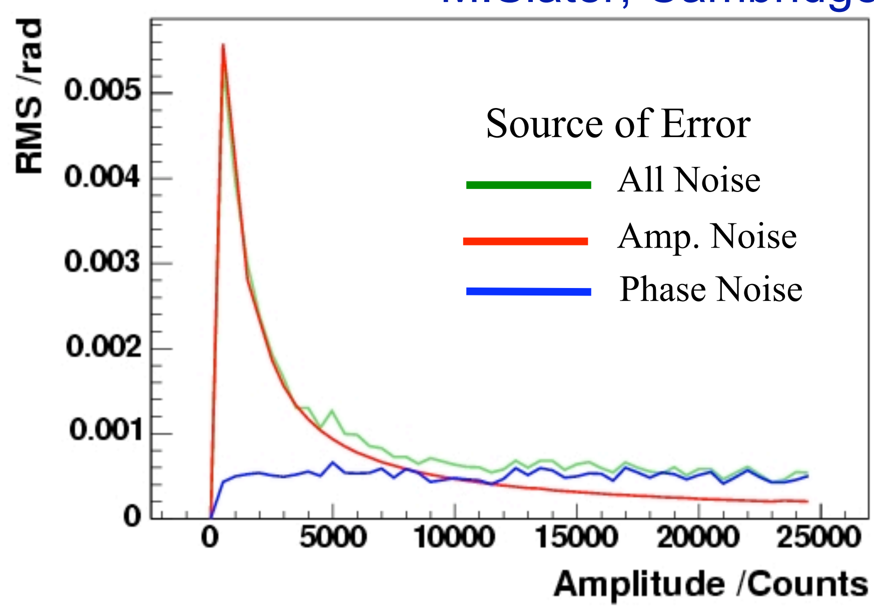
Noise Analysis from Simulation

- Generated **simulated waveforms** (decaying sine waves) using frequencies and decay constants of each channel
- Added measured thermal noise and gaussian phase noise
- Study response of fitting algorithm for pulses of varying amplitudes

M.Slater, Cambridge



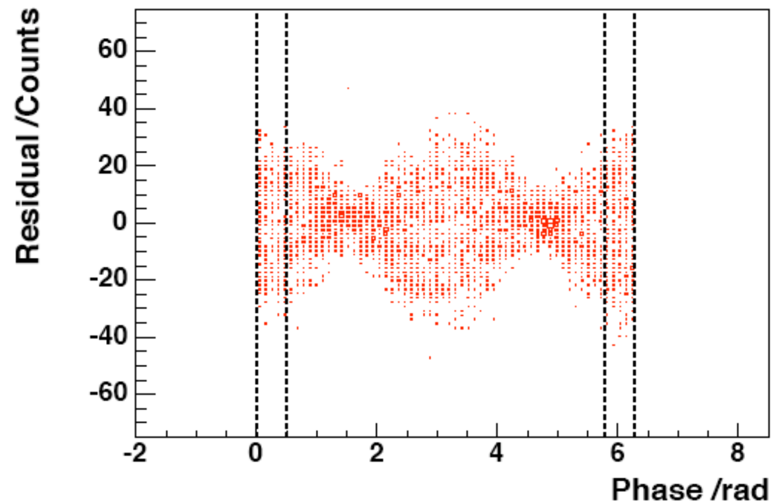
Phase Noise dominates at High Amplitudes



Amplitude Noise dominates at Low Amplitudes

Phase Noise Studies

- Residual vs phase shows "bow-tie" structure:



- Simulated events using information from test tone data
  - Bow-tie effect proportional to phase noise added
- Phase noise quantified by looking at standard deviation of residuals from sine wave fits

Channel	Phase Noise
Reference	2.3 mrad
$1x$	2.7 mrad
$1y$	2.6 mrad
$2x$	2.5 mrad
$2y$	2.4 mrad
$3x$	2.2 mrad
$3y$	3.1 mrad