Linac Coherent Light Source

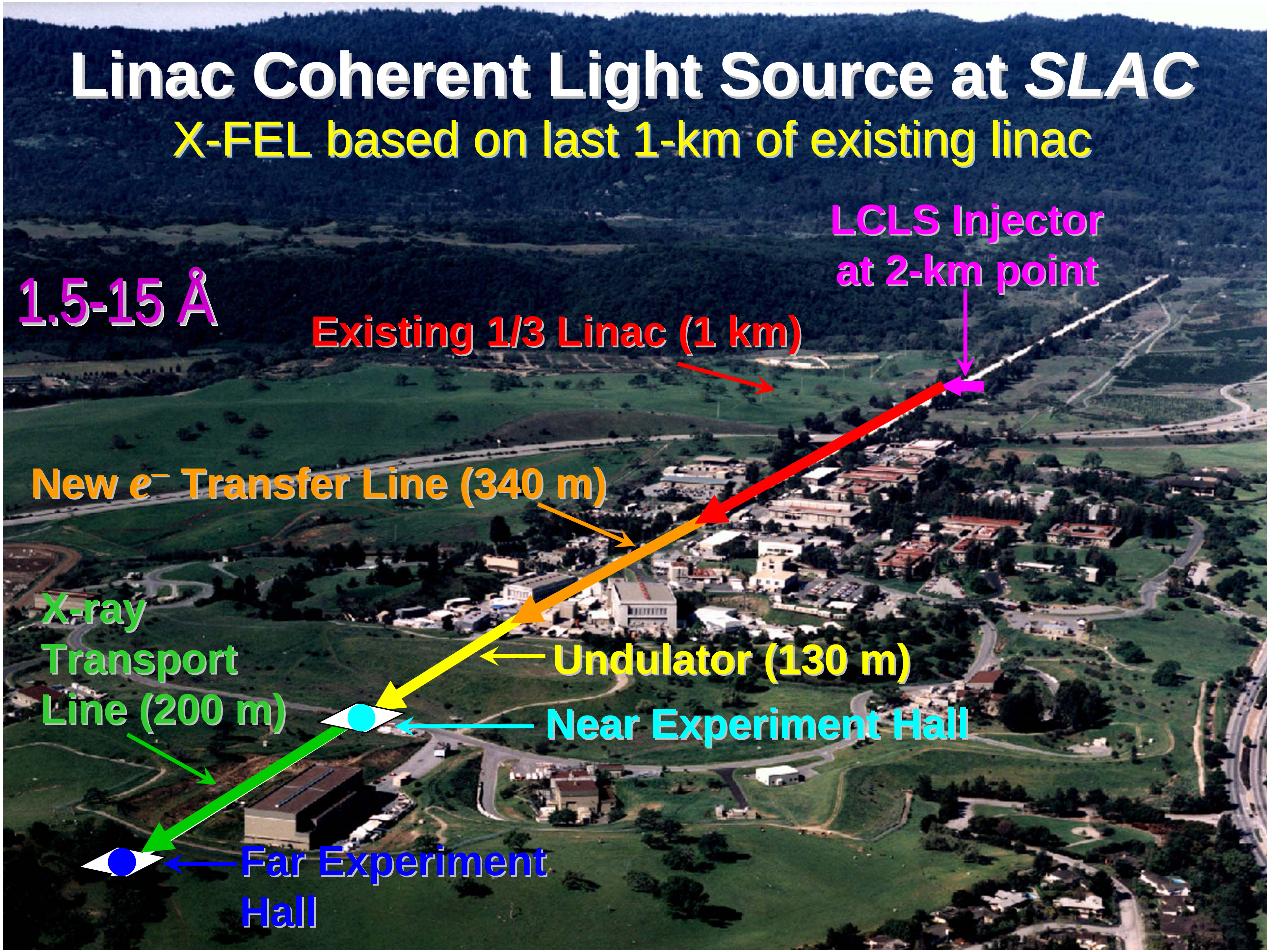
LCLS
&
Cavity
Beam Position Monitors

Steve Smith

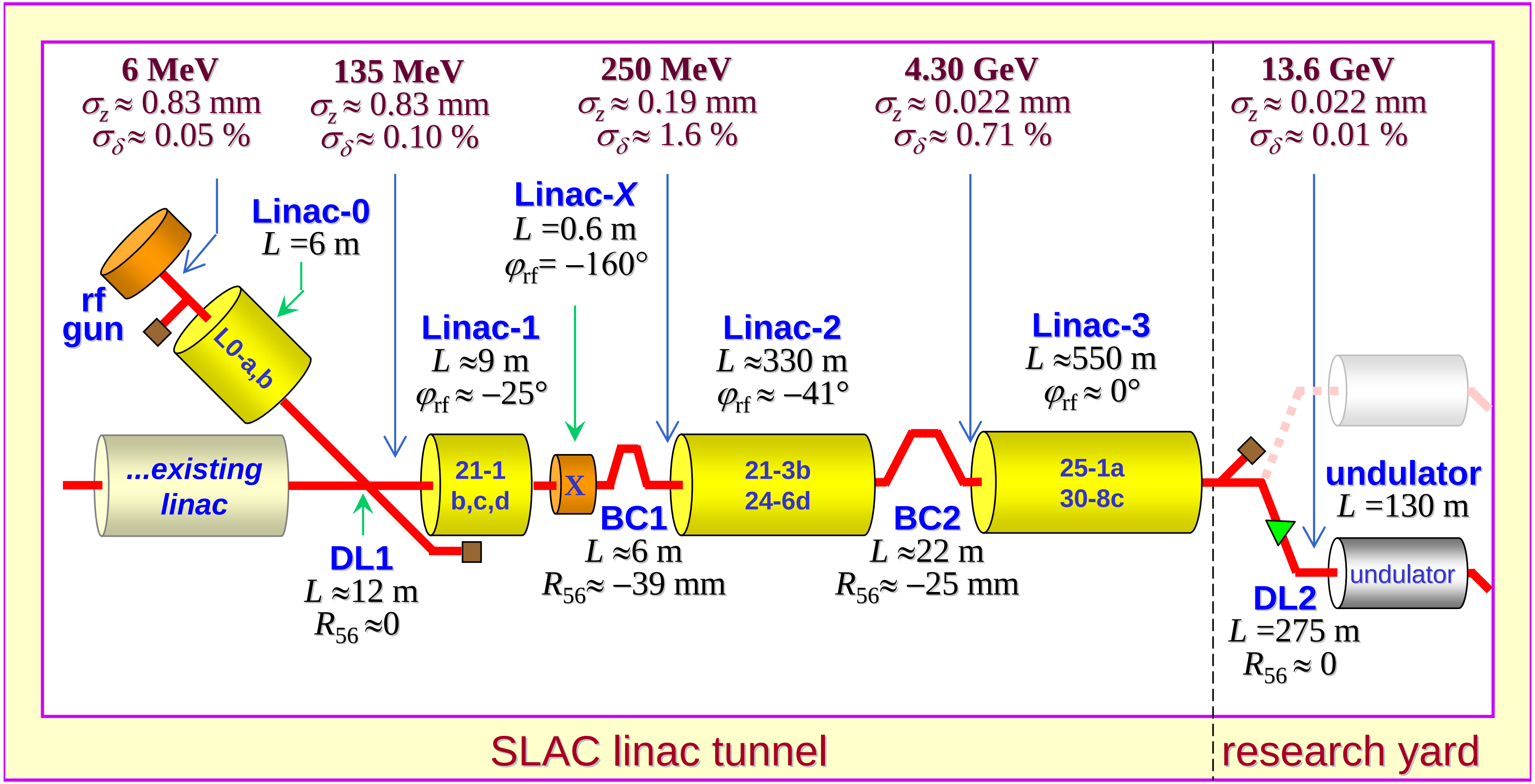
SLAC
NATIONAL ACCELERATOR LABORATORY

DESY

Accelerator Physics Seminar
May 28, 2009


Linac Coherent Light Source at SLAC
X-FEL based on last 1-km of existing linac
LCLS Injector at 2-km point
1.5-15 Å
Existing 1/3 Linac (1 km)
New e⁻ Transfer Line (340 m)
X-ray Transport Line (200 m)
Undulator (130 m)
Near Experiment Hall
Far Experiment Hall

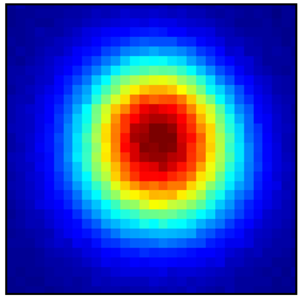
LCLS Accelerator Layout



Now lasing at 1.5 Angstroms

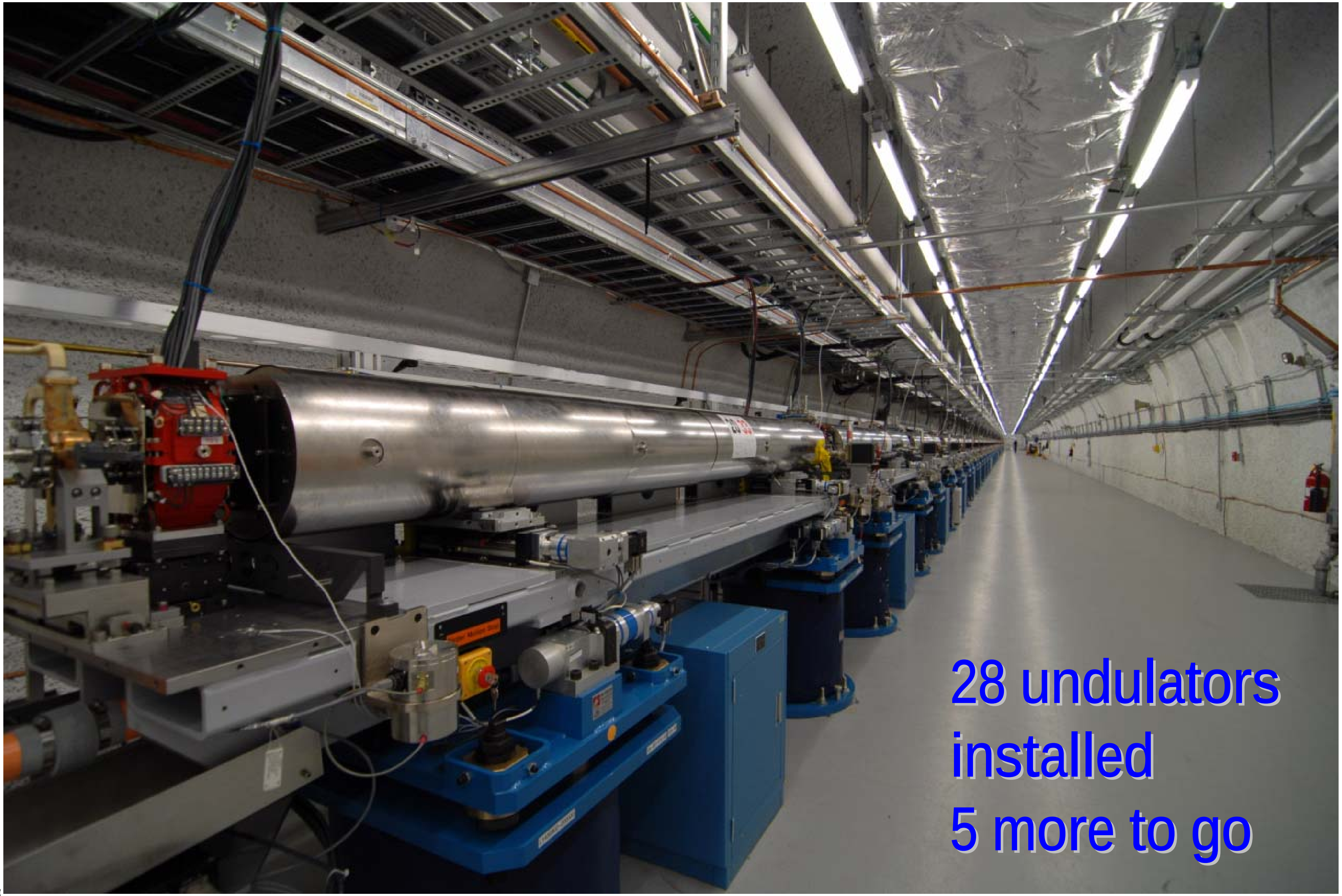
Commissioning Status of *LCLS*

- Laser, gun, & injector commissioned: **2007**
- Linac & bunch compressors commissioned: **2008**
- First beam through undulator beamline: **Dec. 2008**
- 21 undulator magnets installed & ready: **April 7, 2009**
- First lasing at 1.5 Å: **April 10, 2009** (first try!)
- 1.5 Å FEL saturation observed: **April 14, 2009**
  - after beam-based alignment (BBA)

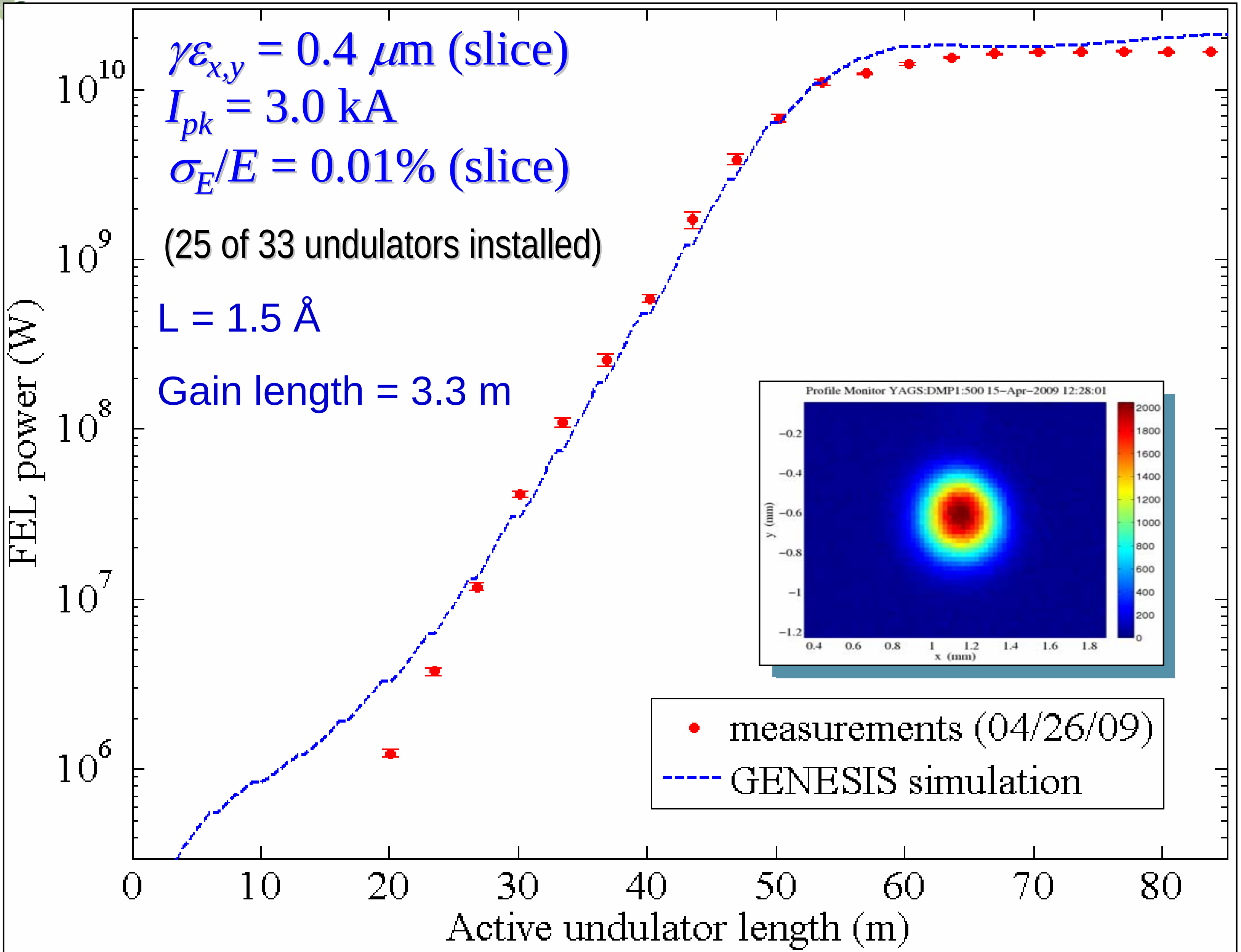


- X-ray diagnostics hall is not ready until early **June**
  - Temporary (makeshift) x-ray diagnostics used so far..
- Now have 28 undulator magnets installed
- User operations start in **Sep. 2009**

Undulator (mostly) Installed

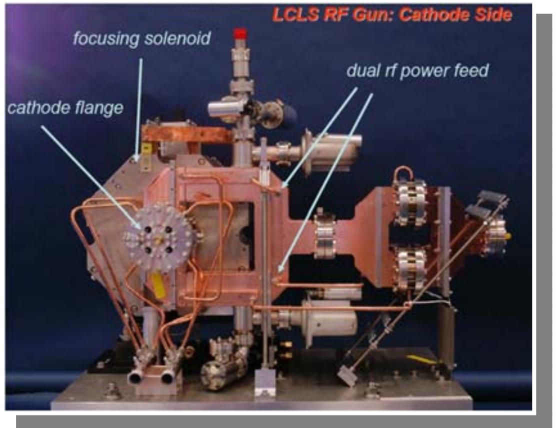


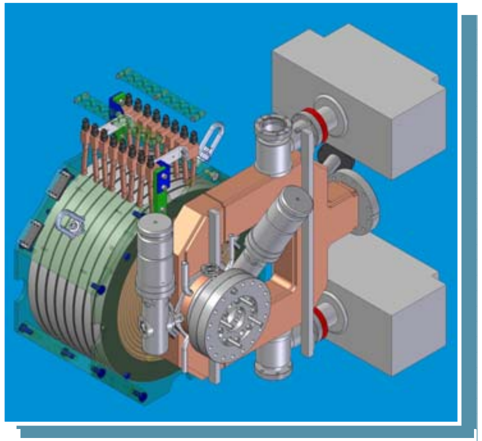
Gain Length Measurement



Injector Transverse Projected Emittance

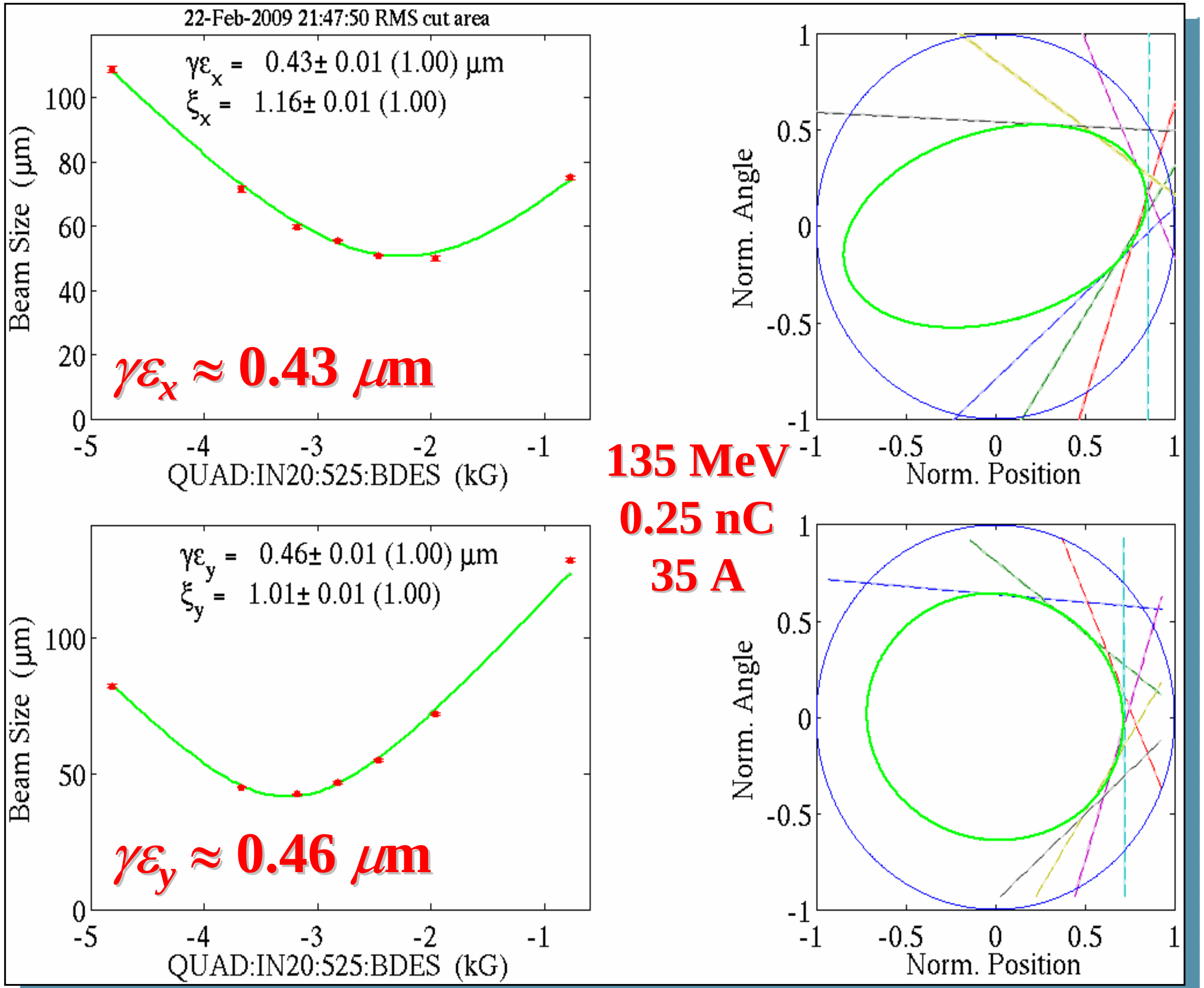
Exceptional beam quality from S-band Cu-cathode RF gun…



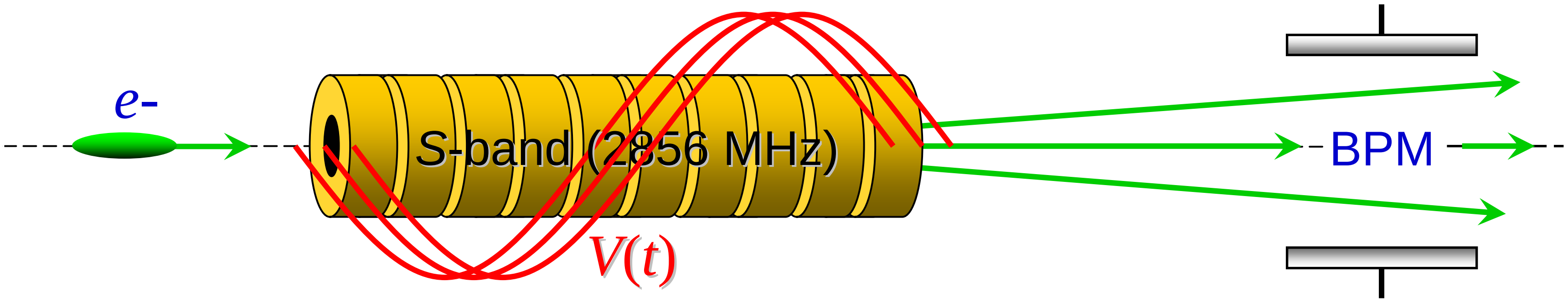


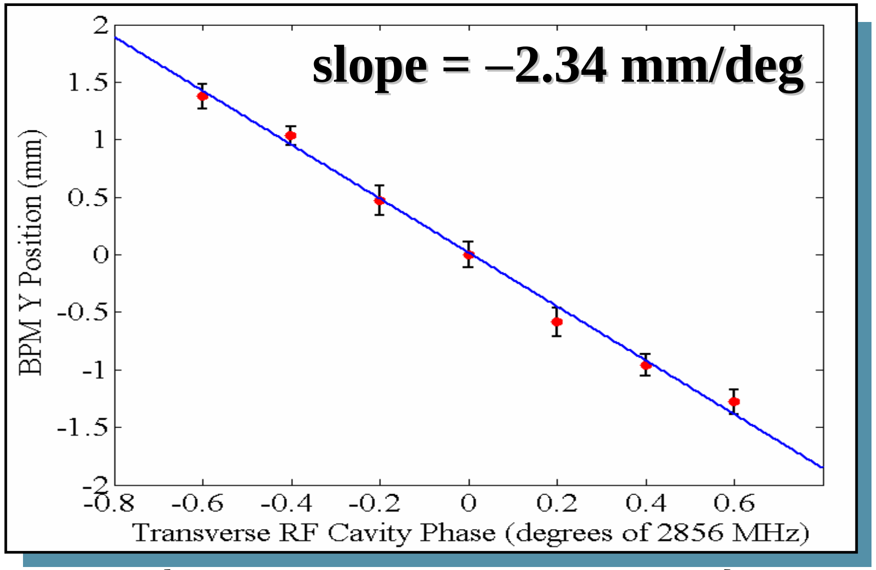
D. Dowell

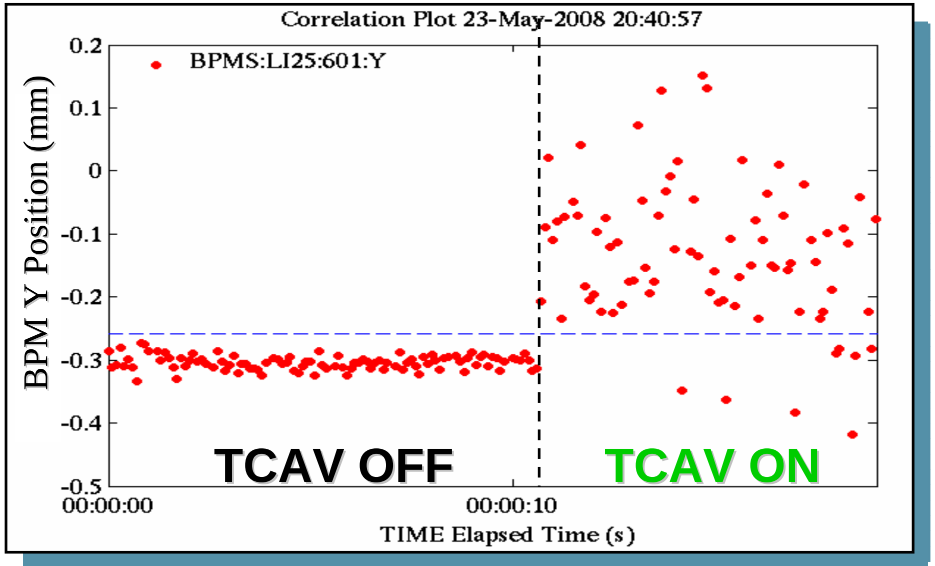
Time-sliced emittance: 0.3-0.4 μm



Arrival Time Jitter via Transverse Cavity







$\Delta t \approx \pm 0.6$ ps

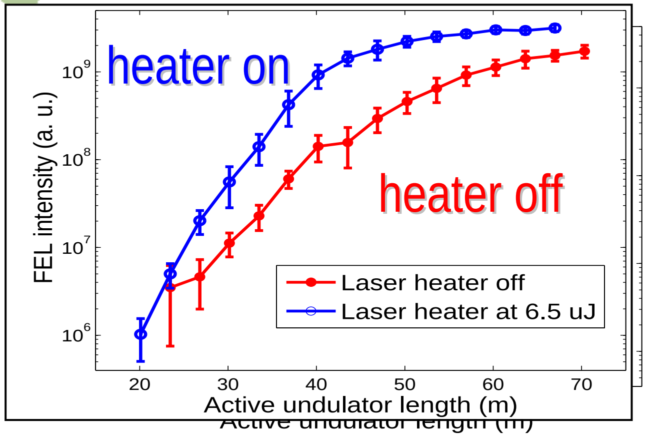
9 μm rms

110 μm rms

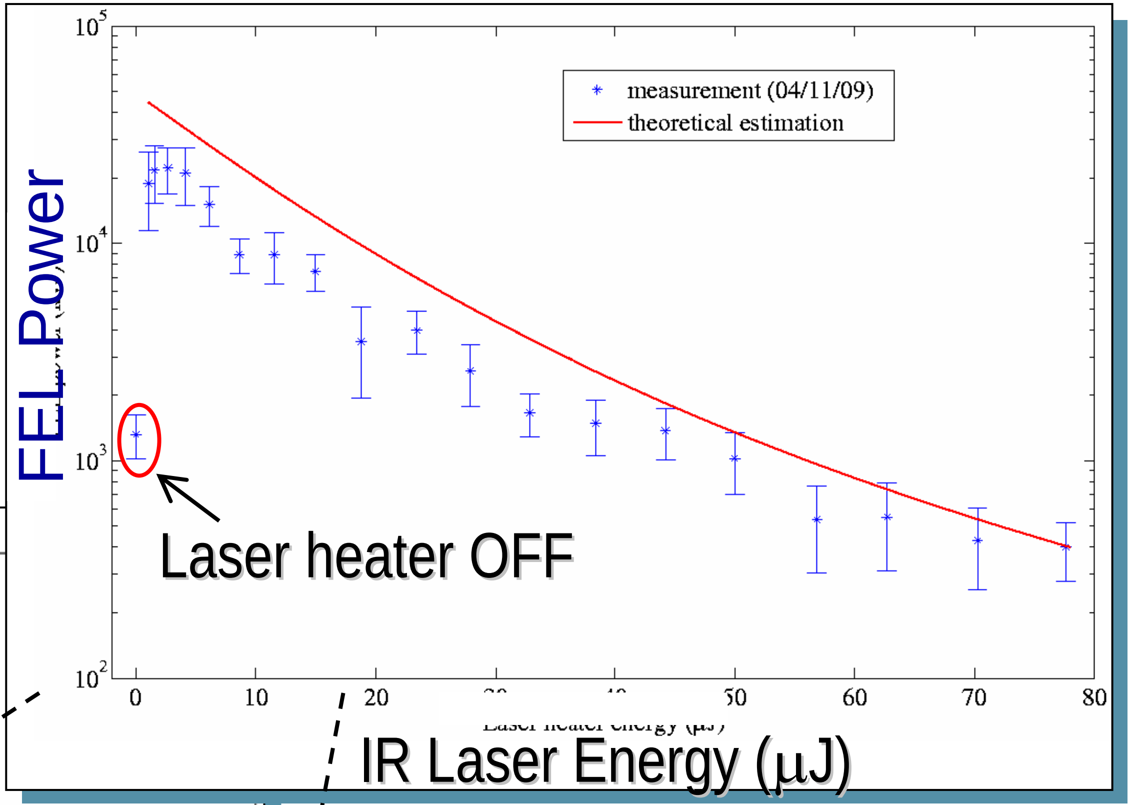
Timing Jitter = (110 μm)/(2.34 mm/deg) = 0.047 deg $\Rightarrow$ **46 fsec rms**

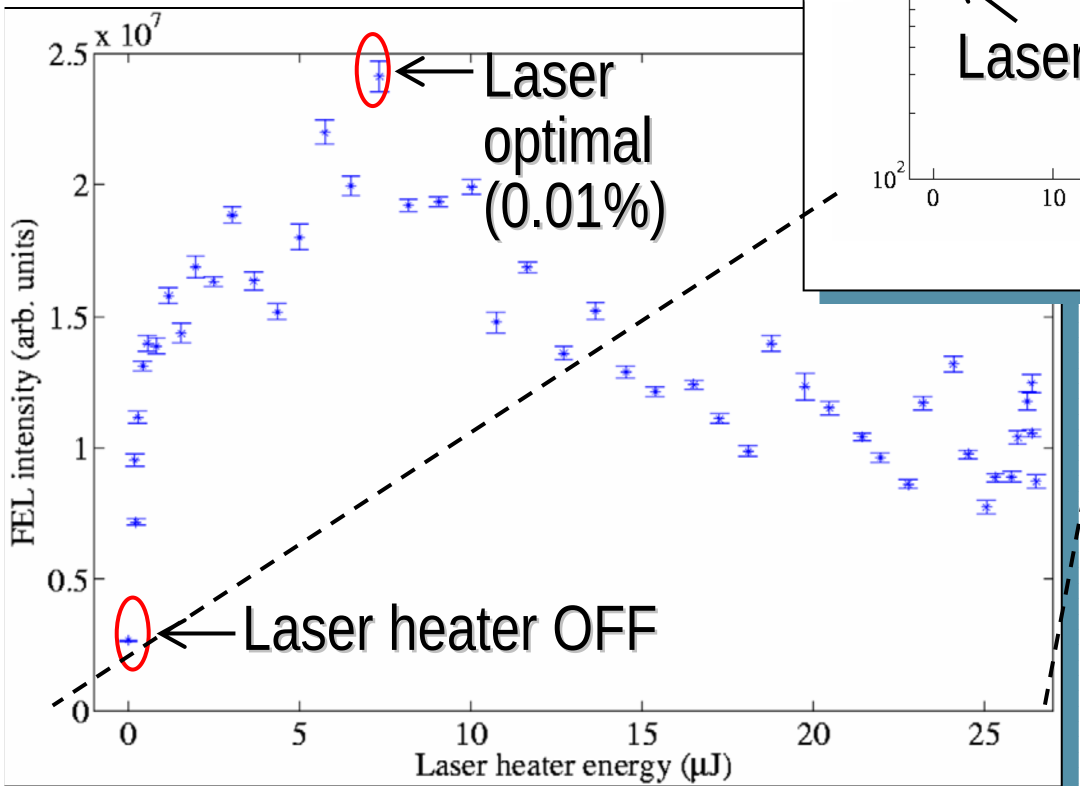
Laser Heater Improves FEL Power

FEL Gain



FEL Power



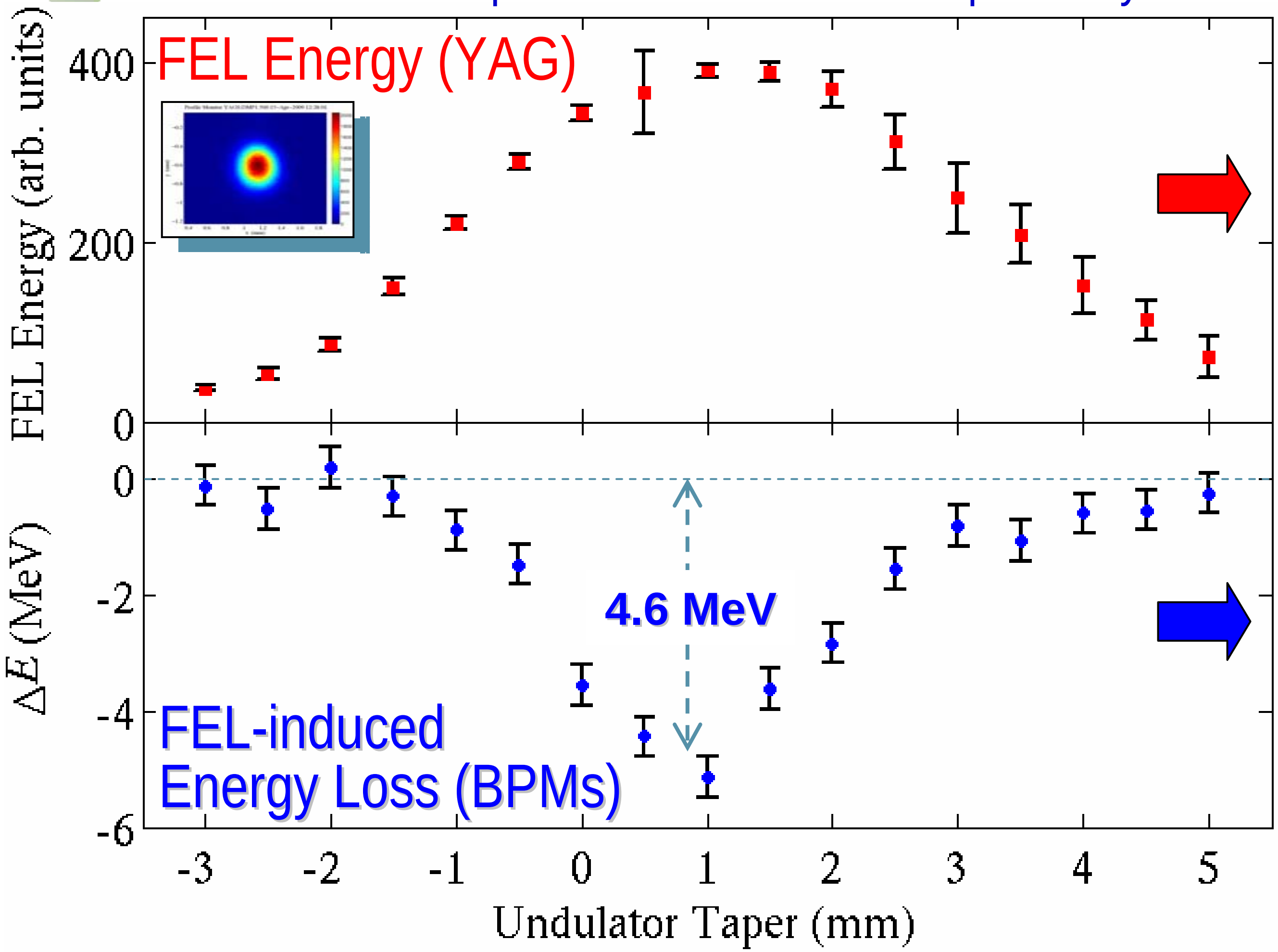


12 undulators inserted
(FEL not saturated here)

preliminary

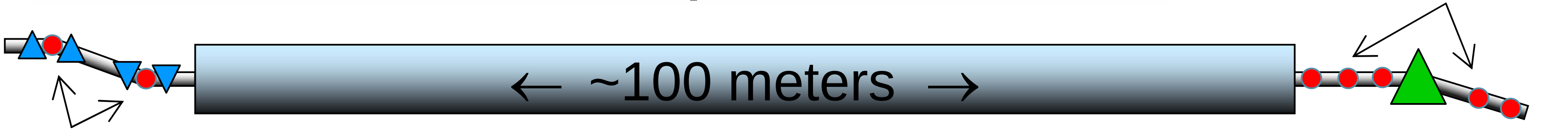
Laser Pulse Energy Measurement

Undulator 'Taper Scan' Shows 1.1 mJ per X-ray Pulse at 1.5 Å



Pixel sum of x-ray YAG screen CCD camera vs undulator *K*-taper

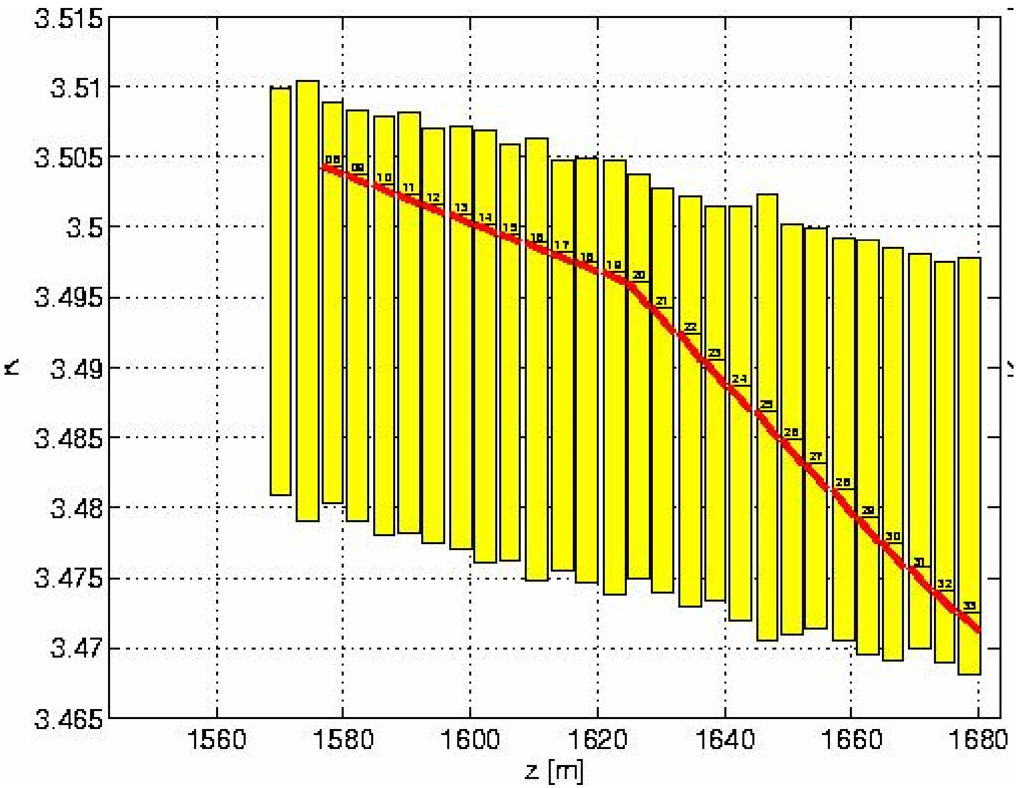
4.6 MeV at 0.25 nC
= 1.1 mJ
= **0.8×10^{12}** γ / pulse
= 15 GW at 75-fs FWHM pulse length
Now see > 2 mJ



Vary the FEL power and record the e^- energy loss

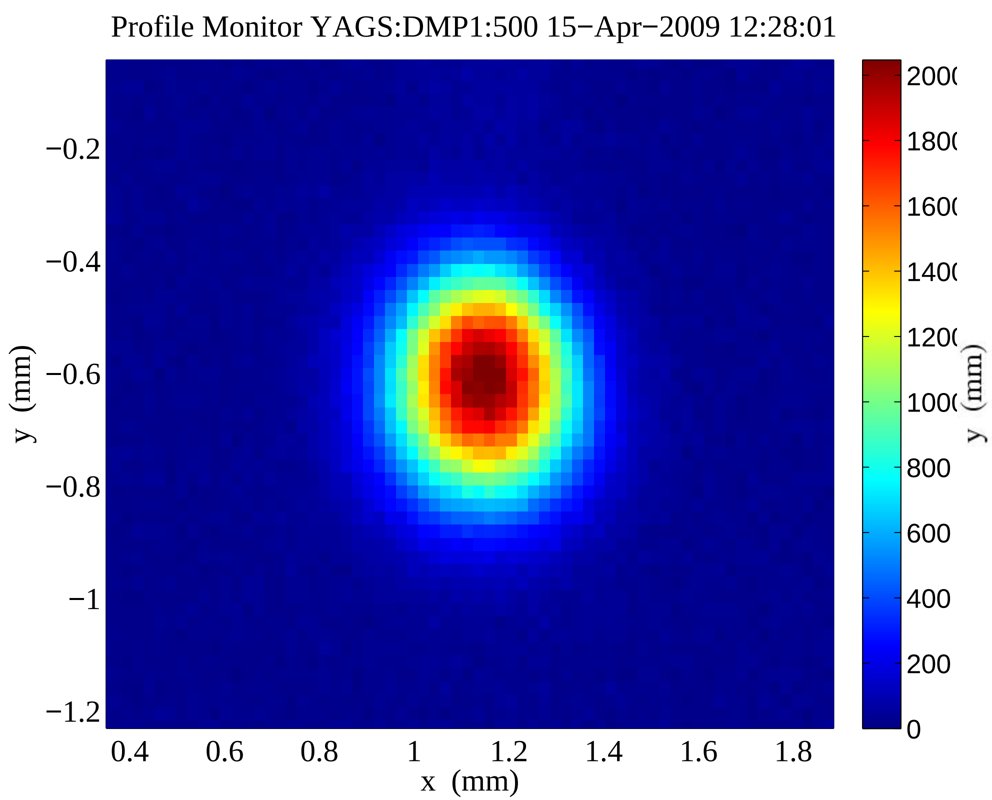
Undulator Taper Matching

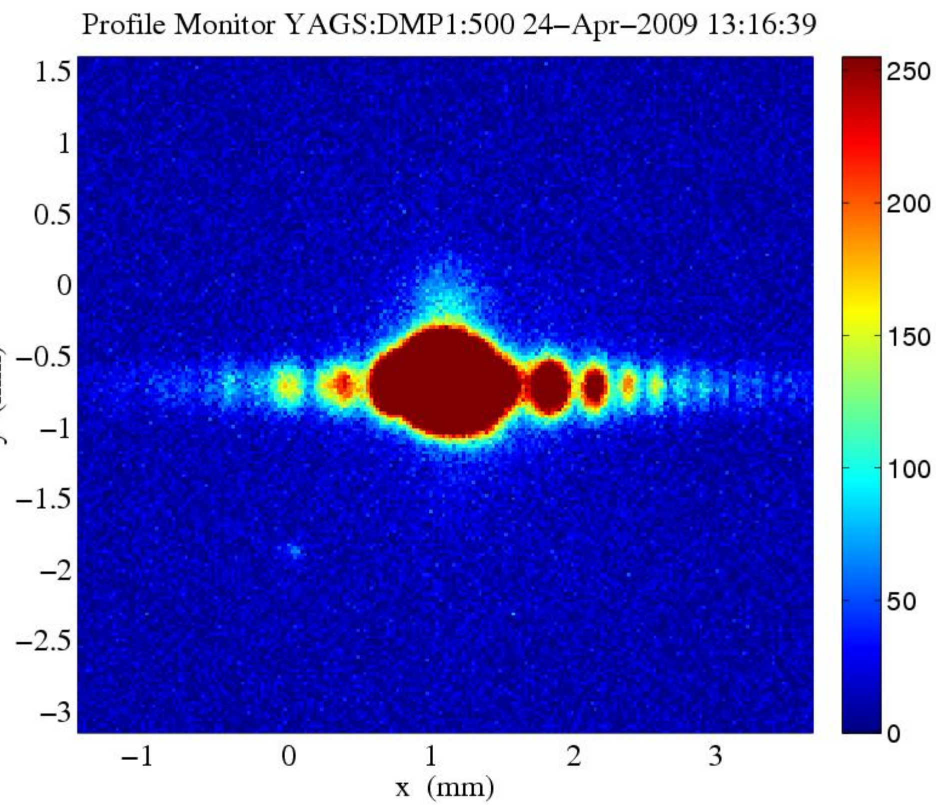
- Match undulator taper (K-factor) to beam energy loss
- Yellow bars show K-range available in each undulator segment
- Initial slope to match wake field and spontaneous emission losses
- After inflection point, coherent radiation dominates



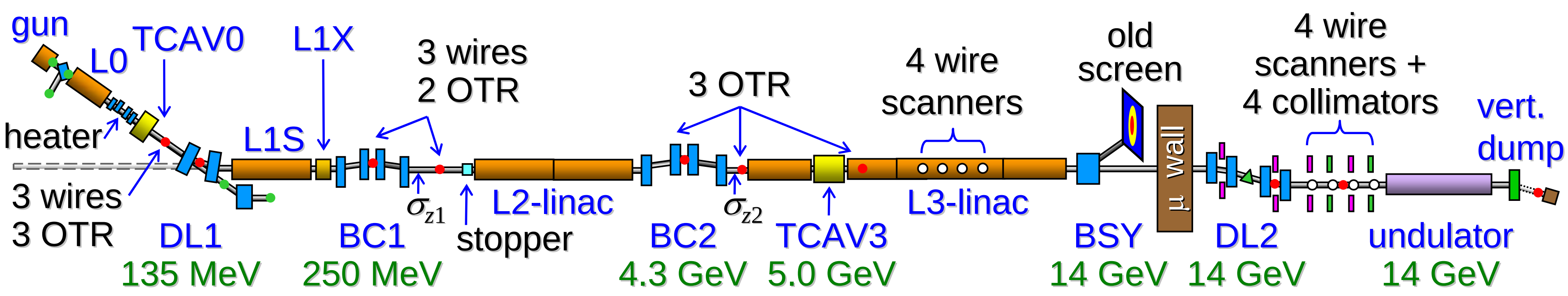
Transverse Coherence

- 2-slit interferometry
- Using beam-finder wire to split beam
  - 40 micron Carbon
- Demonstrates transverse coherence
  - Horizontal & vertical





LCLS Beam Diagnostics



- 2 Transverse RF cavities (135 MeV & 5 GeV)
- 179 BPMs
- 13 Toroids
- 7 YAG screens (at $E \leq$135 MeV)
- 12 OTR screens at $E \geq$ 135 MeV
- 15 wire scanners (each with x & y wires)
- CSR/CER pyroelectric bunch length monitors at BC1 & BC2
- 4 beam phase monitors (2856 – 51 MHz)
- 3 Energy spectrometers: Gun, injector, dump

- YAG screens
- OTR screens
- Wire scanners

Cavity BPM Requirements

- Undulator orbit critical
  - Must keep electrons and photons coincident
  - to fraction of beam size
  - over distance > gain length

Parameter	Requirement	Conditions
Resolution	< 1 micron	200 pC < Q < 1 nC Over ± 1 mm range
Offset Stability	< ±1 micron	1 hour ± 1 mm range, 20 C ± 0.56 C
	< ±3 microns	24 hour ± 1 mm range, 20 C ± 0.56 C
Gain Stability	± 10 %	± 1 mm range 20 C ± 0.56 C
Aperture	10 mm	

Cavity Beam Position Monitors

R. Lill, S. Hoobler, R. Johnson, W.E. Norum, L. Morrison, N. Sereno, S. Smith, T. Straumann, G. Waldsmith, D. Walters, A. Young, D. Anderson, V. Smith, R. Traller,

+ many others

Argonne National Laboratory

- **Cavities**
- **Receiver / downconverter**
- Waveguides
- Stands
- Undulator

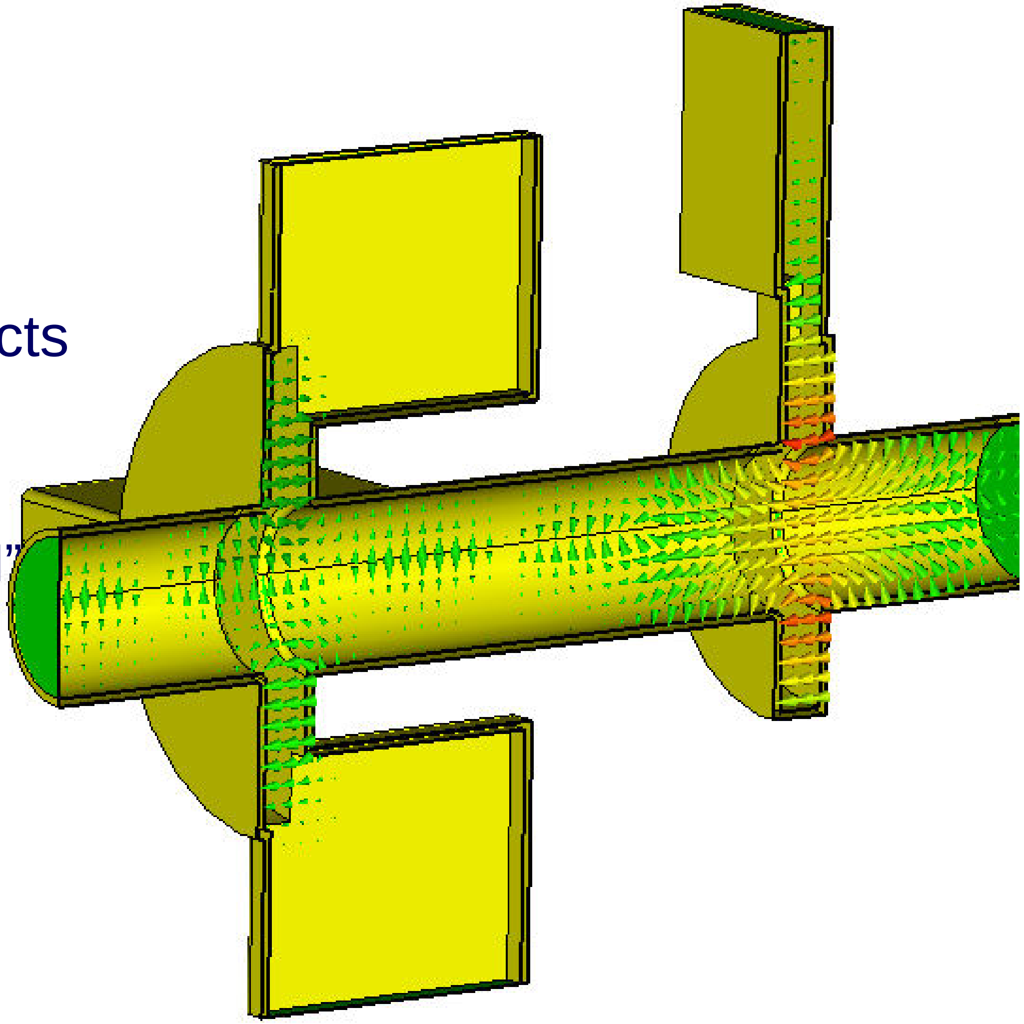
SLAC National Accelerator Laboratory

- Digitizer
- Readout
- Processor
- Power / slow control
- Firmware / software

Design

Concepts

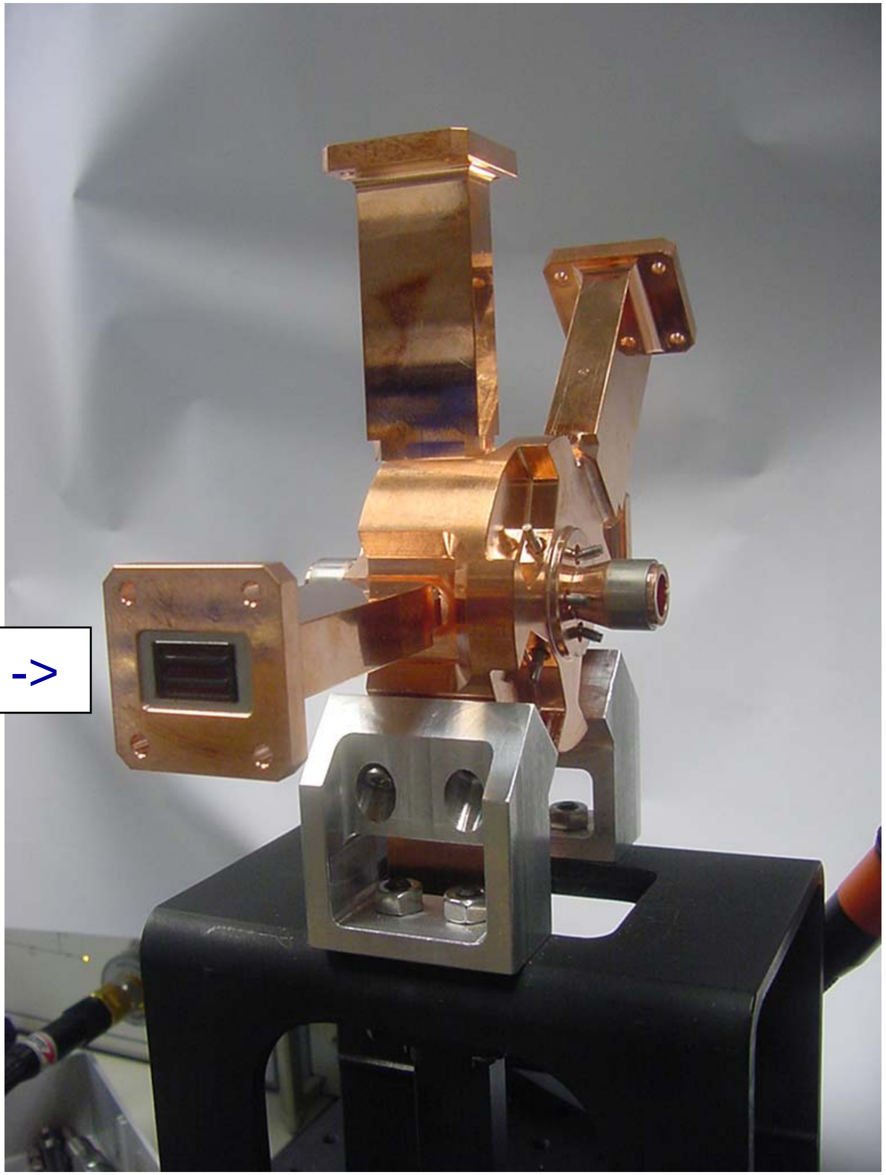
- Avoid the monopole mode
- Cavity-waveguide coupler rejects monopole mode by symmetry
  - Zenghai Li (PAC 2003)
  - T. Shintake, “Comm-free BPM”
  - V. Balakin (PAC 1999)
- Predecessor at KEK’s ATF
  - 16 nm resolution in test beam Walston, (NIM 2007)



Choices

- Single, degenerate X&Y cavity
- Reference cavity per BPM

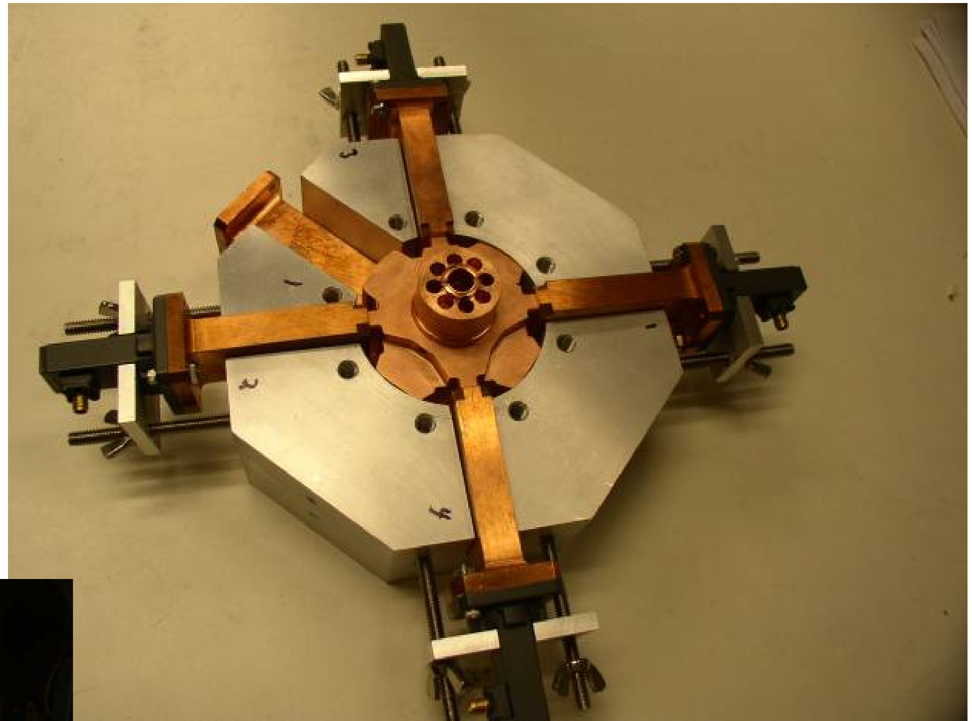
Prototype Cavity

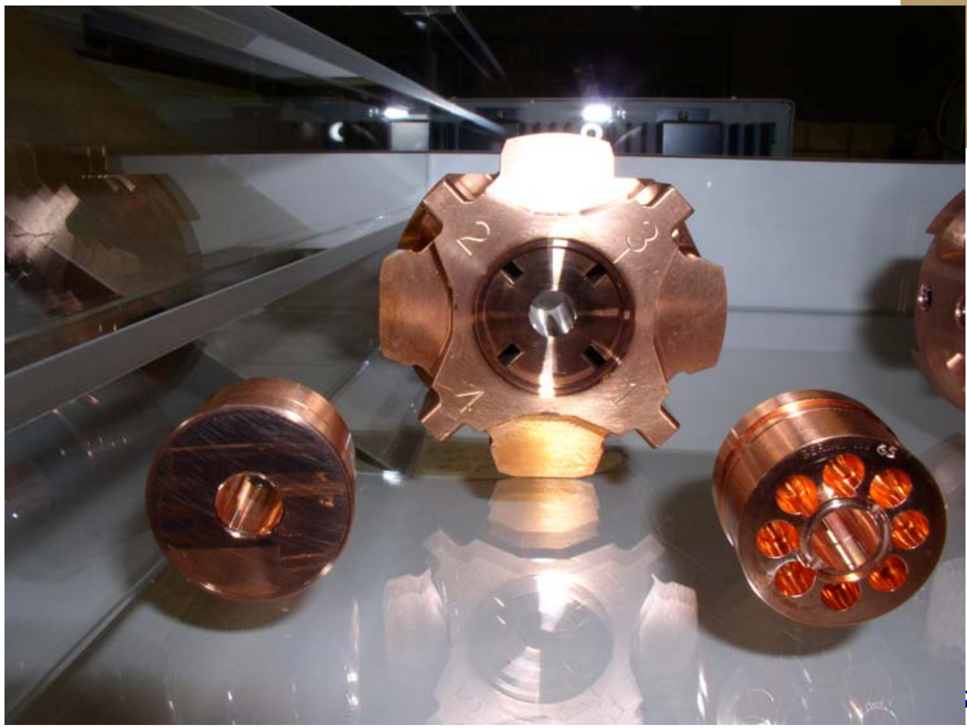


RF vacuum window ->

Cold Test Set-Up for Pre-Braze test

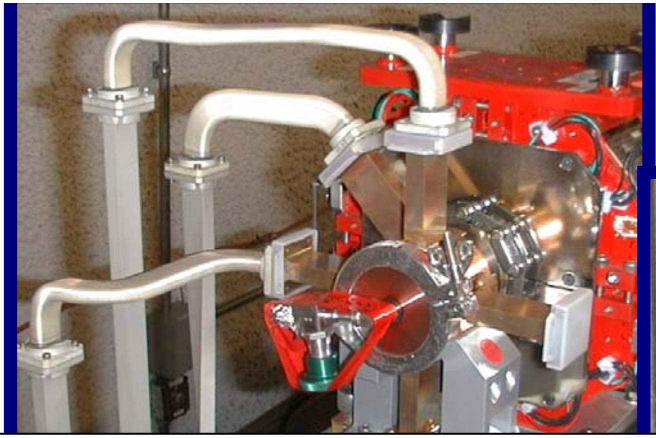
- All BPMs are tuned and cold tested before brazing
- Tuning accomplished by micro-machining end-caps
- Good correlation between cold test data before and after braze



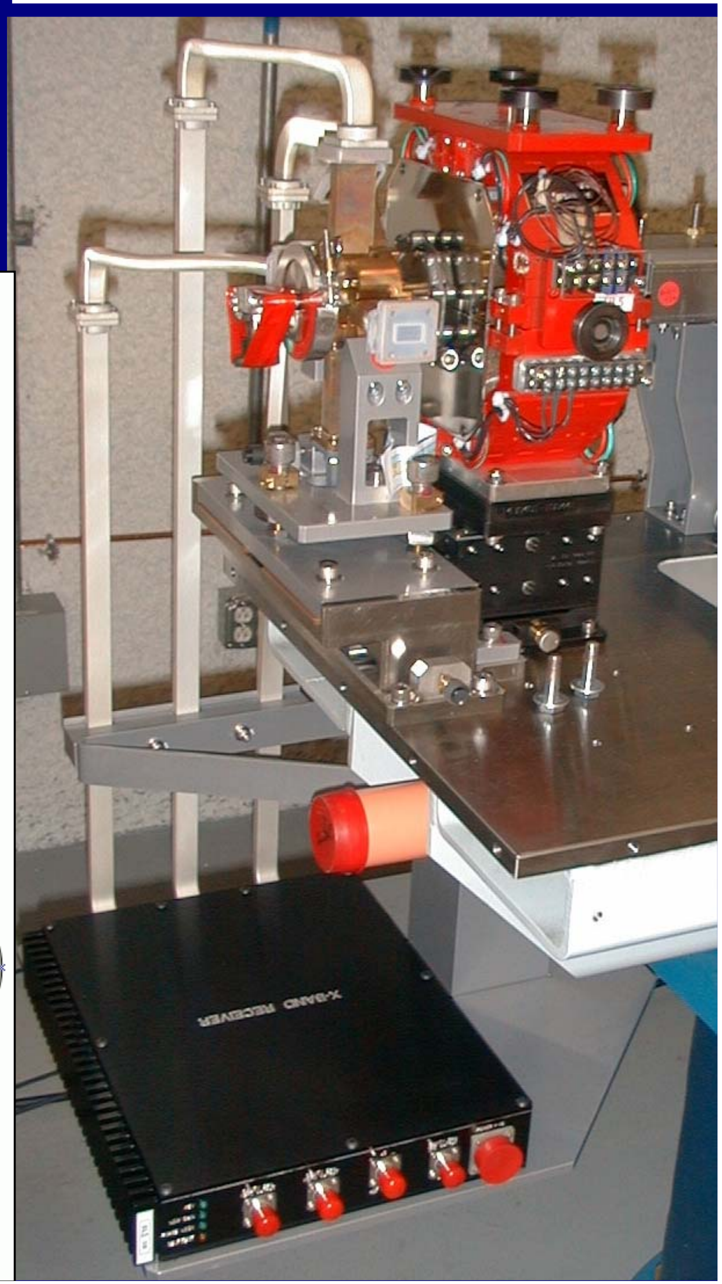


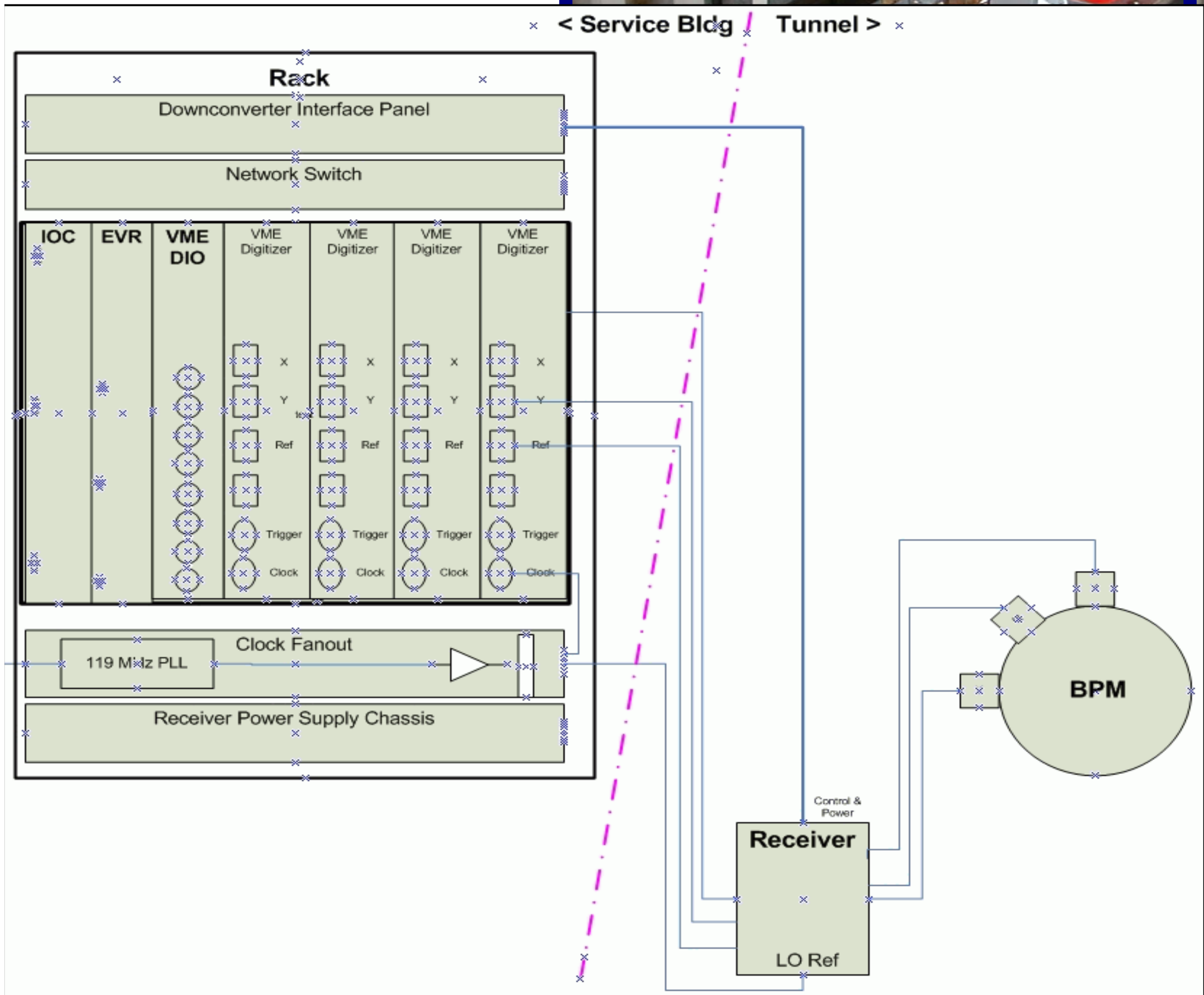
- Position and reference cavities machined in common block
- Closed with endcaps

BPM System

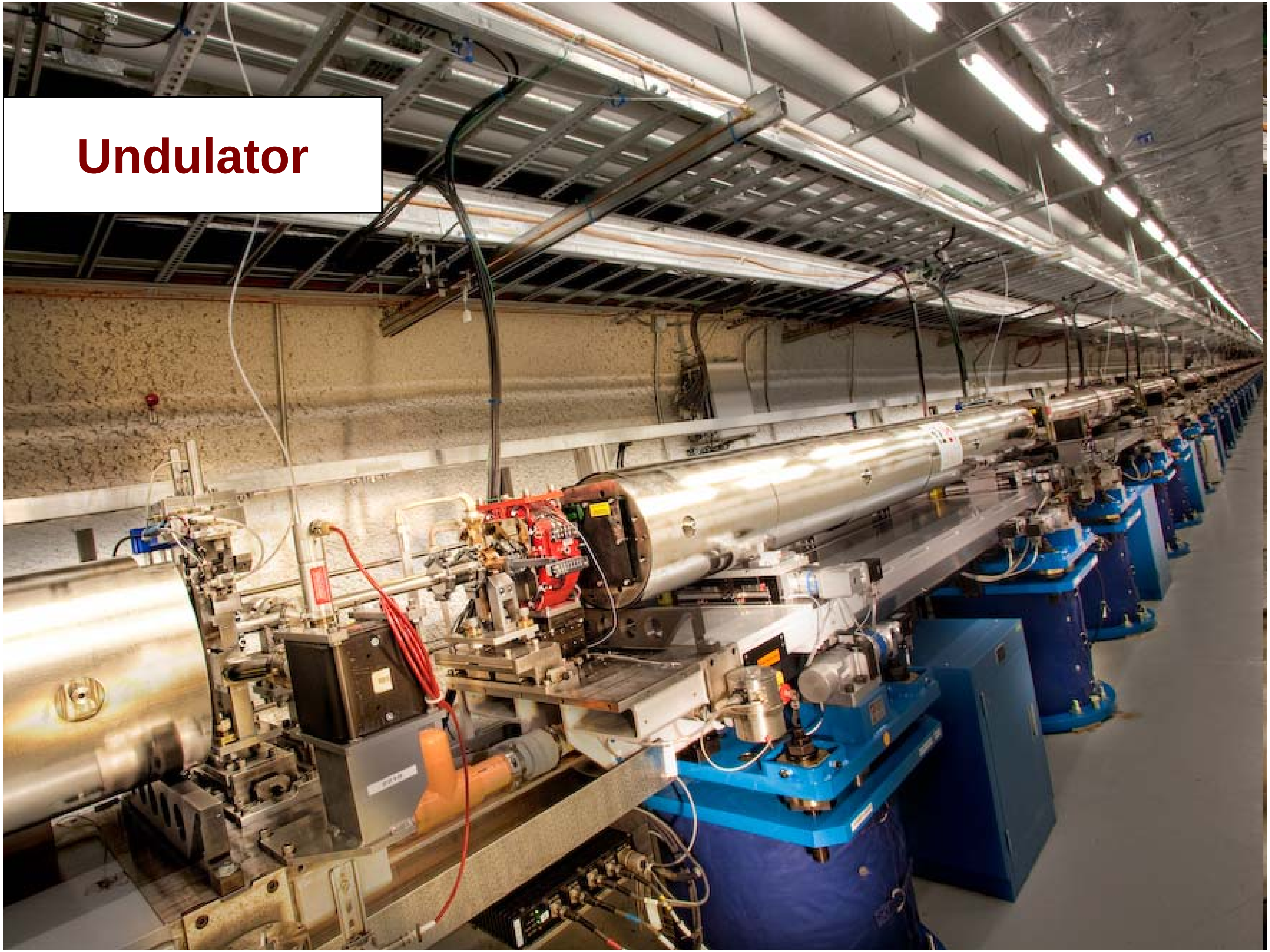


BPM & Receiver



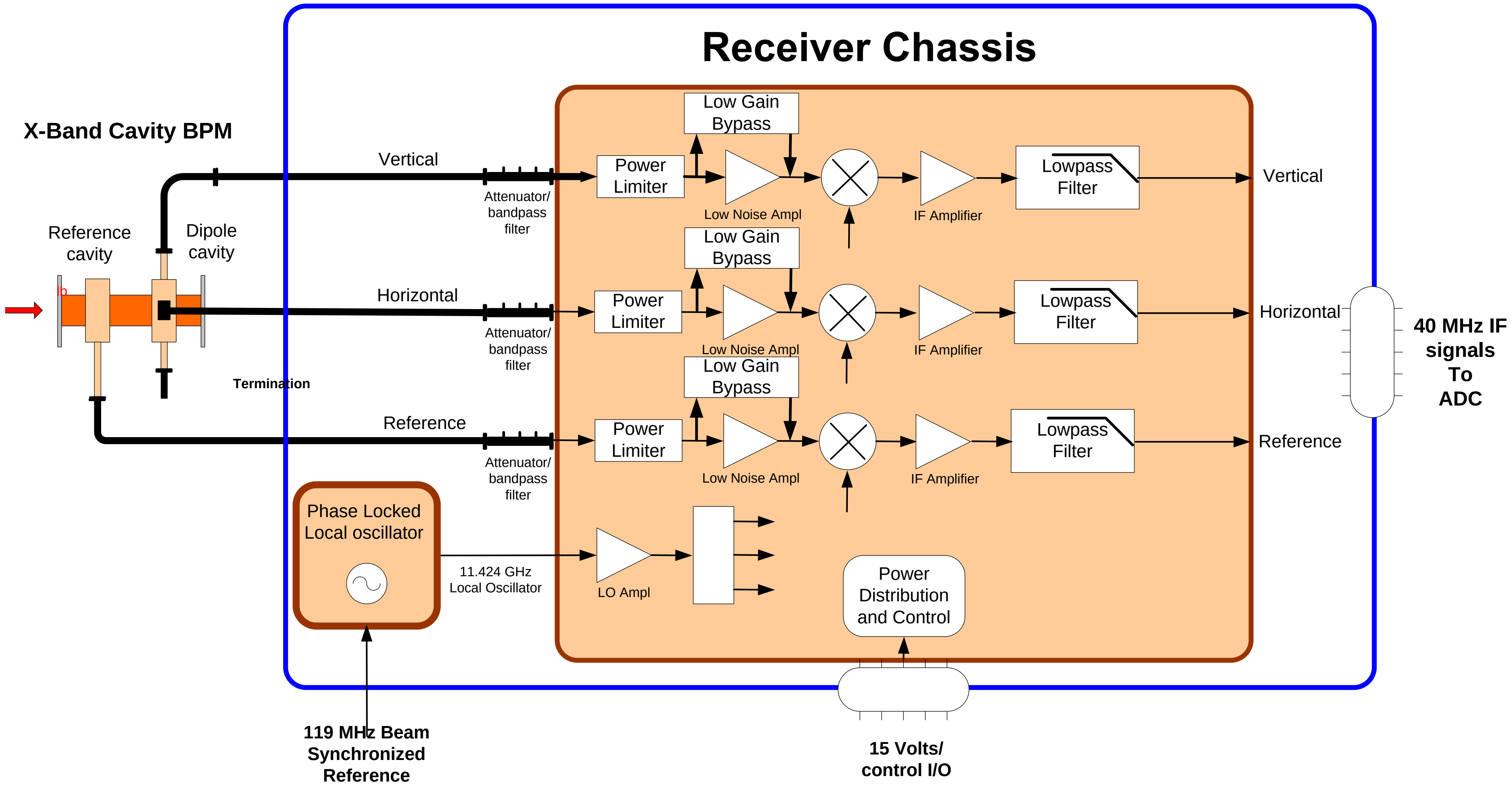


Undulator



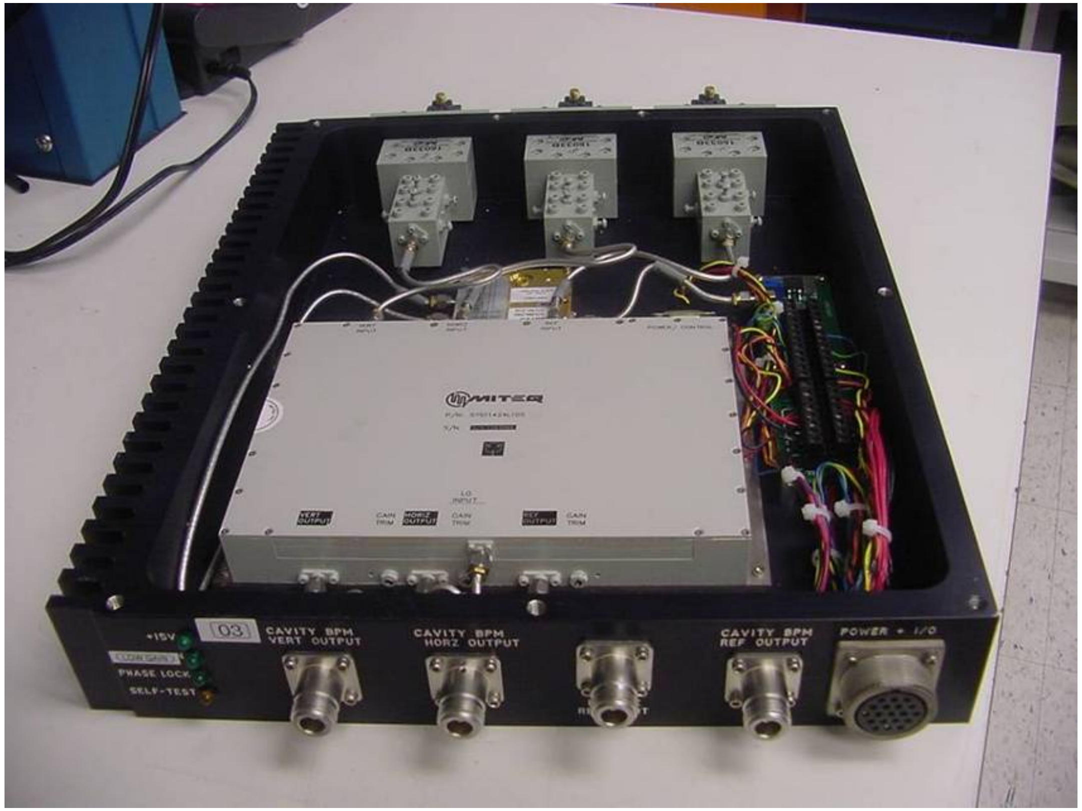
Receiver

- Downconverts X-band to ~40 MHz IF
- Mounted on undulator stand



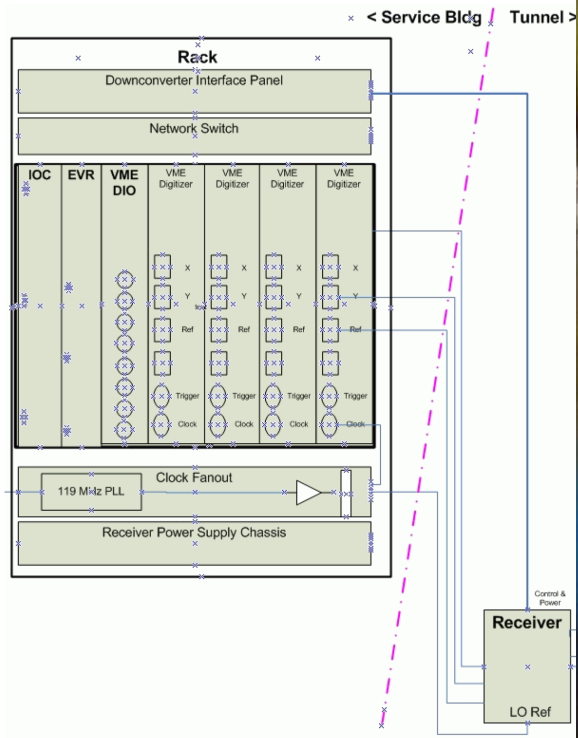
Receiver Chassis

- Three channel receiver
  - X, Y, Reference
- Downconvert 11.4 GHz RF to 40 MHz IF
- Waveguide in
- Coax out
- Located underneath undulator



Data Acquisition

4 Channel VME ADC
(1 of 36)



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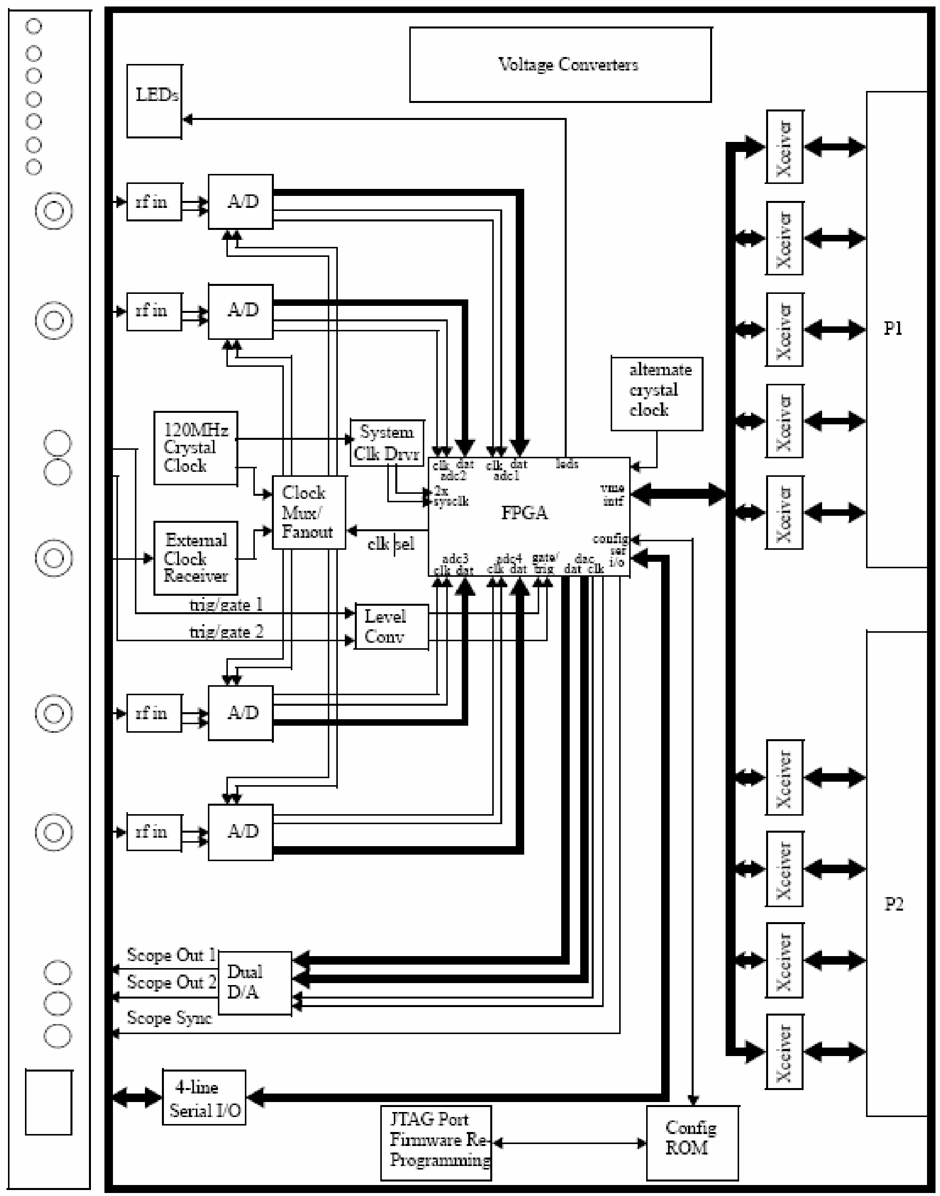
Undulator Readout Racks (1 of 2)

SLAC 4-Channel VME Digitizer

- 4 channels
- 16 bits
- LTC2208 ADC chip
- Up to 130 M samples/sec
  - Optional: use internal 120 MHz clock
  - Typically use external 119 MHz clock locked to linac RF
- Optional quadrature digital IF downconversion in FPGA
  - (not used at present)

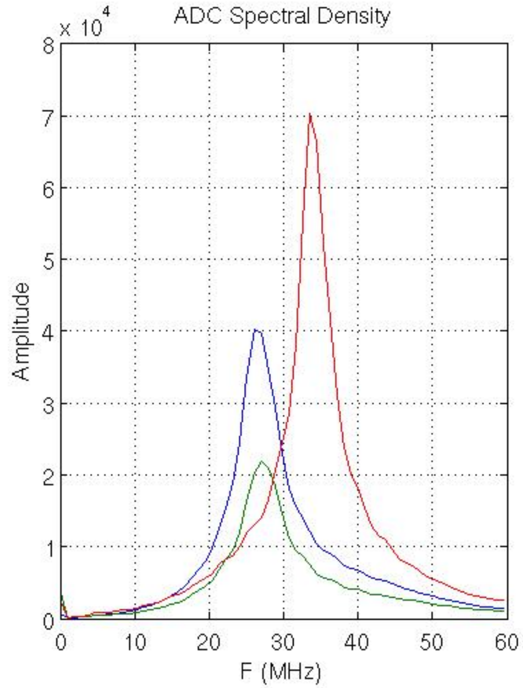


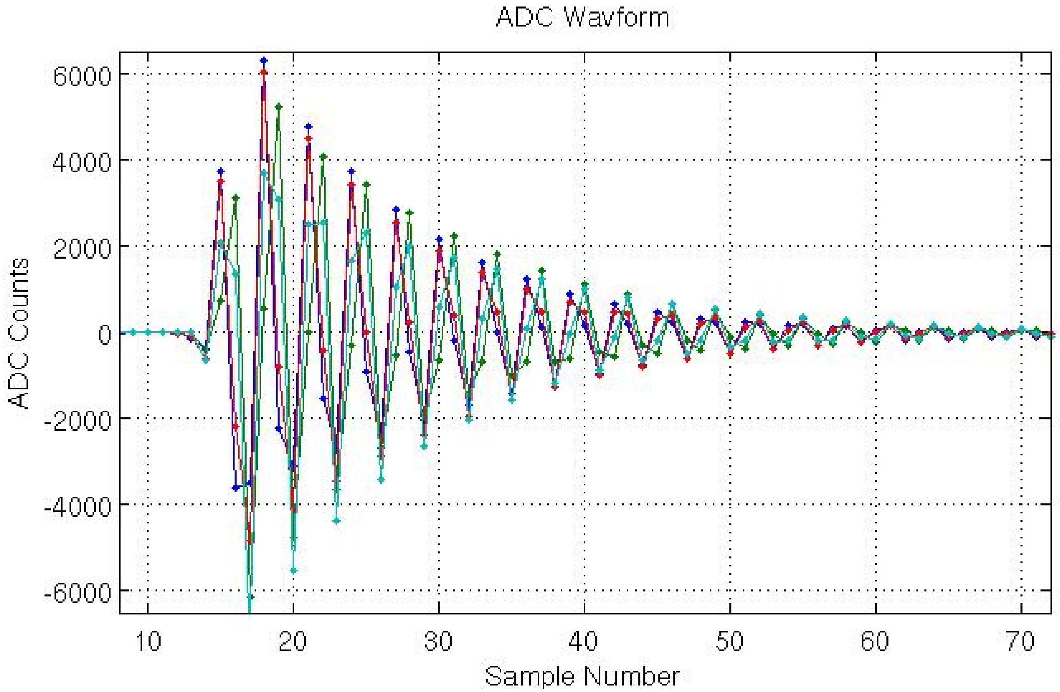
Algorithms

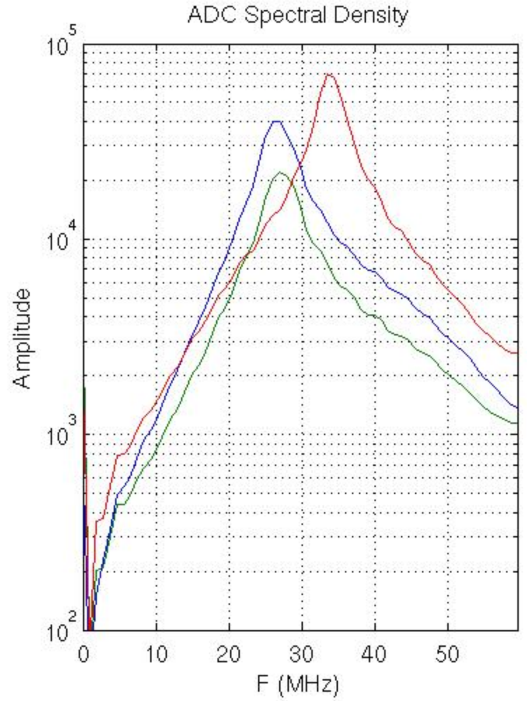
- Reduce each waveform to amplitude & phase (I,Q)
- Normalize position signal to reference (amplitude and phase)
  - X' = X/Ref (complex normalized amplitude)
  - Y' = Y/Ref
- Calibrate:
  - move BPM
    - observe normalized amplitude vs. BPM position
    - Can use other BPMs (uncalibrated) to remove beam jitter
    - Extract phase & scale of position signal in normalized amplitude
- Measurement
  - Rotate normalized amplitude by phase angle from calibration
  - Project real component
  - Scale and remove position offset

Waveform / Spectrum

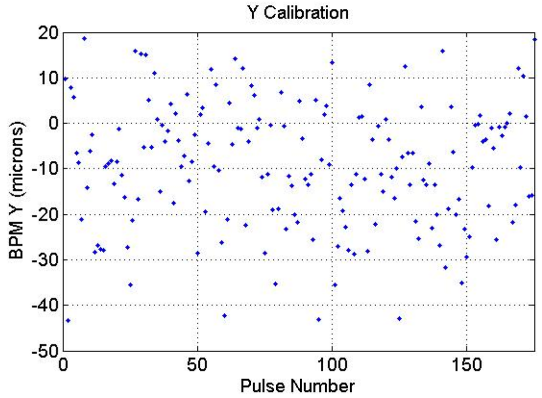
- Cavity IF waveform sampled at 119 MHz
- 16 bit digitizer
- Extract amplitude, phase of
  - X, Y, Reference







Calibration



Move BPM

Measure complex amplitudes

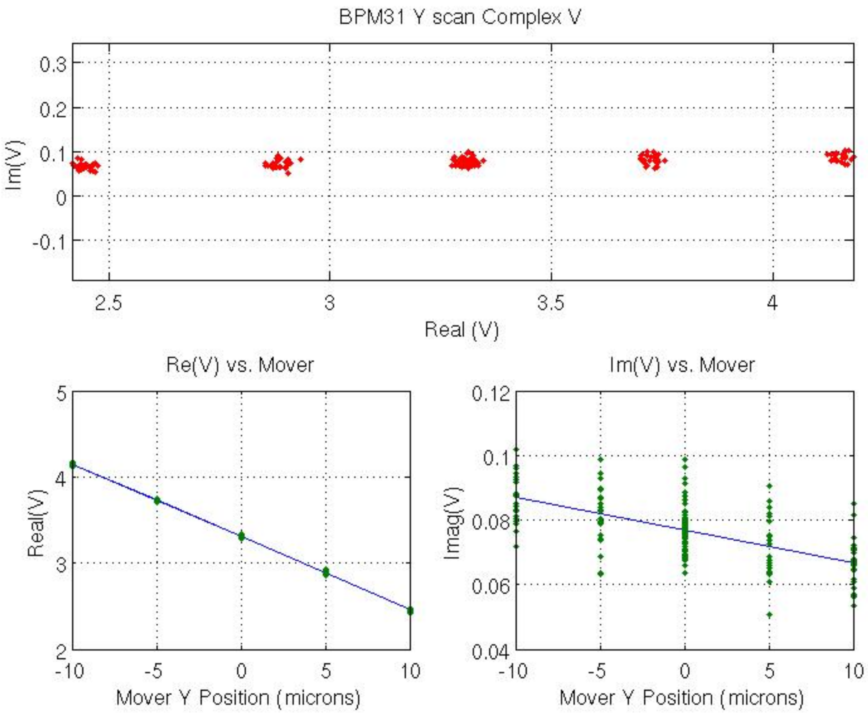
X, Y, Ref

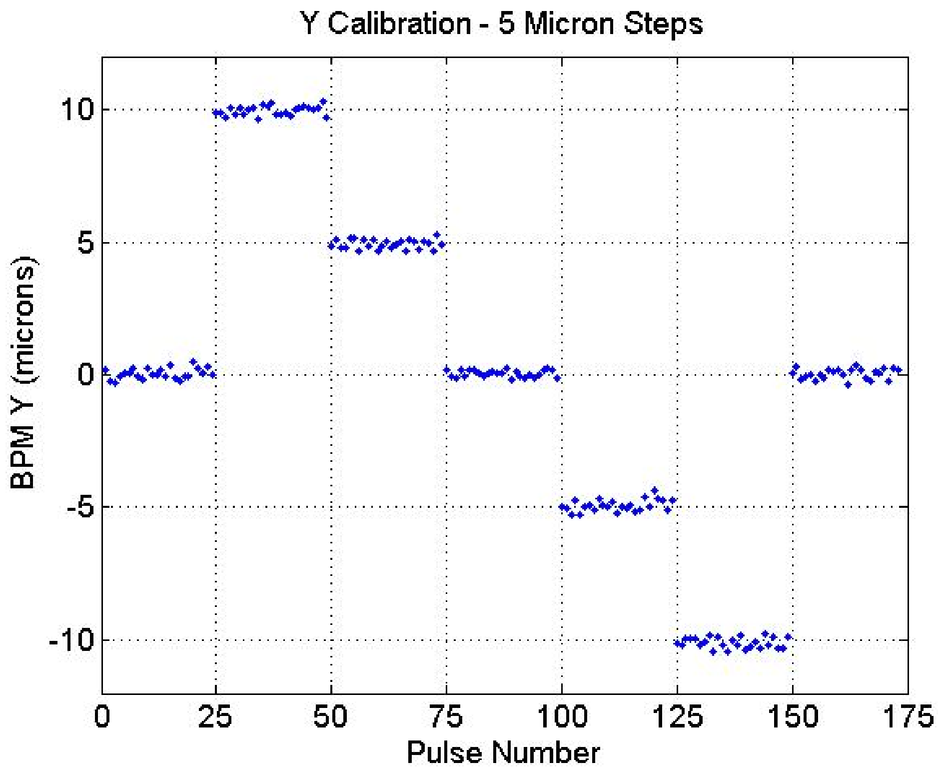
Normalized amplitude = Position/Reference (Complex)

Remove beam jitter using adjacent upstream BPMs

Fit complex normalized amplitude to mover position

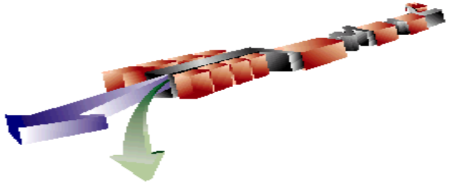
Repeat for off-axis component



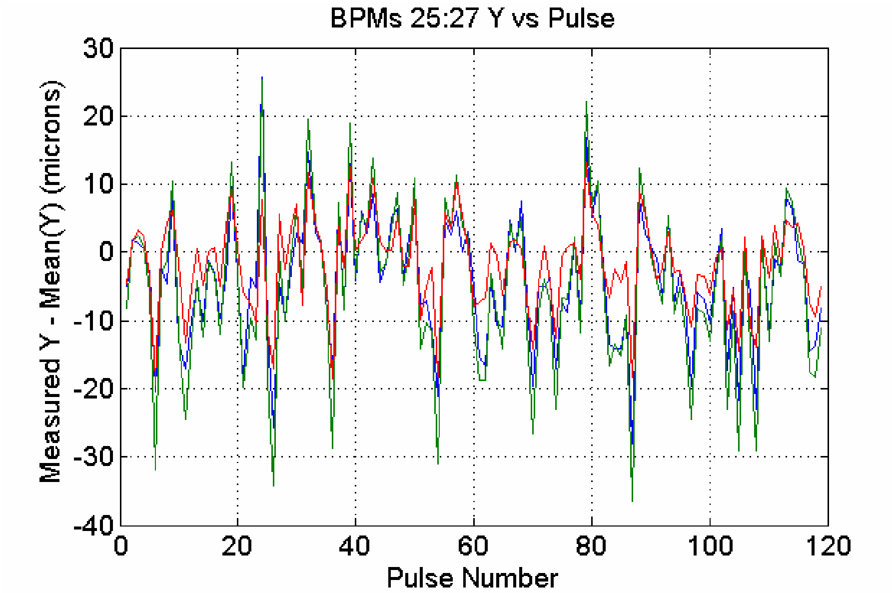


Resolution Measurement

- Measure resolution via correlation between BPMs
  - Coherent acquisition over
    - Many pulses e.g. 120 pulses
    - Many BPMs, e.g all 36 cavity BPMs
- Least-squares fit of each BPM (X,Y)
  - to linear combination of neighboring BPMs
- Model-independent
- Slightly biased estimate
  - underestimates resolution very slightly due to fit
    - Insignificant bias for Npulses >> Nbpms
  - Overestimates resolution slightly, assumes other BPMs are noise-free
    - Real resolution should be better by roughly 10%
    - Correction would depend on beta functions



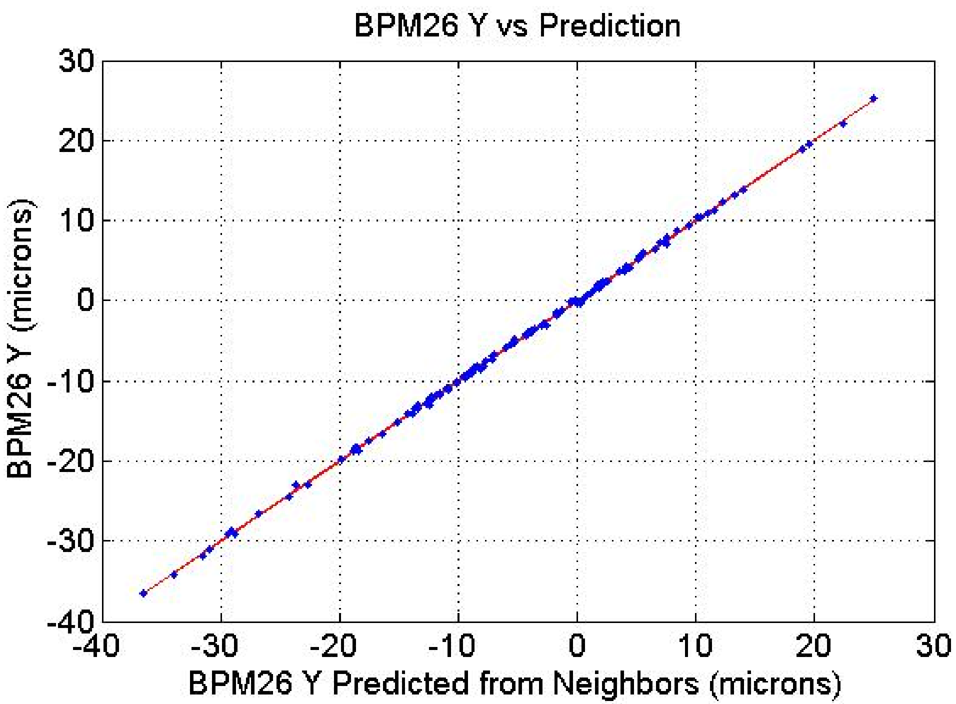
Resolution Measurement

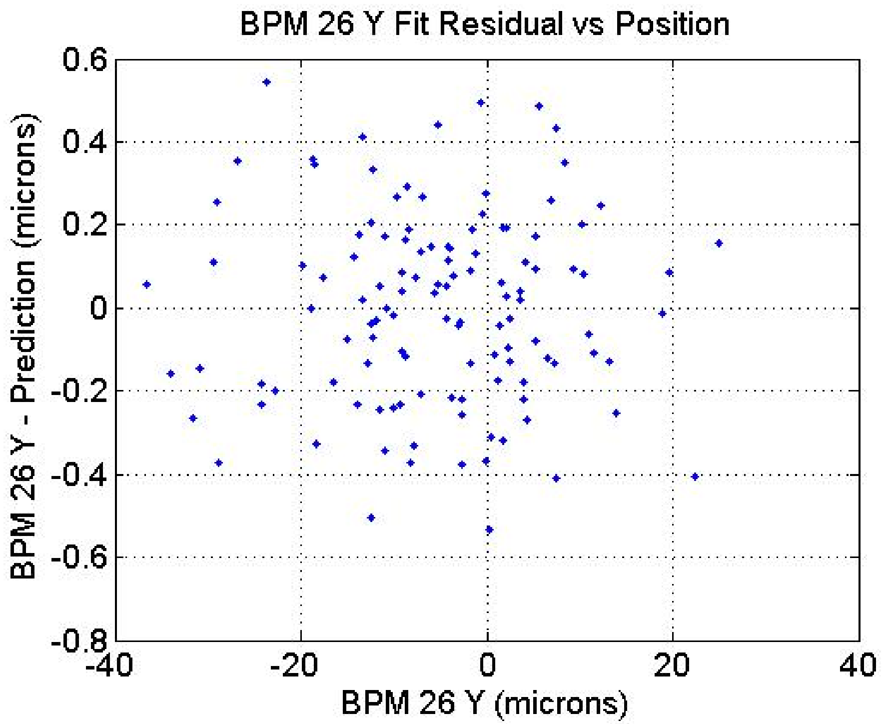


Example:

Fit the 26th BPM (the BPM on the 23rd undulator girder) to a linear combination of Y measurements in previous 2 BPM and next 2 BPM 120 beam pulses.

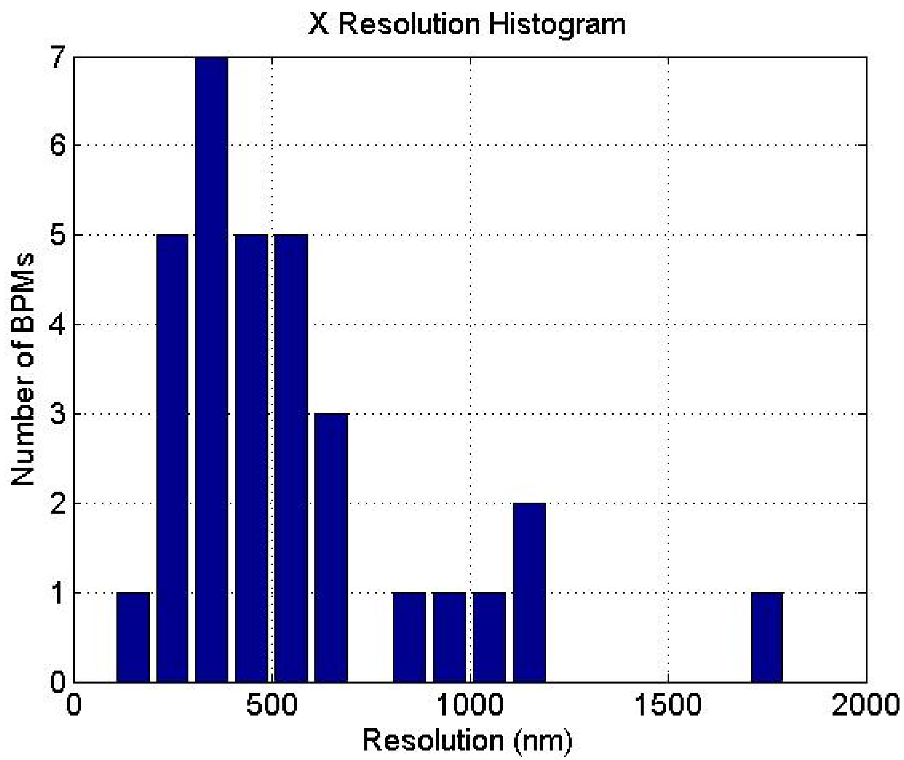
Plot fit & residual.

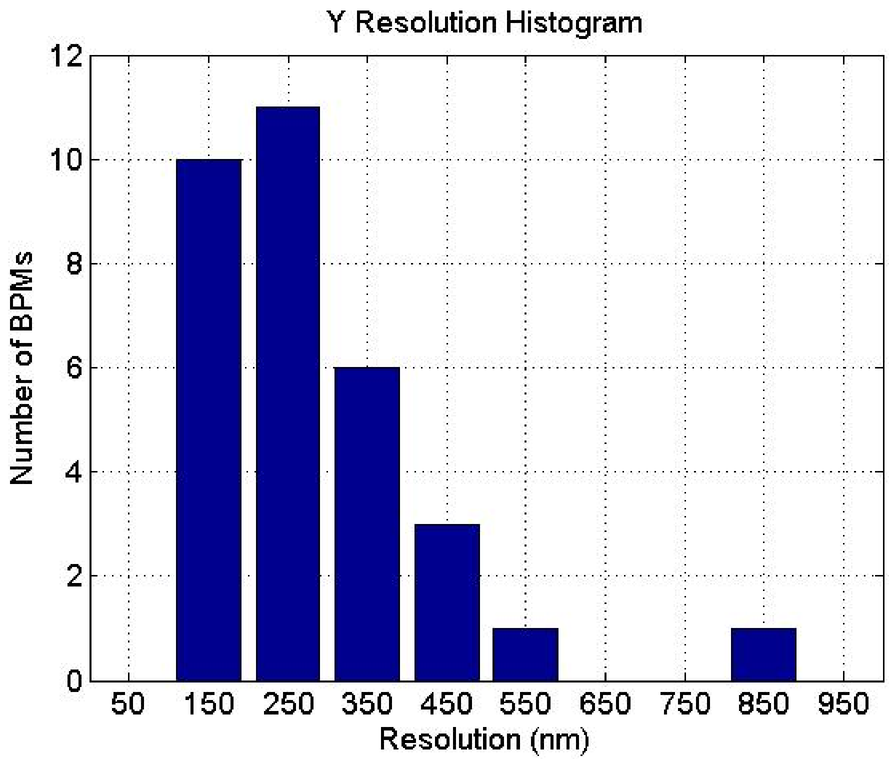




Position Resolution

- 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?
- Distribution of measured resolution:

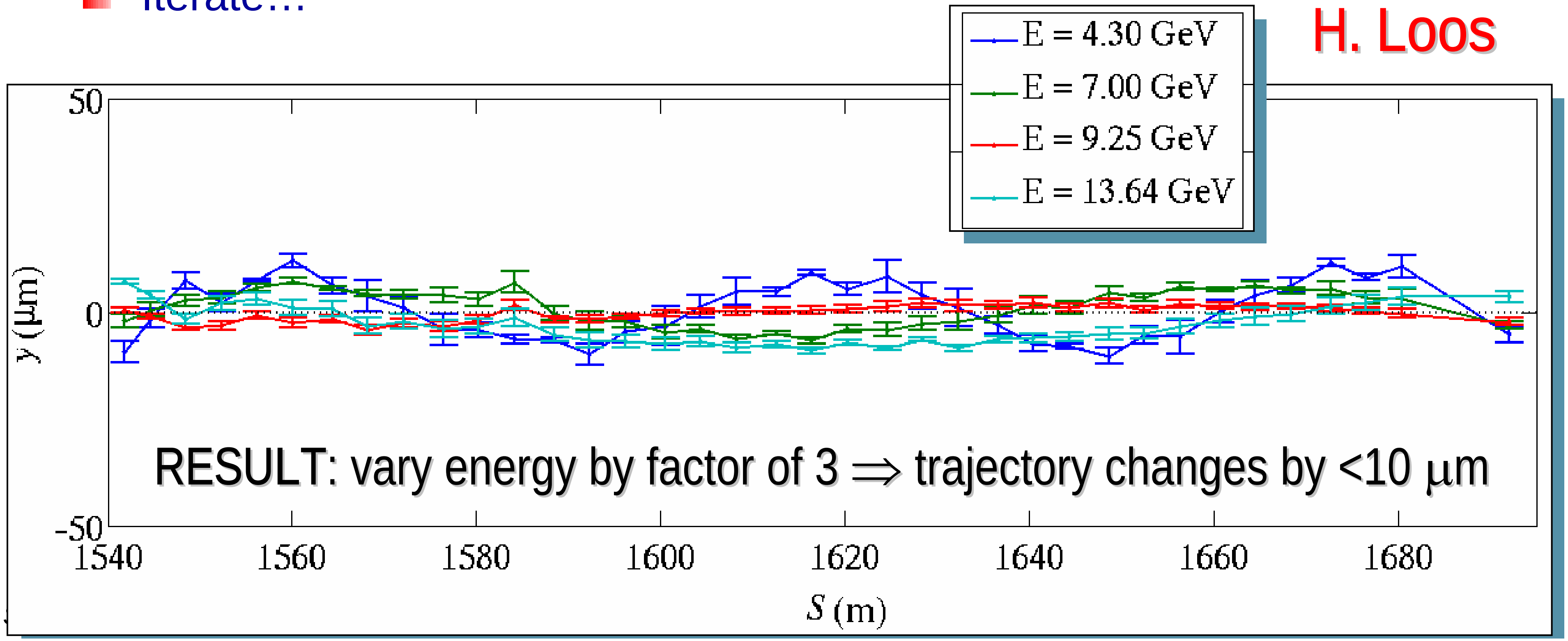




Beam-Based Undulator Alignment

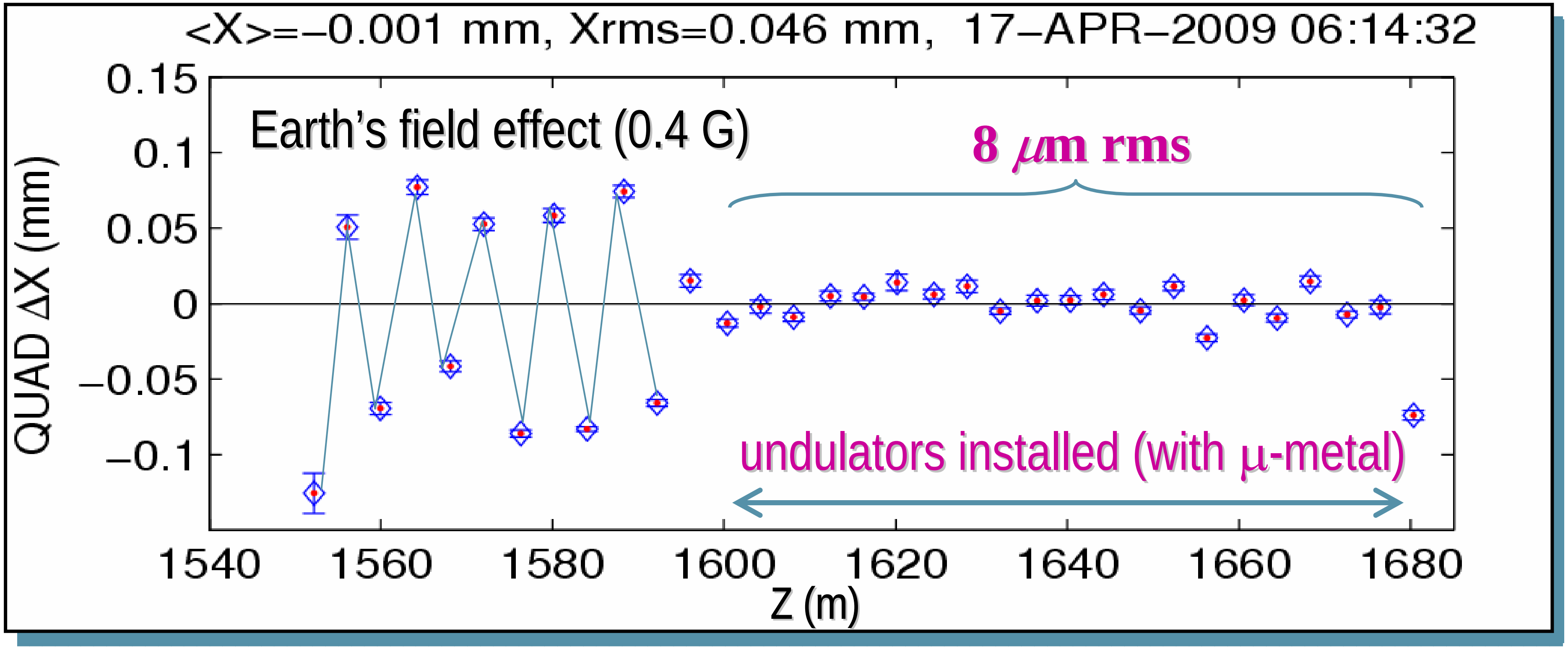
- Measure undulator trajectory at 4 energies (4.3, 7.0, 9.2, & 13.6 GeV)
- Scale all linac & upstream transport line magnets each time
- Do not change **anything** in the undulator
- Calculate… (*Matlab* GUI)
- Move quads and adjust BPM offsets for dispersion free trajectory
- Iterate…

H. Loos



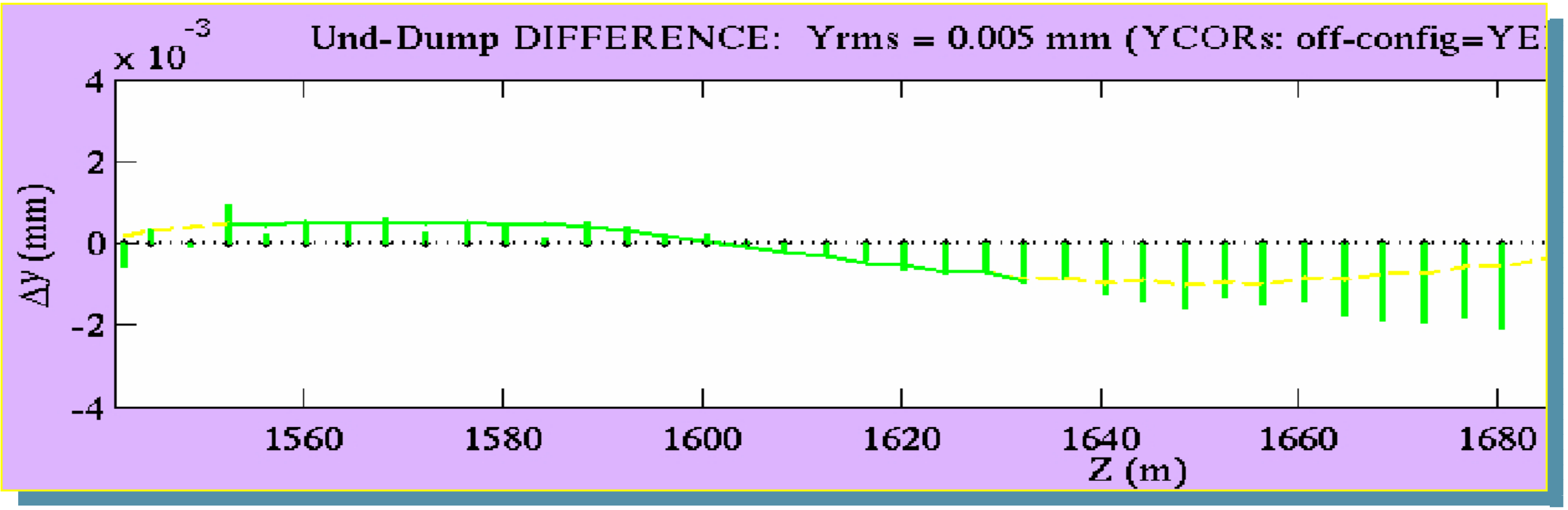
Undulator Quadrupole Alignment <u>after BBA</u>

- Vary each quadrupole magnet gradient by 30% sequentially
- Record kick angle using both upstream & downstream BPMs, adjusting for incoming jitter
- Calculate quadrupole magnet transverse offsets



Orbit fit in BPMs

- Three-parameter fit to difference orbit in 20 BPMs along undulator
  - y_0, y'_0, and $\Delta y'$
- Measure 30 nano-radian kick due to quad



±4 μm

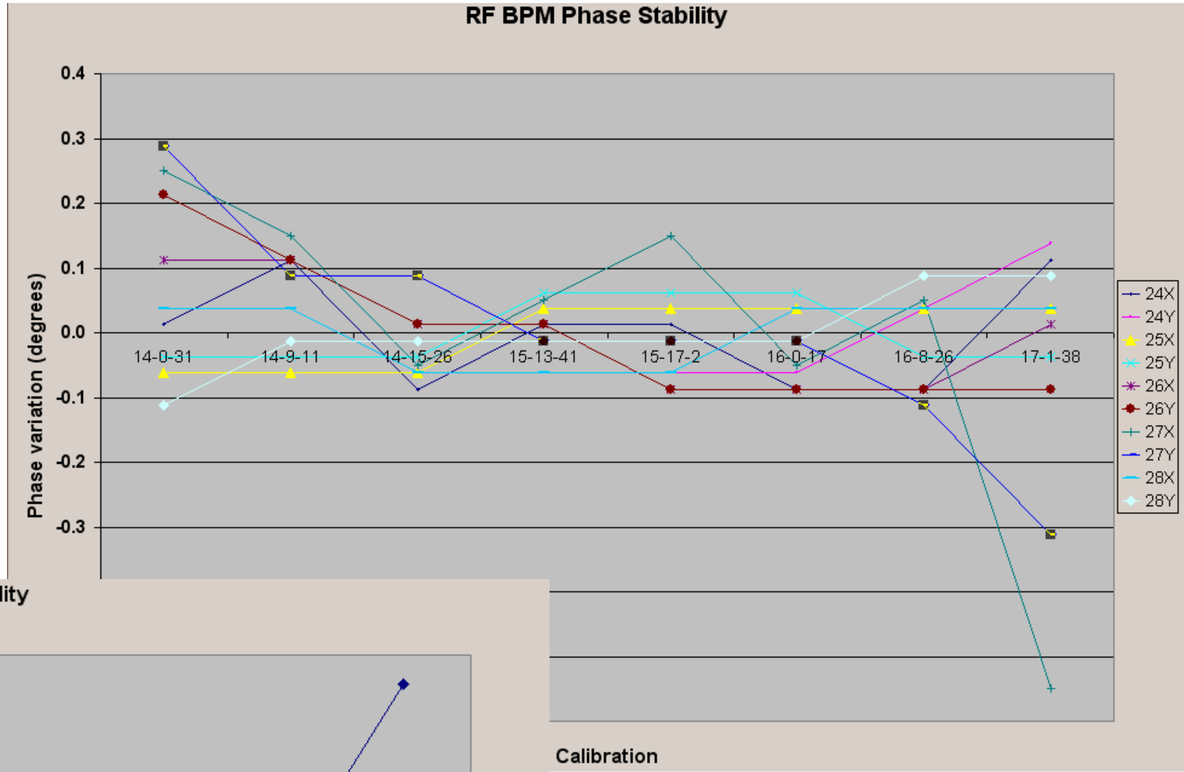
Stability of Calibration

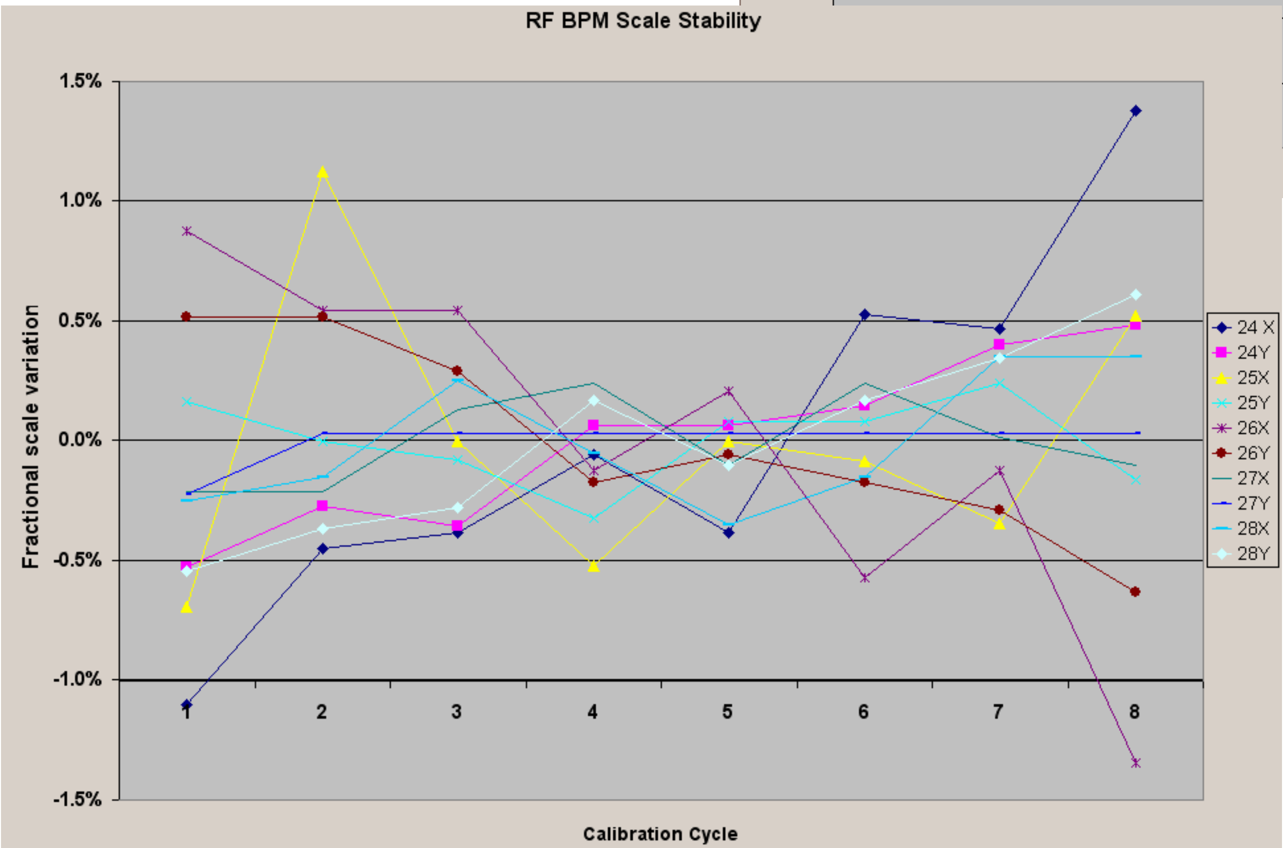
- Calibrate every shift for 3 ½ days

- Compare parameter drifts from day-to-day
- Compare new calibration to calibration taken weeks earlier
- Phase of position cavity with respect to reference cavity
  – stable short and long term to fraction of degree.
- Gain (coefficient of ratio of position to reference amplitude) possibly varies at ½% level, must check

Calibration Stability

- Calibrate BPMs
  - Mover calibration
  - once / shift for 3 days
- Phase stable to 0.1 deg
- Scale stable to <0.5%

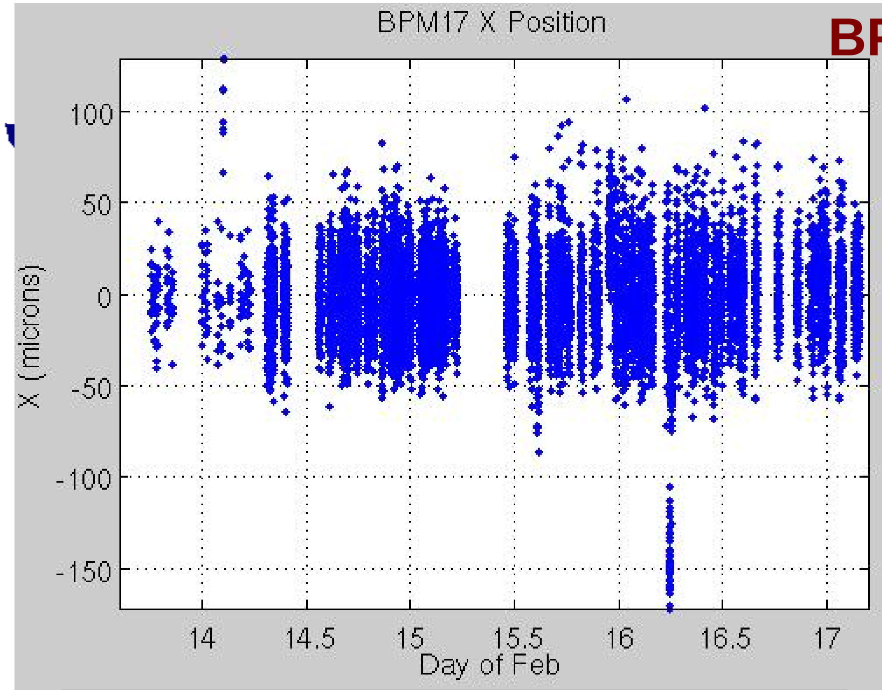


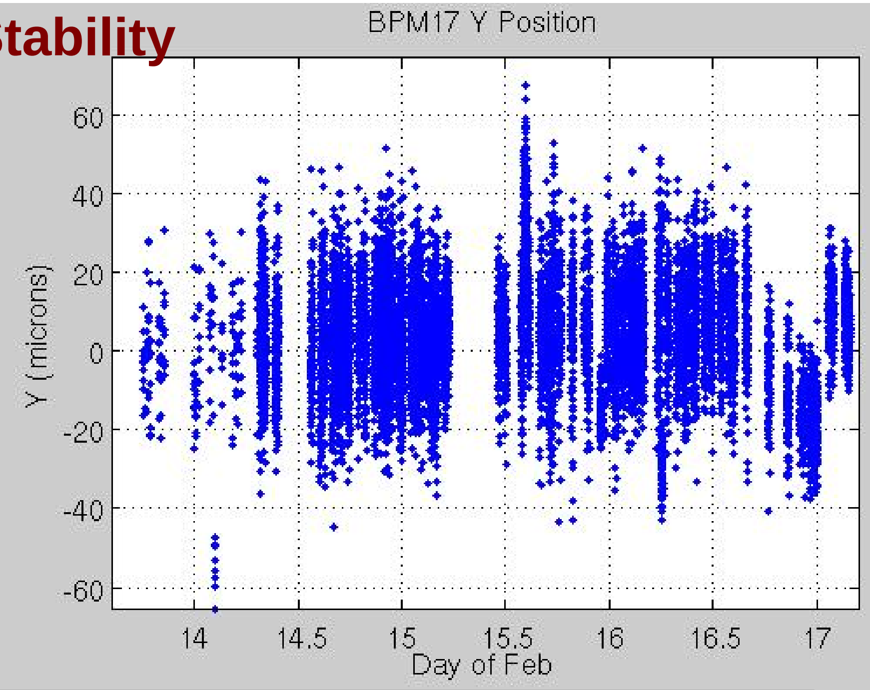


Measuring Stability in Presence of Beam Jitter

- Accumulate data parasitic to beam operations
- Take data periodically 120 shots every 20 min over 3½ days
  - Total >15,000 beam pulses
- Ignore first 10 girders
  - undulator feedback moves these to maintain launch into undulator
- Ignore downstream girders
  - periodic mover calibration running
- Beam jitter ~10 microns at this time
- Beam steering sometimes > 100 microns
- Must remove real beam motions:
- Take one run (120 pulses) from middle of weekend to learn correlation between each BPM and its neighbors
  - Fit linear coefficients to predict:
    - X_n from X_{n-1} and X_{n+1}
    - Y_n from Y_{n-1} and Y_{n+1}
    - Use these coefficients to predict Xn, Yn
    - Compare measurement to prediction BPMs pulse-by-pulse

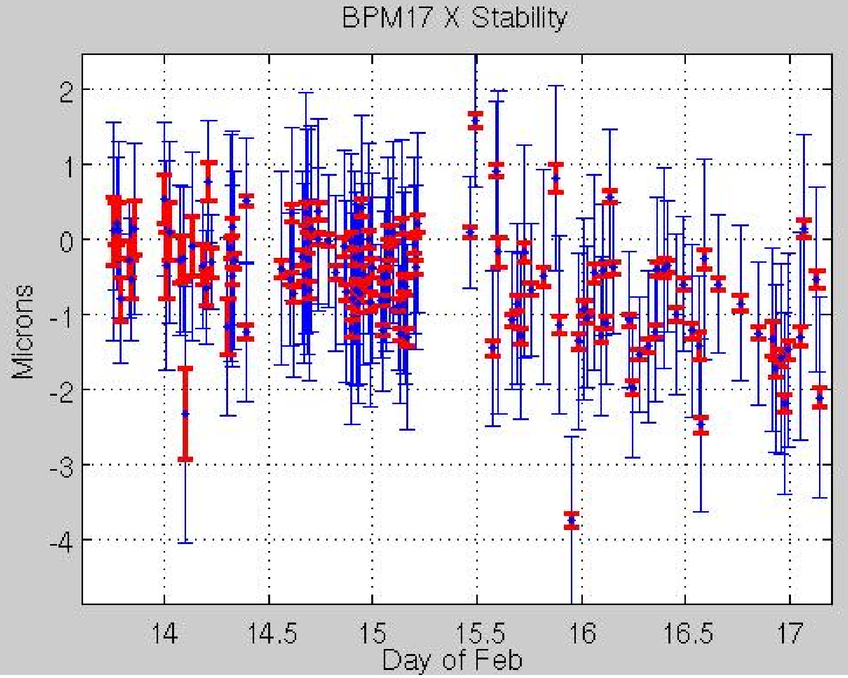
BPM Stability

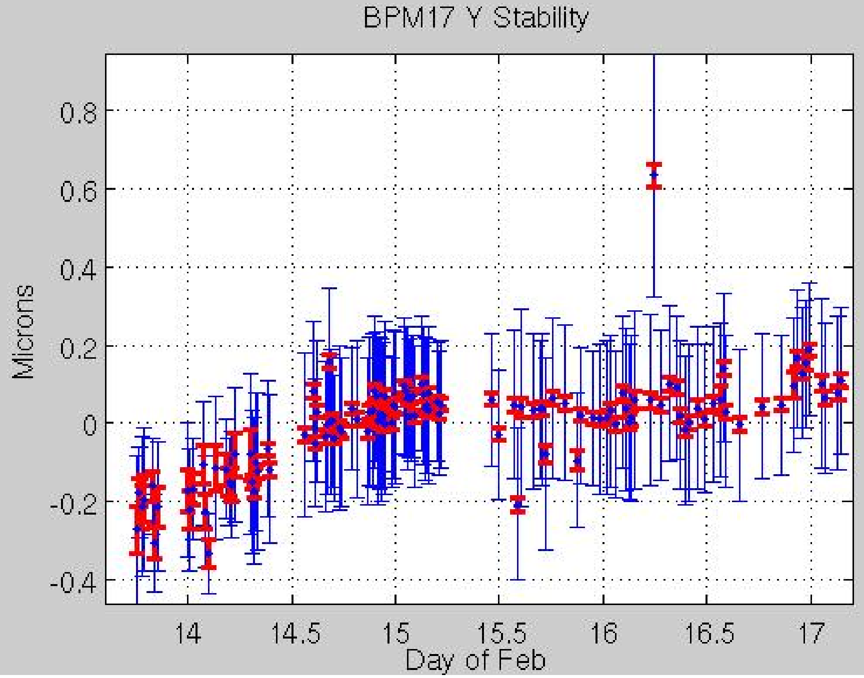




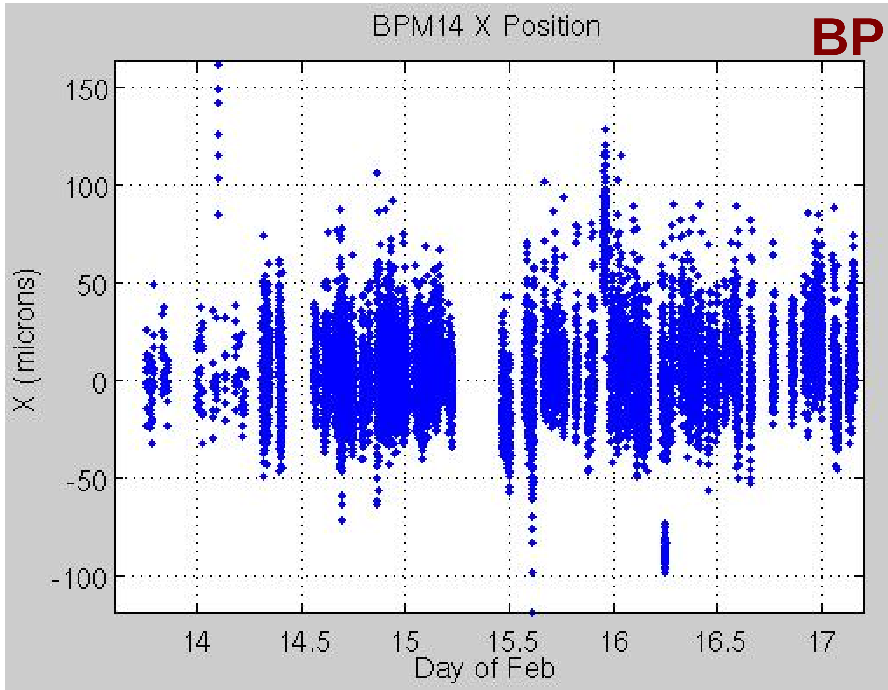
X resolution ~700 nm Stable to ~ 1 micron /day

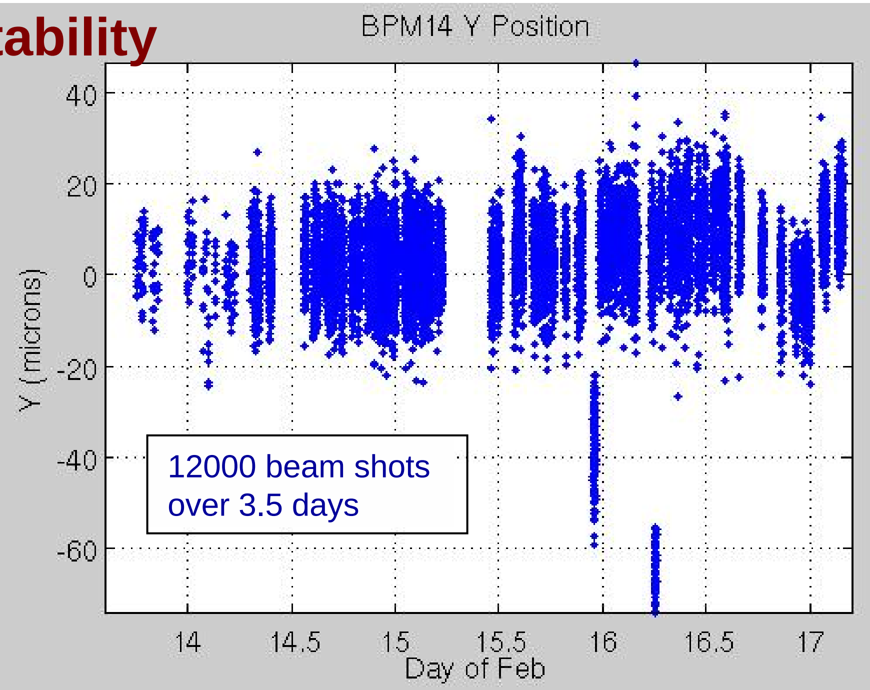
Y resolution ~180nm Stable to < 200 nm over 3 days





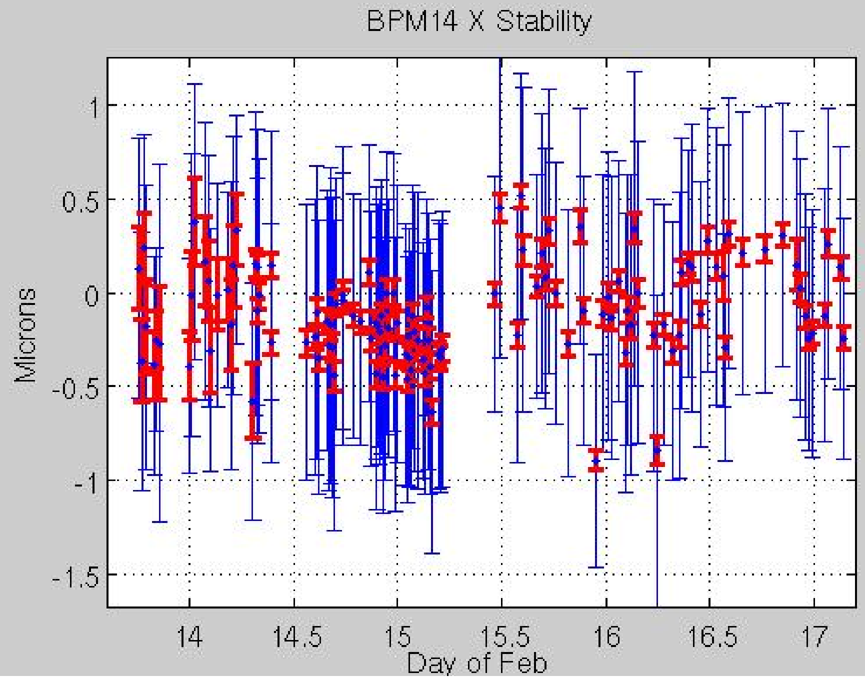
BPM Stability

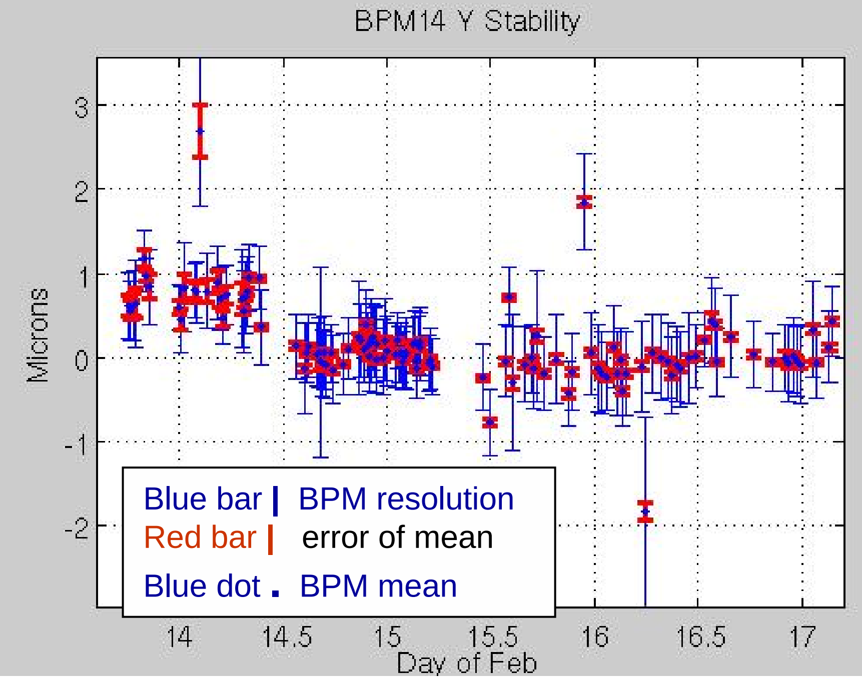




X resolution ~750 nm Stable to ~ 1/2 micron /day

Y resolution ~400nm Stable to <1 micron per day





Longer-Term Stability Issue

- Above stability tests done in February
- March shutdown to install undulator
- Begin undulator operation in April
- Find substantial gain changes in BPM X-band receivers
- Up to 10 dB worst case
- Unlikely pssibilities:
  - Radiation
  - Overvoltage
- Investigating:
  - EXamples sent back to ANL and to Miteq 3 weeks ago

Offsets

- Currently don't know much about BPM offsets
  - Early studies showed BPM offsets ~50 microns in Y
  - Up to 400 microns in X
  - Should be symmetric
  - Alternating pattern of X-offsets matches what is expected to compensate earth's field, but scale is 3X expected.
- So far FEL commissioning has priority over understanding BPM offsets

Potential Improvements

- Understand receiver gain loss
- Lower noise figure possible
  - Noise figure dominated by input pad
  - Can absorb out of band power without attenuating in-band signal
  - Potential to improve resolution by up to 14 dB
- In-line calibration
  - Can introduce calibration signal from opposite ports
  - Presently terminated
- Subliminal calibration
  - Can calibrate with beam motion << beam jitter
  - Could perform continuous calibration while lasing
  - using with few-micron amplitude motion