Next Linear Collider Beam Position Monitors

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October 23, 2002

What's novel, extreme, or challenging?

- Push resolution frontier
  - Novel cavity BPM design for high resolution, stability
  - Push well beyond NLC requirements
- Push bandwidth frontier
  - Stripline BPM with very high bandwidth and resolution
- Pickup-less BPM
  - HOM-Damped RF structures as position monitors
- Low propagation delay BPM
  - Feedback within bunch-train crossing time (250 ns)

NLC Linac BPMs

- "Quad" BPM (QBPM)
  - In every quadrupole (Quantity ~3000)
  - Function: align quads to straight line
  - Measures average position of bunch train
  - Resolution required: 300 nm rms in a single shot
- Structure Position Monitor (SPM)
  - Measure phase and amplitude of HOMs in accelerating cavities
  - Minimize transverse wakefields
  - Align each RF structure to the beam
  - 22 k devices in two linacs
- "Multi-Bunch" BPM (MBBPM)
  - Measure bunch-to-bunch transverse displacement
  - Compensate residual wakefields
  - Measure every bunch, 1.4 ns apart
  - Requires high bandwidth (300 MHz), high resolution (300 nm)
  - Line up entire bunch train by steering, compensating kickers

Other NLC BPMs

- Damping Ring
  - Button pickups
  - Rather conventional, like 3rd generation light sources
  - But higher readout rate (~MHz)
- Interaction Point Intra-Train Deflection Feedback
  - Correct beam-beam mis-steering within time of train crossing
  - Low propagation delay!

NLC "QBPM"

- Mainstream workhorse BPM
- In every quadrupole +
- Requires high resolution 300 nm
- Stability
- Single bunch to 180 bunches
- Stripline vs. cavity pickup?
- Cavity with novel coupler

QBPM Requirements

Parameter	Value	Conditions
Resolution	300 nm rms	@ 10^{10} e^- single bunch
Position Stability	1 μm	over 24 hours **(!)**
Position Accuracy	200 μm	With respect to the quad magnetic center
Position Dynamic Range	$\pm$2 mm	
Charge Dynamic Range	5×10^8 to 1.5×10^{10} e^- per bunch	
Number of bunches	1 - 190	Singlebunch - multibunch
Bunch spacing	1.4 ns	

Use Striplines for Q BPM?

- Electronics in tunnel enclosure
- Signal amplitudes in a ~30 MHz band around 714 MHz are demodulated and digitized
- Critical elements:
  - Front-end hybrid
  - Calibration signals
  - Sampler / digitizer choices:
    - Direct analog sampling chip + slow, high resolution ADC?
    - IF downconversion + fast, high resolution ADC?
  - Digital receiver algorithms for amplitude reconstruction
    - bandpass filter
    - digital downconversion
    - low pass filter
  - Position proportional to ratio of amplitude difference/sum

Can we achieve 300 nm resolution?

- Example: Final Focus Test Beam Position Monitor
  - Achieves single bunch resolution of ~1.2 µm rms @ 9 x 109 e-
  - Algorithm: low pass filter, sample, digitize
  - Bandwidth ~30 MHz
  - Micron resolution is a few dB above thermal noise floor

- NLC Q-BPM
  - Beam pipe radius is factor of two smaller
  - Process signal where it is big, i.e. 714 MHz instead of 32 MHz
  - Noise floor is not an issue
  - Must control systematics

What's wrong with striplines?

- Striplines are difficult to fit into limited quad ID
- Accuracy hard to establish
  - Works on small differences of large numbers
- Position accuracy / stability requires precision of many elements
  - Internal elements
    - Stripline position
    - Feedthroughs
    - Termination
  - External elements
    - Cables
    - Connections
    - Processor

QBPMs Should be Cavities!

- Cavity BPM features:
  - Signal is proportional to position
  - Less common-mode subtraction than for strips
  - Simpler geometry
  - Accuracy of center better, more stable
  - Pickup compact in Z dimension

- Cavity Drawbacks:
  - Higher processing frequency
  - Are wakefields tolerable?

Cavity BPM

- Pick a basic design and evaluate characteristics
- Pillbox cavity, for example
- Choose frequency, processing scheme
- Calculate
  - Dimensions
  - Sensitivity
  - Noise figure budget
  - Common-mode rejection
  - Wake fields

Operating Frequency

- Sensitivity increases with frequency
- Size decreases with frequency
- Cable loss increases
- Cost of electronics increases
- Should be multiple of 714 MHz bunch spacing
- Possible operating frequencies:
  - 2856 MHz (cavities are too big!)
  - 5712 MHz (inexpensive commercial parts)
  - 11.424 GHz (share phase cavity with LLRF)
  - 14.280 GHz (integrate position cavities with RF structure)
- Example: 11.424 GHz

Cavity BPM Parameters

Parameter	Value	Comments
Dipole frequency	11.4 GHz	
Monopole frequency	7.2 GHz	
Cavity Radius	16 mm	
Wall Q	~4000	Ignoring beam duct, etc
Cavity coupling	$\beta = 3$	
Loaded Q	1000	
Bandwidth	11 MHz	
Beam aperture radius	6 mm	
Sensitivity	7 mV/nC/μm	(too much signal!)
Bunch charge	0.7×10^{10} e^-	Per bunch
Signal power @ 1μm	- 29 dBm	Peak power
Decay time	28 ns	
Required resolution	$\sigma = 200$ nm	
Required Noise Figure	57 dB	For $\sigma = 100$ nm, thermal only
Wakefield Kick	0.3 volt/pC/mm	Long range
Structure wakefield kick	~2 volt/pC/mm	Per structure
Short-range wakefield	~1/200th of structure	

Common Mode

How much does monopole mode leak into dipole mode frequency?

This creates an apparent beam centering offset.

But processor looks only at dipole-mode frequency

And uses odd-mode coupler to eliminate even-symmetry mode

Comparison	Voltage	Ratio
Ratio of monopole mode voltage to dipole mode voltage due to 1 mm beam offset, measured at outer radius of pillbox	4200	72 dB
Tail of monopole mode at dipole-mode frequency	3.5	11 dB
Coupler rejection of monopole mode (-30dB)	0.1	-19 dB

So the common-mode leakage is negligible.

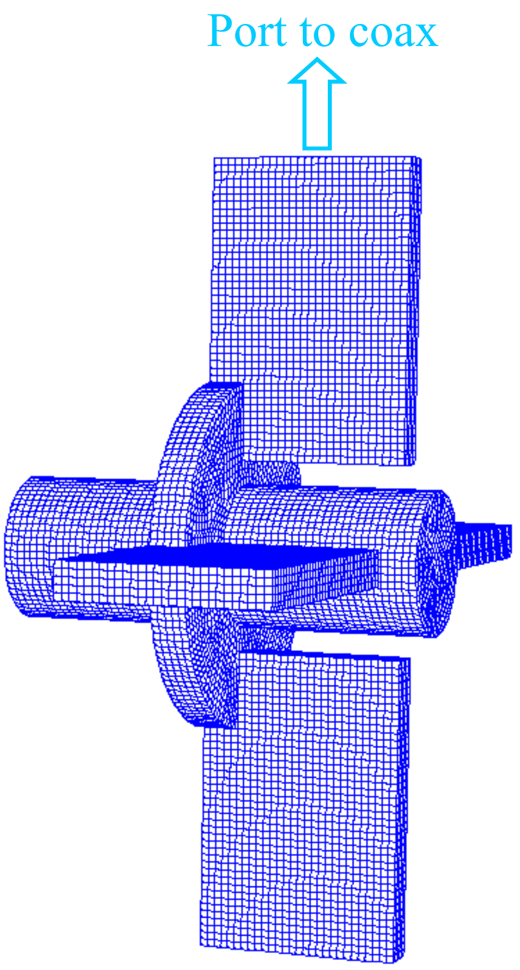
(Even if the offset were tens of microns, its just a fixed offset)

BPM Cavity with TM_{110} Couplers

- Dipole frequency: 11.424 GHz
- Dipole mode: TM11
- Coupling to waveguide: magnetic
- Beam x-offset couple to "y" port

- Sensitivity: 1.6mV/nC/μm
  (1.6×10^{9}V/C/mm)

- Couple to dipole (TM11) only
- Does not couple to TM01
  - May need to damp TM01
  - OR, use stainless steel to lower Q
- Compact
- Low wakefield



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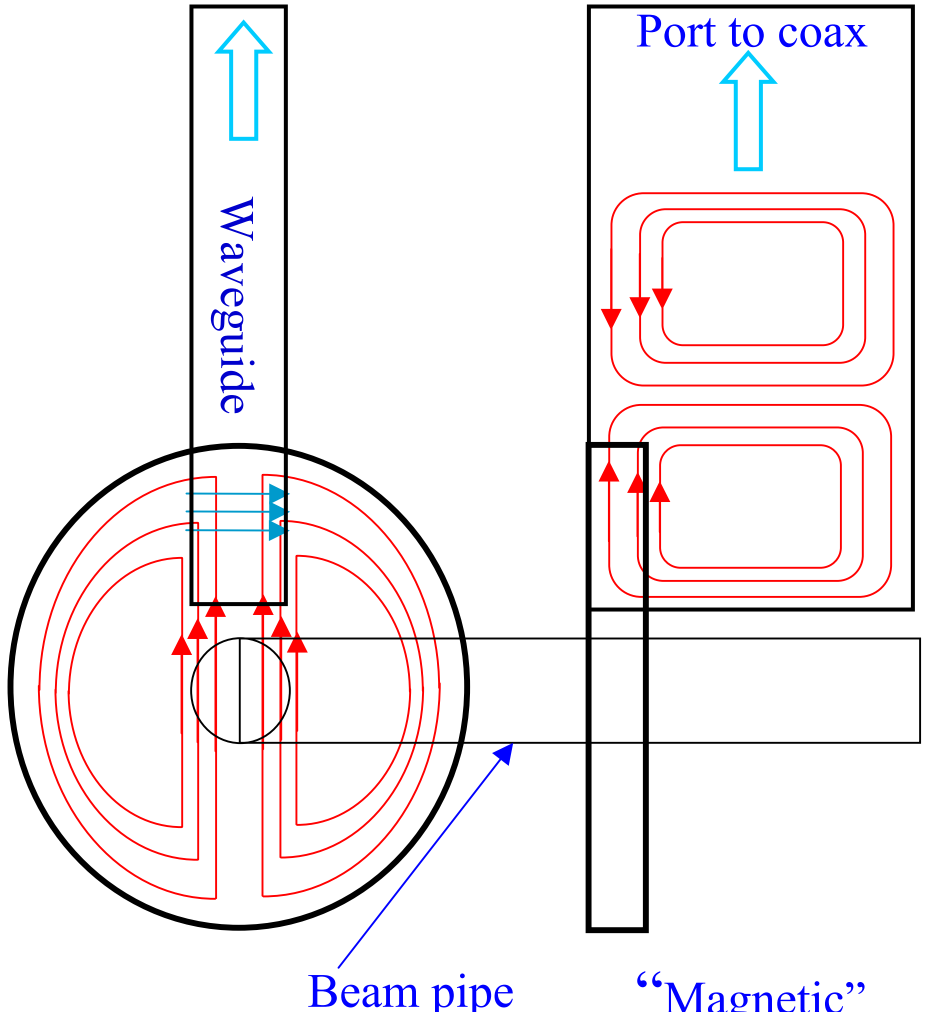
TM_{110} Mode Coupler



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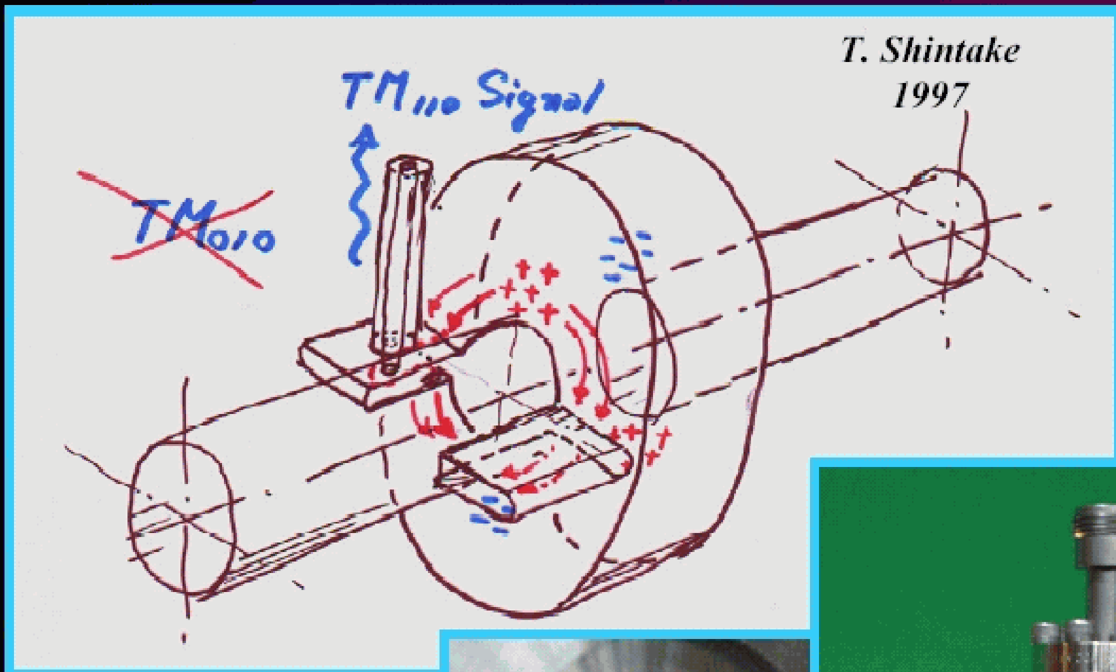
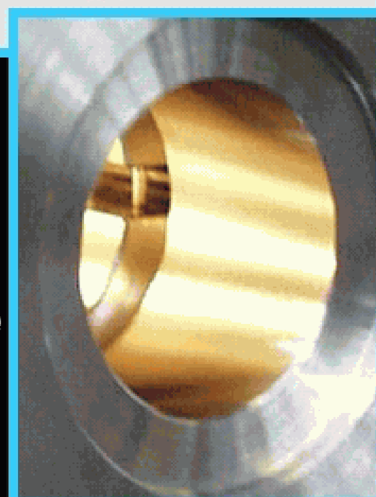
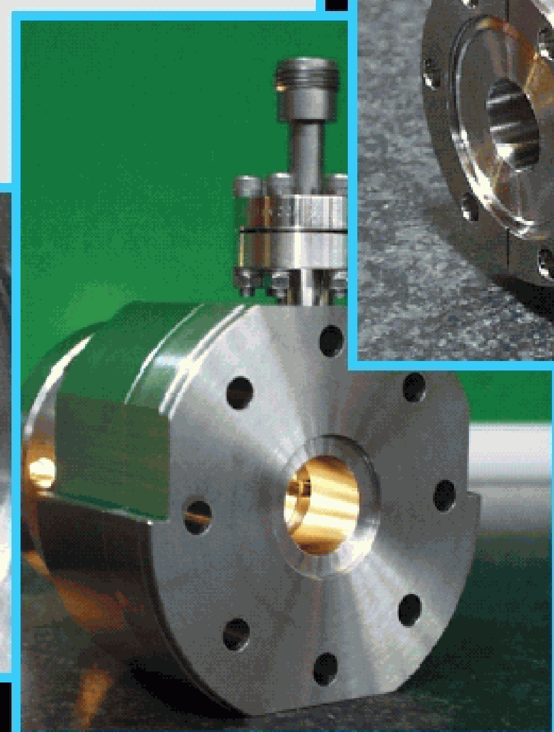
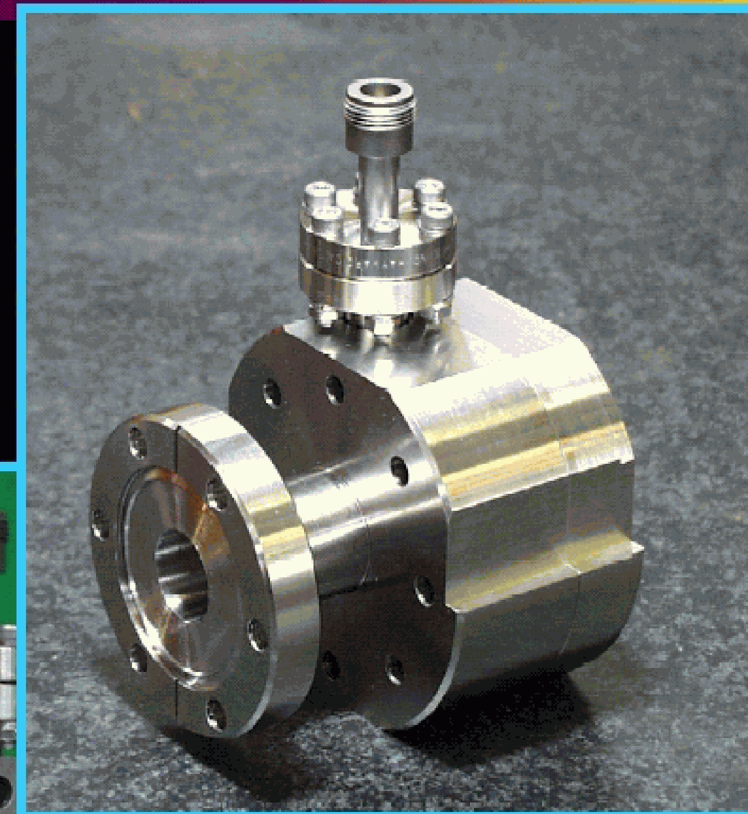
COM-Free BPM





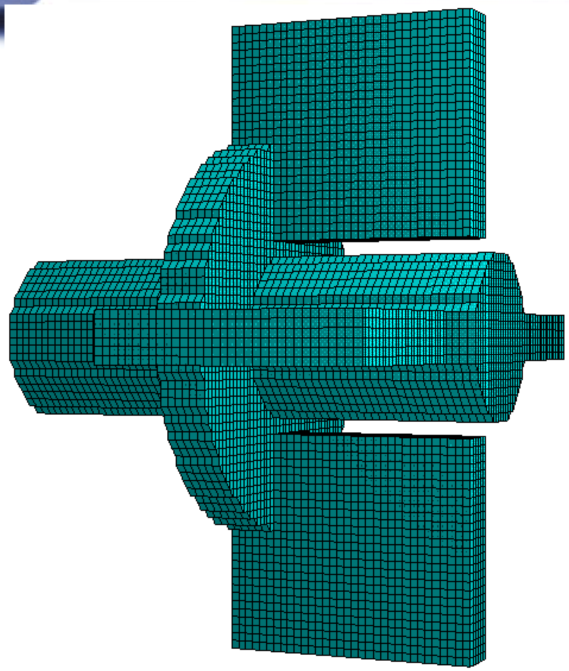


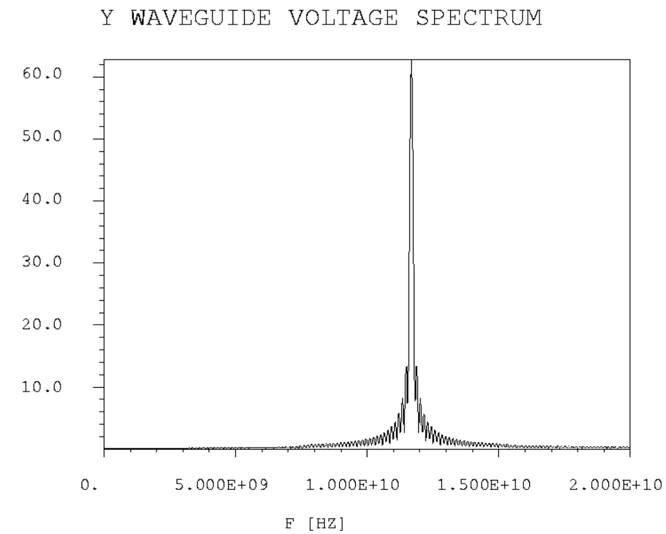


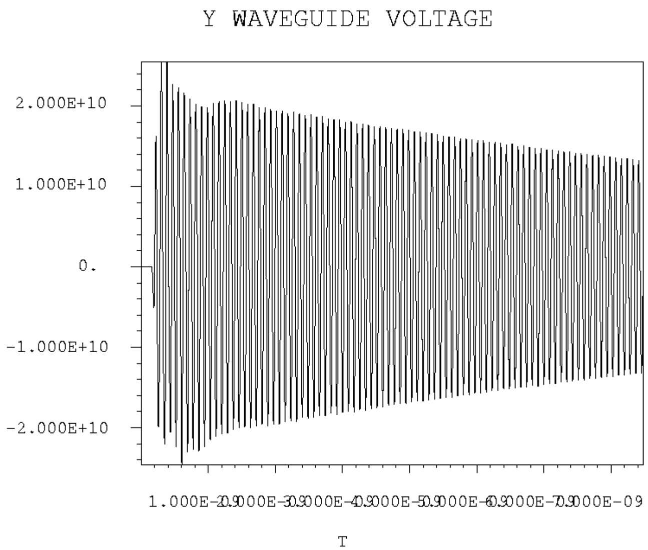
TM010 mode does not couple out to pickup antenna.

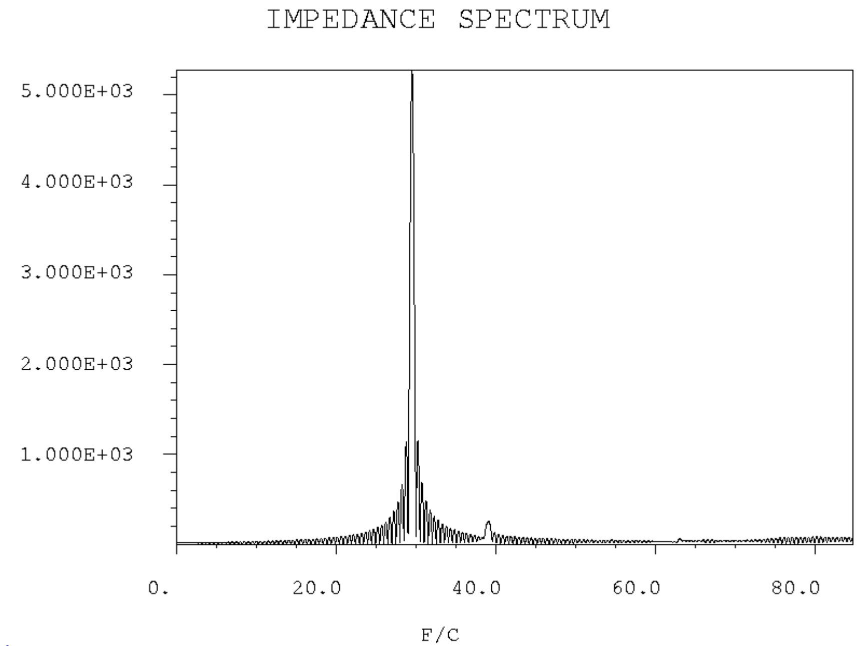
will be used for C-band Accelerator Alignment

Waveguide Signal With Beam Excitation









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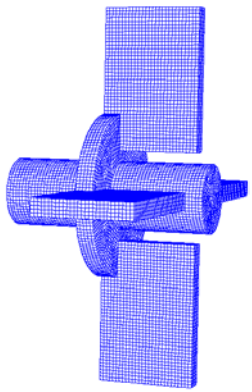
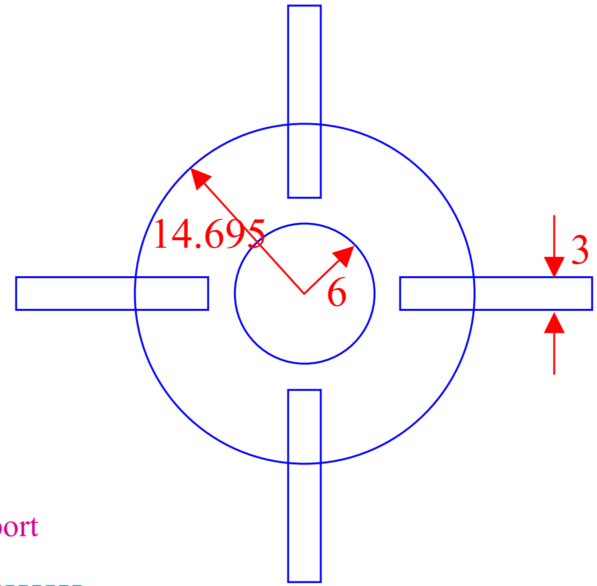
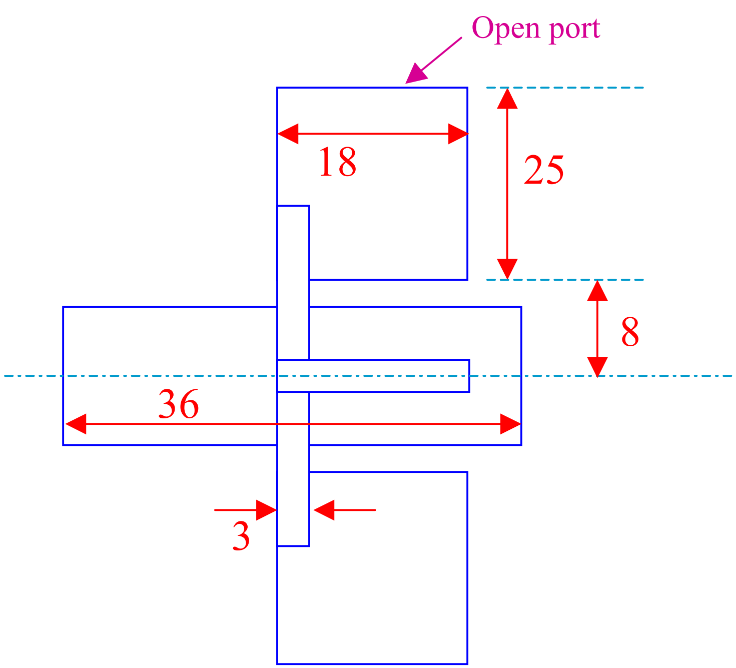
Cavity Dimensions





Cavity sensitivity (?)

- dF/db: -0.78 MHz/μm
- dF/da: +0.022 MHz/μm
- dF/dL:+0.042 MHz/ μm



sharp iris	MAFIA	Omega2	Omega2 prediction
$r_{cav\ (mm)}$	14.2	14.2	14.695
F_1 (with guide)	12.17413		11.424
F_1 (no guide)	12.30448	11.96617	11.55435
ΔF_1	0.13035		

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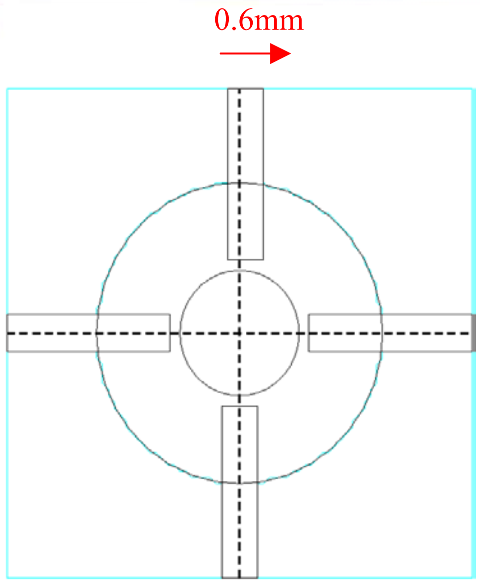
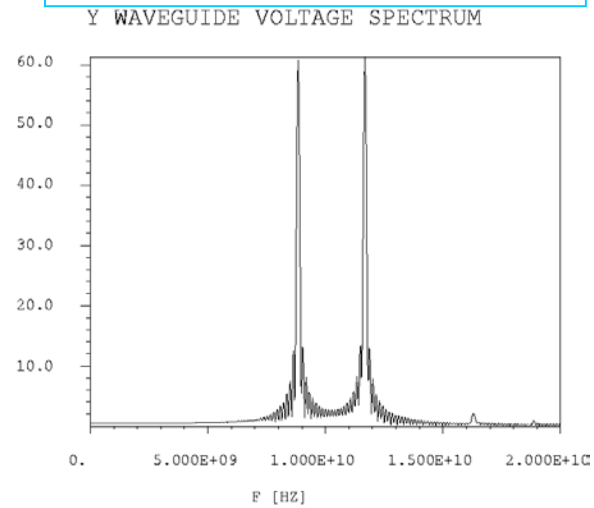
Azimuthal Misalignment

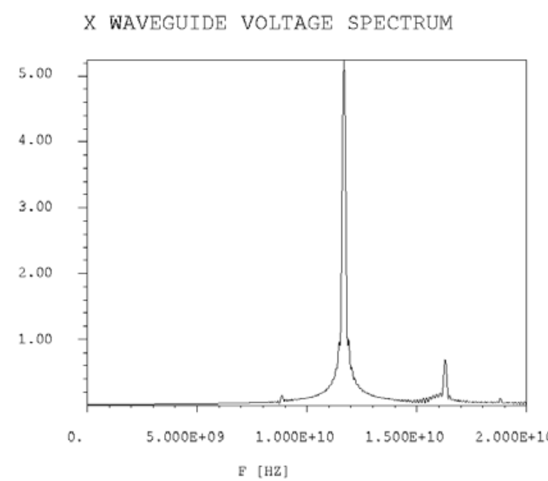


Beam offset: 1.2mm
TM01+TM11 in misaligned port



- Monopole modes sensitivity to displaced coupler:
  - dx’/dx ~ 2 in power ratio
  - <0.01 monopole mode measured at dipole mode frequency
- We do get X-Y coupling

X-Y Coupling



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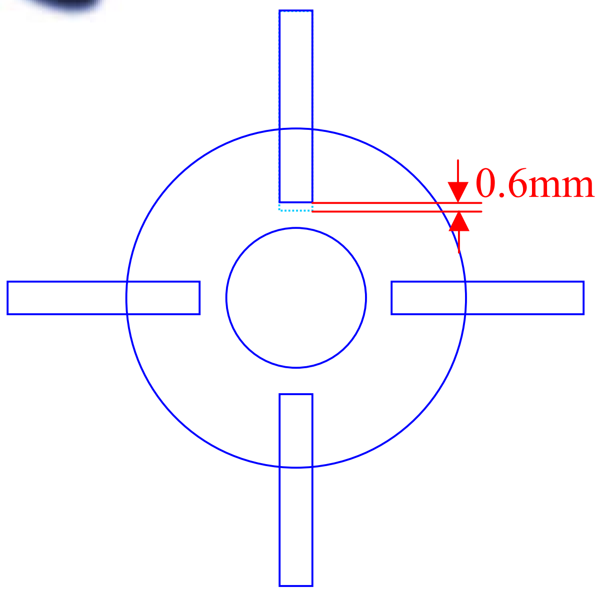
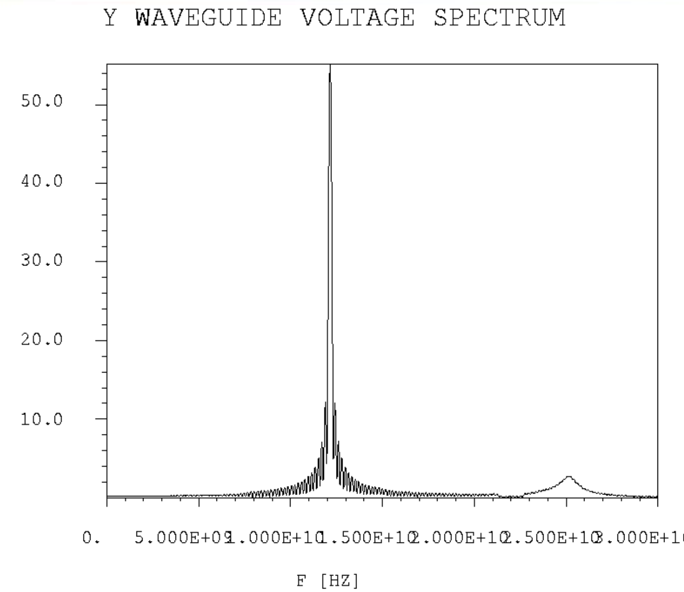
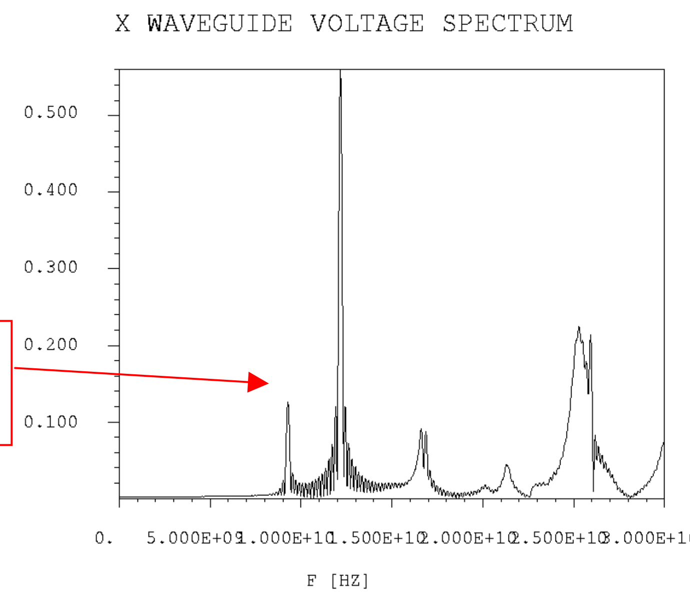
Radial Misalignment







- Small x-y coupling
- Little fundamental mode

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Excellent Performance (in simulation)

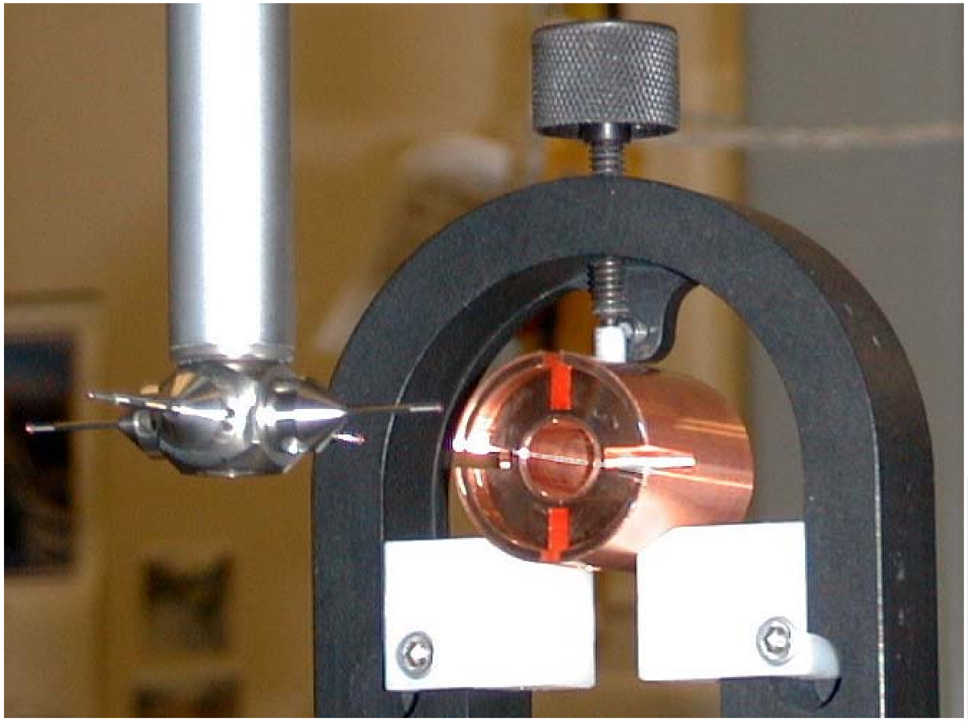
- Relatively easy to fabricate
- Tolerant of errors
- Strong signal
- Good centering
- Small wakefields

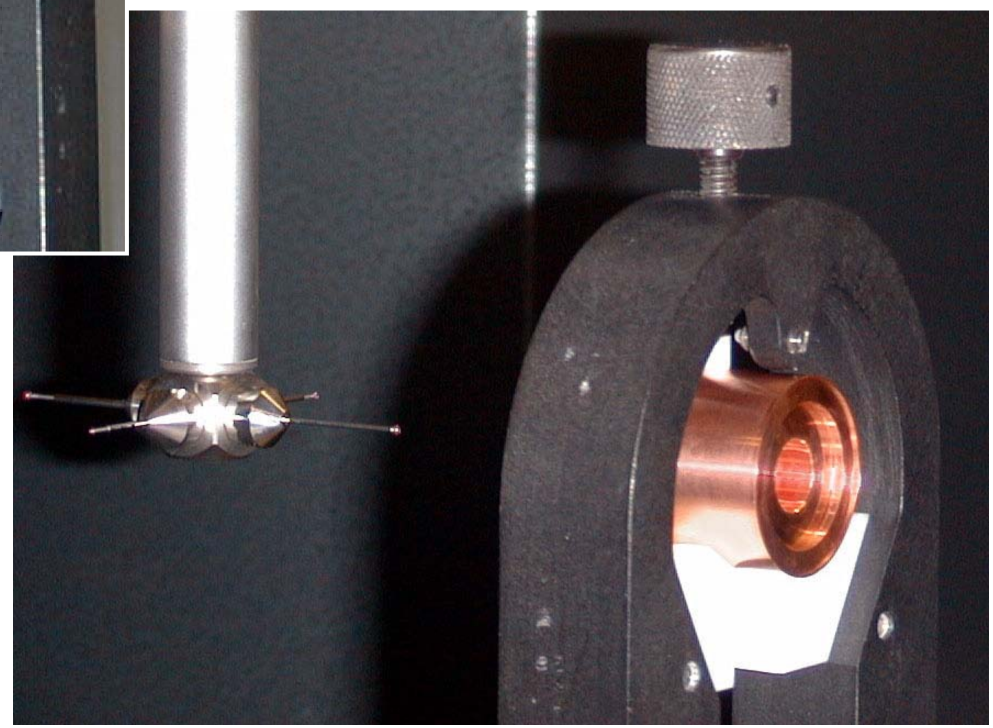
- $\Rightarrow$ Build prototypes

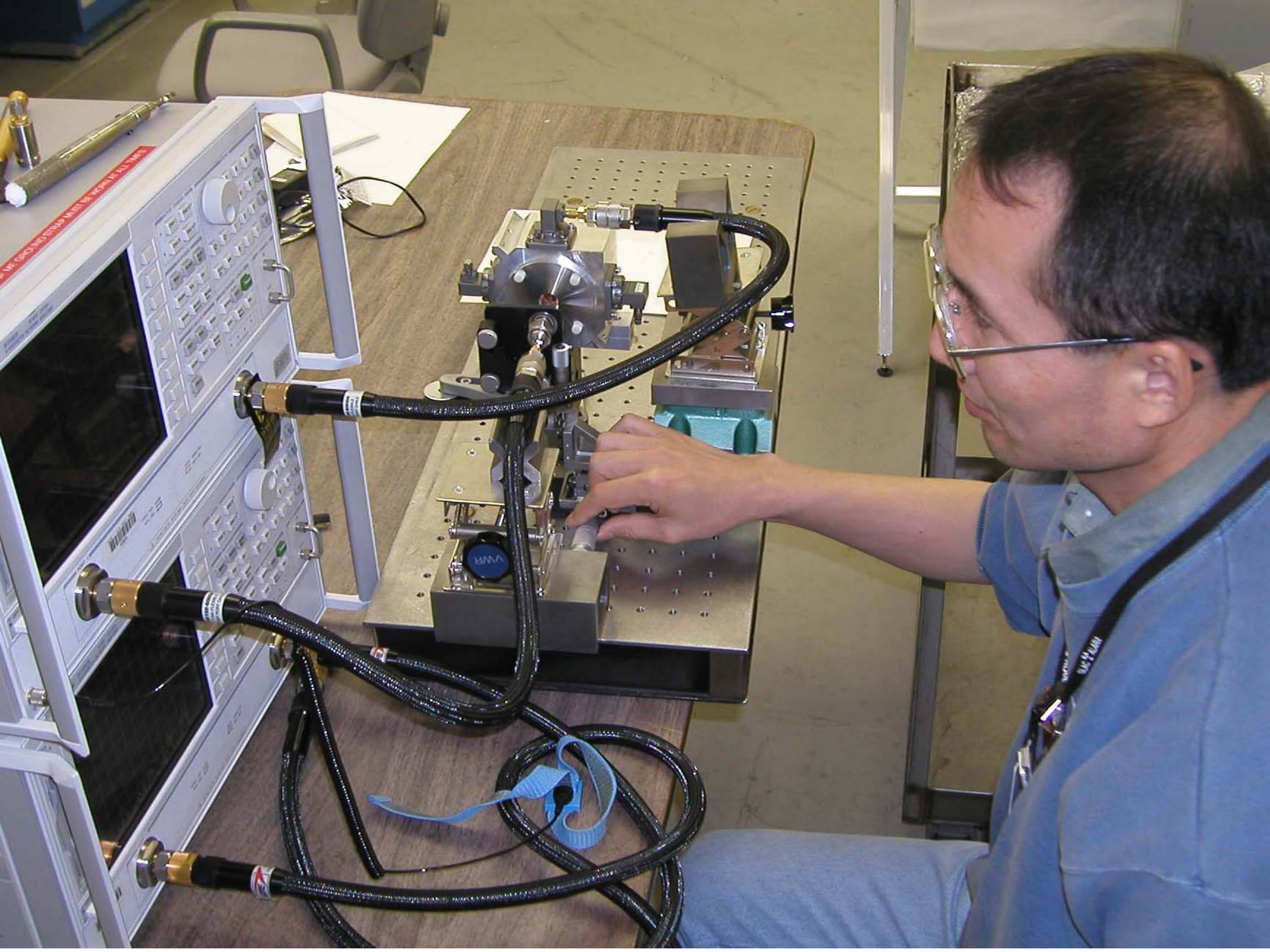
Develop Cavity BPM Prototype

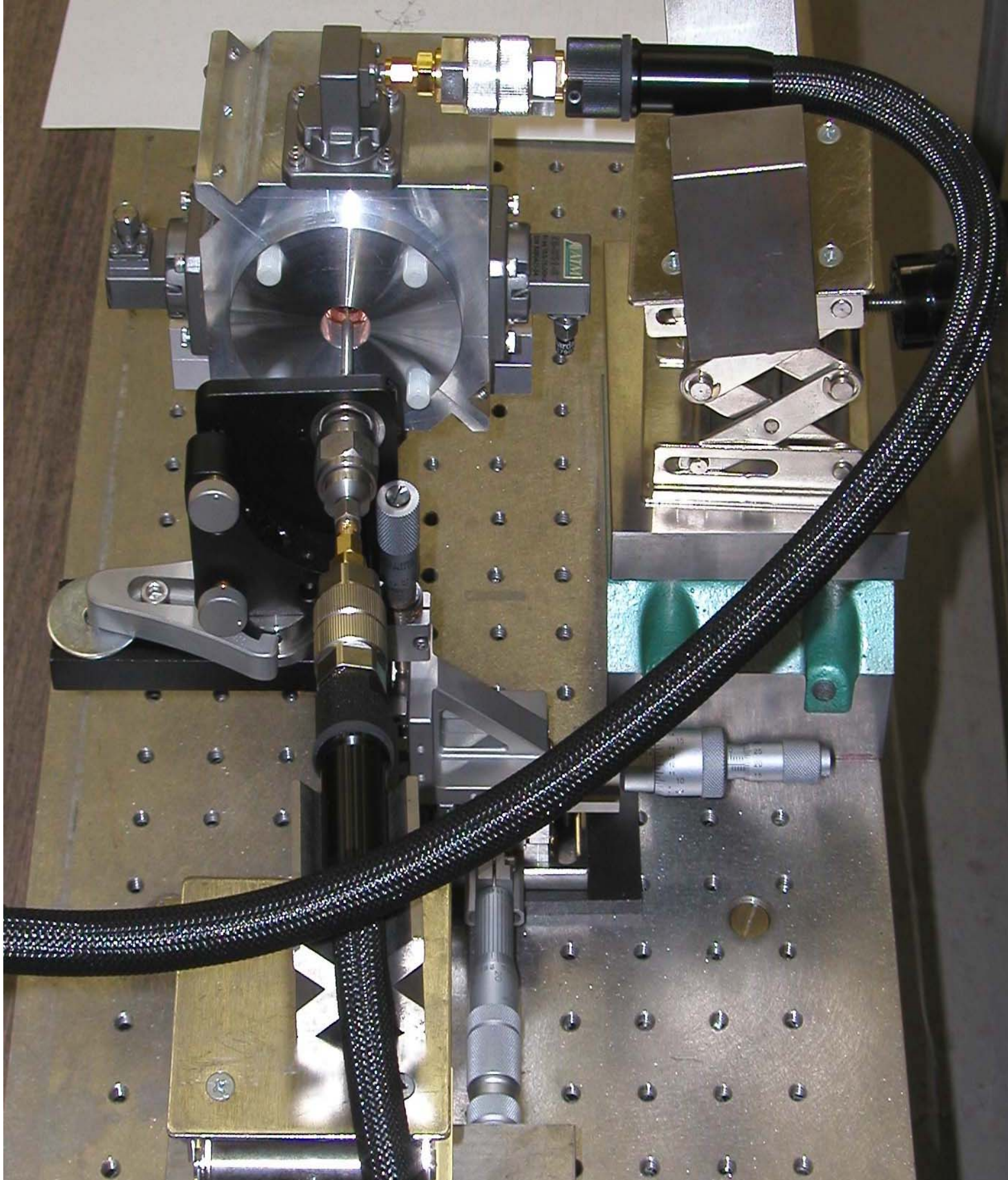
- Team:
  - Ron Johnson, Zenghai Li, Takashi Naito, Jeff Rifkin, S. Smith
- Frequency: 11.424 GHz
- Axially symmetric X-Y cavity
- TM_{110} mode couplers designed by Z. Li
- Two couplers per mode for prototype cavity
- Integrate fundamental mode phase reference cavity in same block.
- Measure on bench
- In beam

Cavity Body

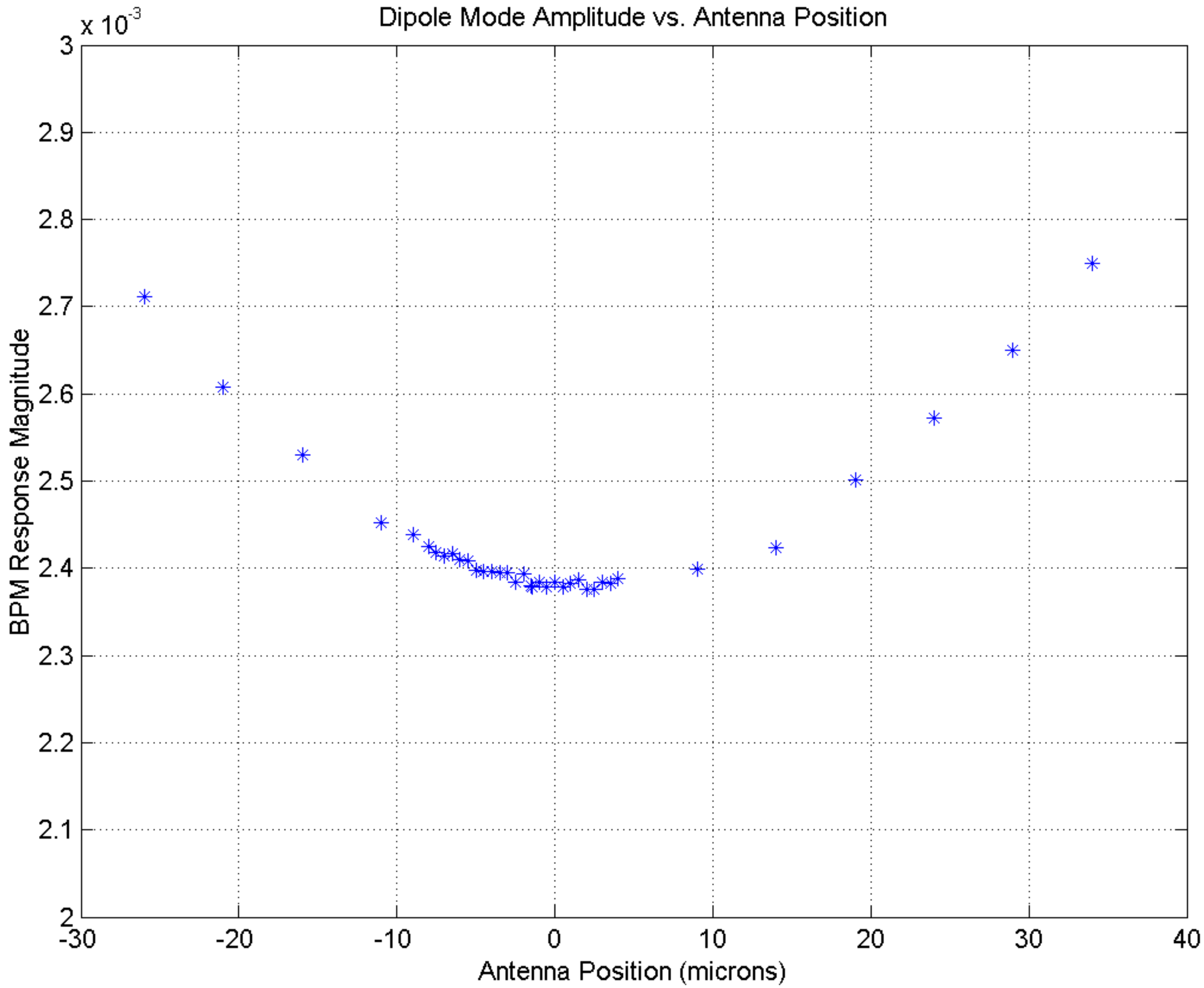






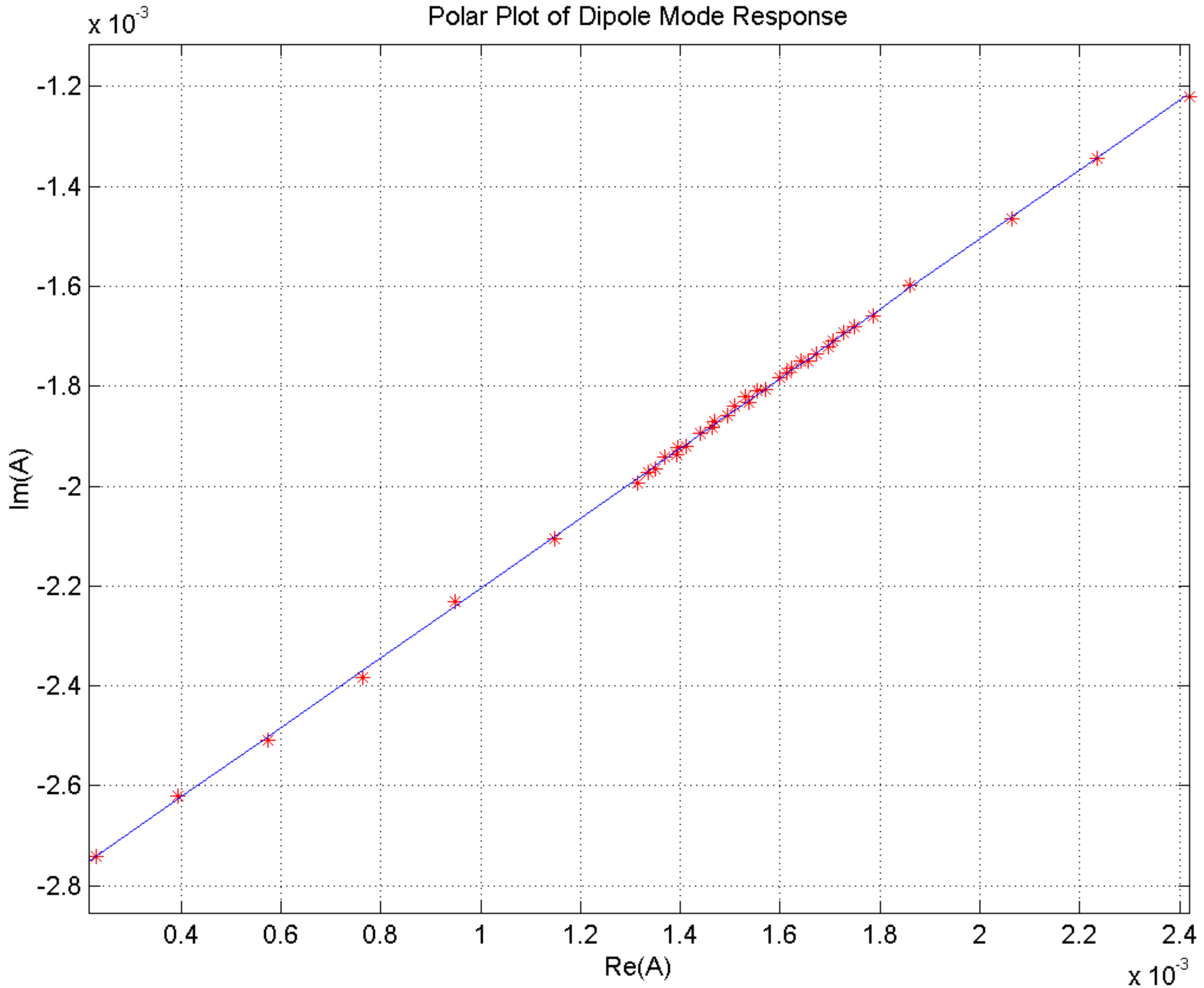


Cavity Antenna Test

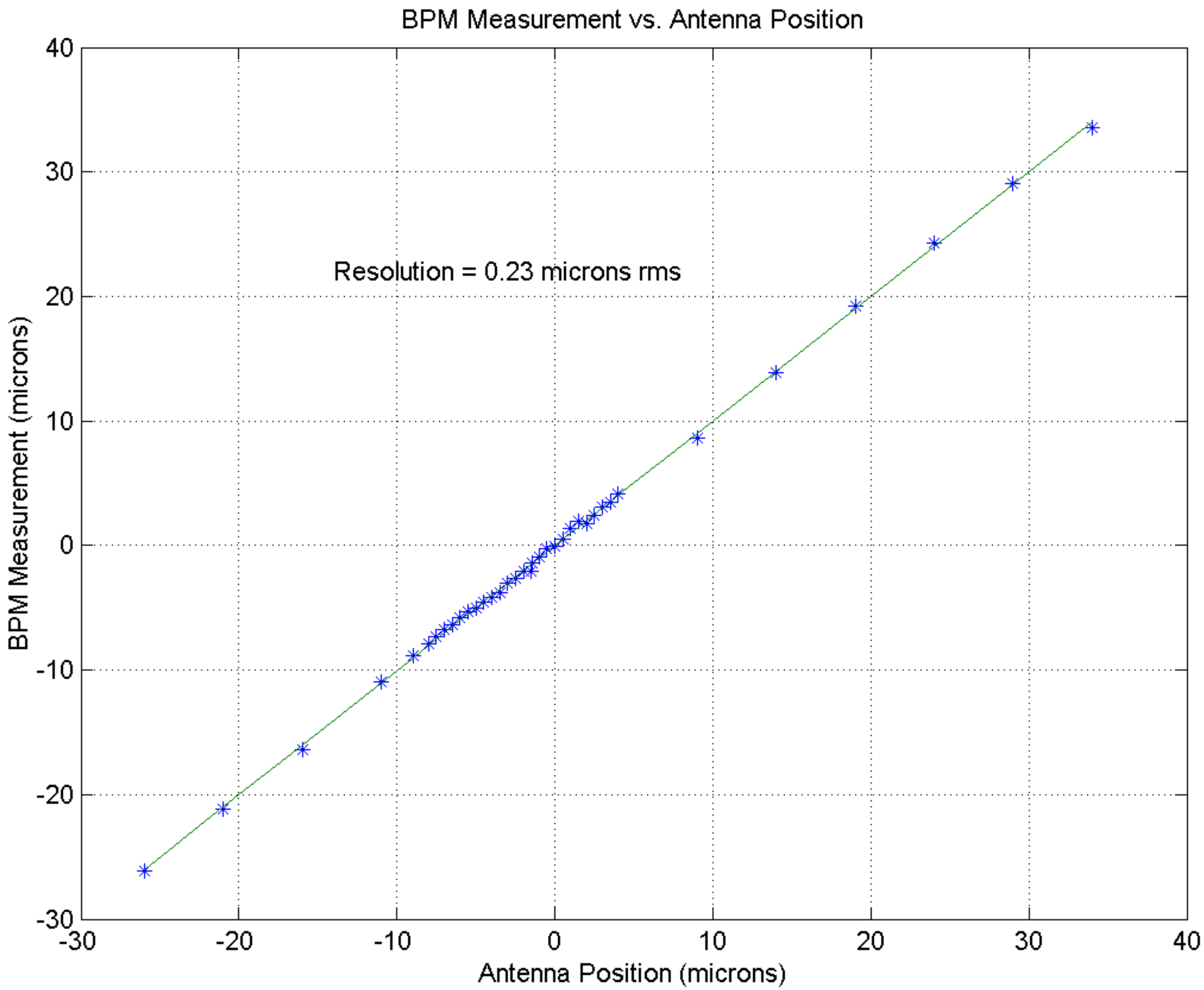


Antenna Test – Phasor Response

Next Linear Collider

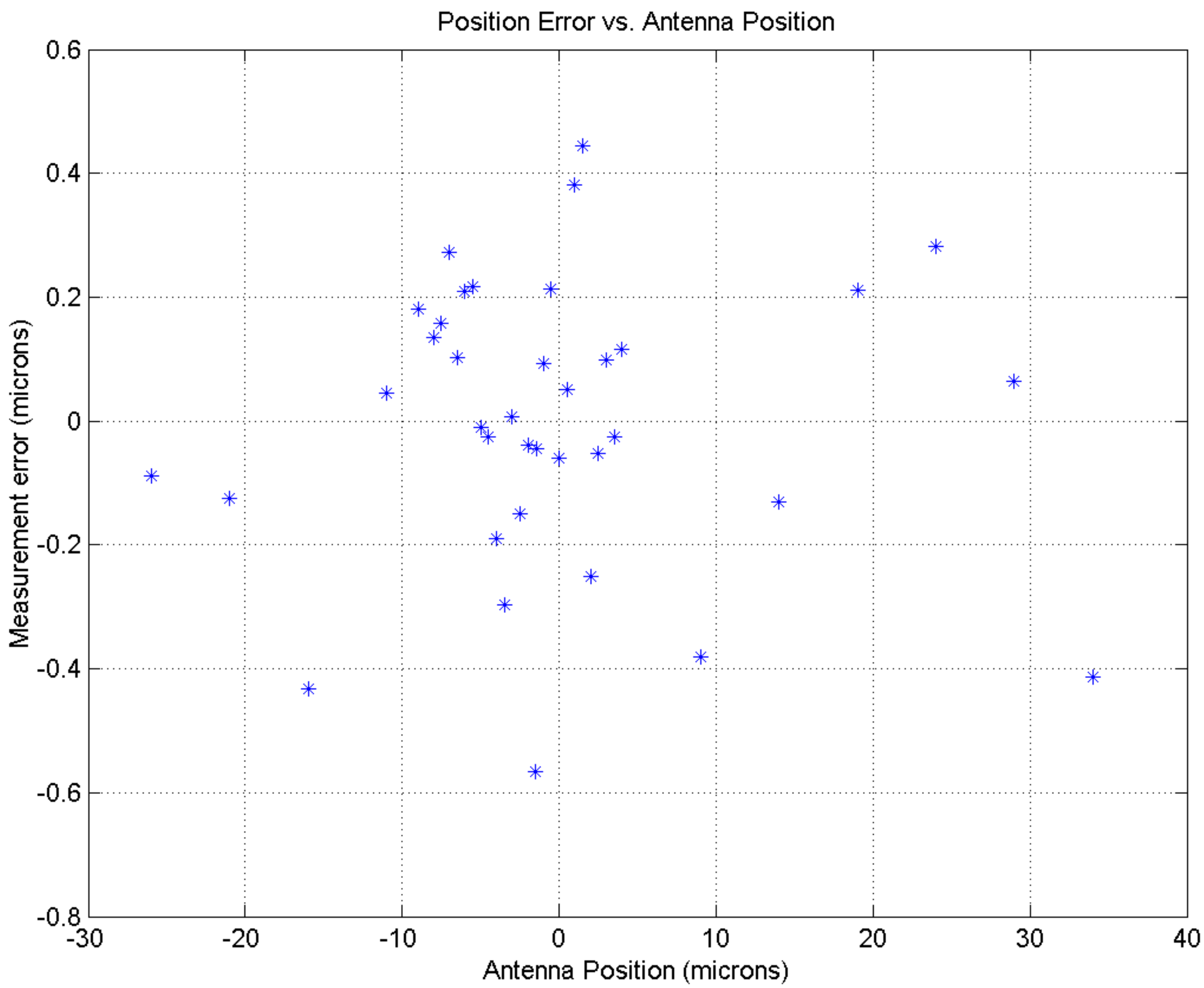


Antenna Position



Antenna Test –Residual Plot

Next Linear Collider



Prototype Cavity Conclusions

- Excellent position response.
- Linear across null.
- Resolution is 230 nm rms.
- Resolution may be dominated by micrometer stage

Cavity Q-BPM Conclusions

- It is easy to get signal
- Resolution can be much better than required
- Signal is proportional to displacement
- Accurate centering is much easier than for striplines
- Common-mode is not a problem
- Wake fields are OK
- Requires microwave processing

Limits of Cavity BPM

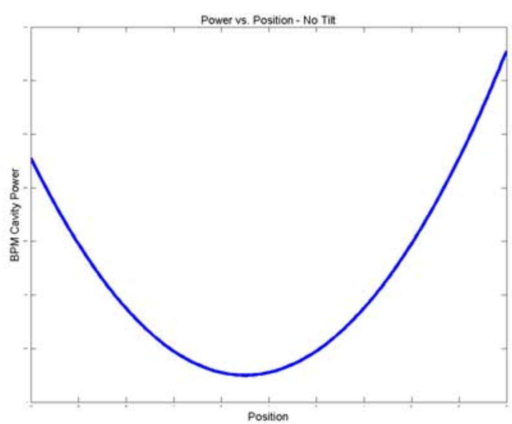
- How far can you push cavity BPM technology?
- Way beyond NLC machine requirements!
  - QBPM designed for low Q, low coupling
- Signal to thermal noise limit for resolution-optimized cavity
  - $\sigma = 0.1$ nm for 11 GHz pillbox cavity and 10^{10} e^- in a single bunch.
- Is a nanometer resolution BPM useful?
- Ground isn't stable at this level
- Active stabilization needed.
  - But is available, and demands beam tests!
    - Passive isolation
    - Geophone feedback
    - Optical anchor (interferometer)

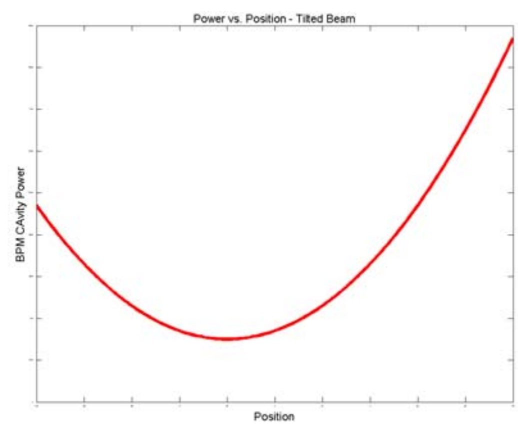
Nanometer Resolution BPMs

- Push cavity BPM technology to its limits
- Push existing C-band cavities to 1nm at ATF (KEK)
- Harder at 5.7 GHz than 11.4 GHz !

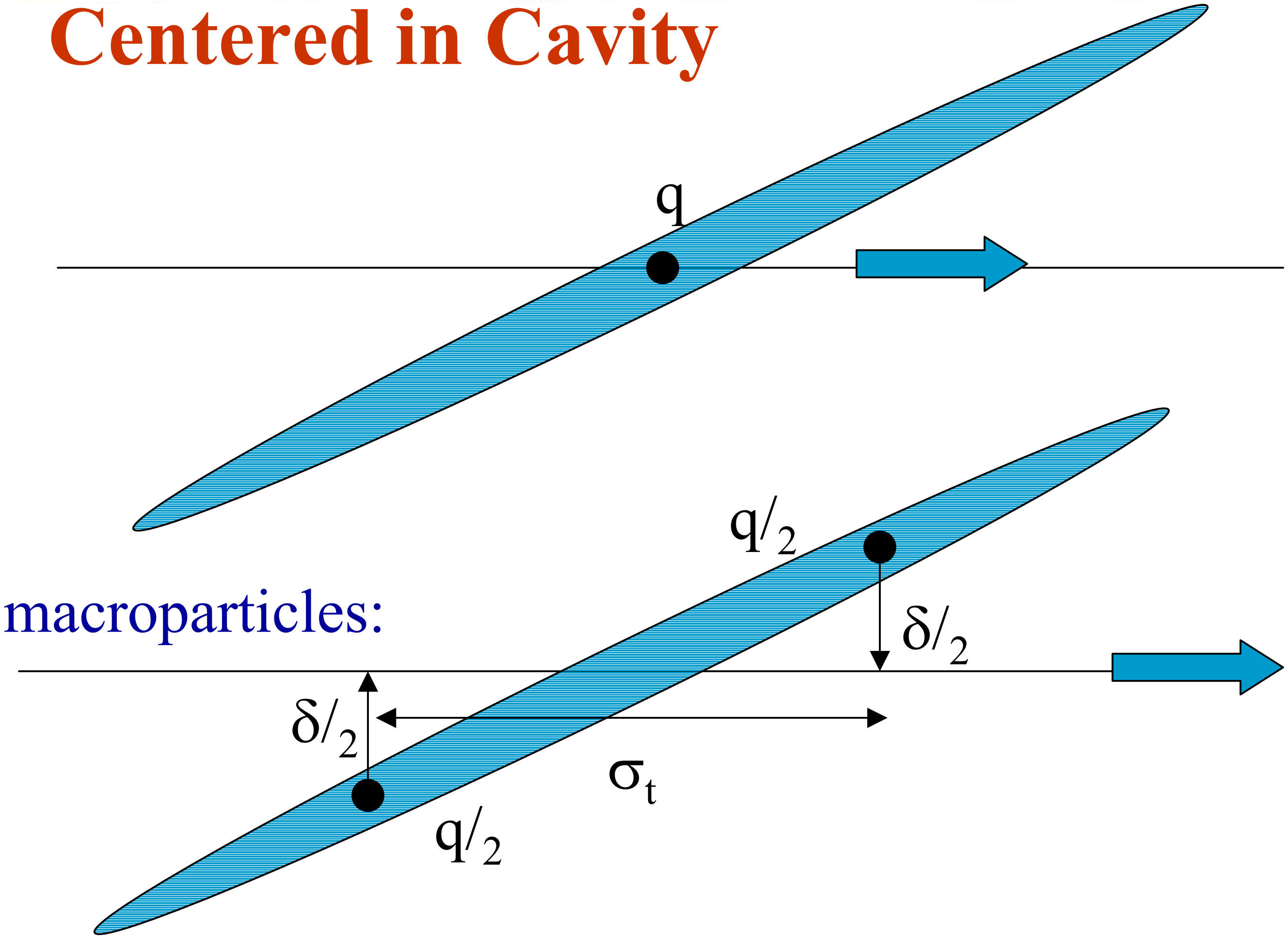
Bunch Tiltmeter

- NLC alignment tolerances and diagnostic requirements derive from wakefield emittance dilution.
- Transverse wakefields cause head-tail displacement
- Can we measure this directly, rather than by position of the mean charge of the bunch?
- Observation at ASSET:
  - BPM Cavity power vs. beam position has minimum which depends on bunch tilt
  - Tilt signal is in quadrature with position signal





Response of BPM to Tilted Bunch Centered in Cavity



Treat as pair of macroparticles:

$$V(t) = a\frac{q}{2}\frac{\delta}{2}\sin\omega(t-\frac{\sigma_t}{2}) - a\frac{q}{2}\frac{\delta}{2}\sin\omega(t+\frac{\sigma_t}{2}) = \frac{a\delta q}{2}\cos\omega t\sin\frac{\omega\sigma_t}{2}$$

Tilted bunch

- Point charge offset by δ
- Centered, extended bunch tilted at slope δ/σ_t
- Tilt signal is in *quadrature* to displacement
- The amplitude due to a tilt of δ/σ is down by a factor of:

  with respect to that of a displacement of δ

  (~bunch length / Cavity Period)

$$V_y(t) = aq\delta \sin(\omega t)$$

$$V_t(t) = \frac{a\delta q}{2} \cos \omega t \sin \frac{\omega \sigma_t}{2}$$

$$V_t / V_y = \frac{\omega \sigma_t}{4} = \frac{\pi \sigma_t}{2T}$$

Example

- Bunch length $\sigma_t = 200\ \mu m/c = 0.67$ ps
- Tilt tolerance $d = 200$ nm
- Cavity Frequency $F = 11.424$ GHz
- Ratio of tilt to position sensitivity $\frac{1}{2}\pi f\sigma_t = 0.012$
- A bunch tilt of 200 nm / 200 μm yields as much signal as a beam offset of 0.012 * 200 nm = 2.4nm
- Need BPM resolution of ~ 2 nm to measure this tilt
- Challenging**!**
  - Getting resolution
  - Separating tilt from position
- Use higher cavity frequency?

Position-Tilt Discrimination

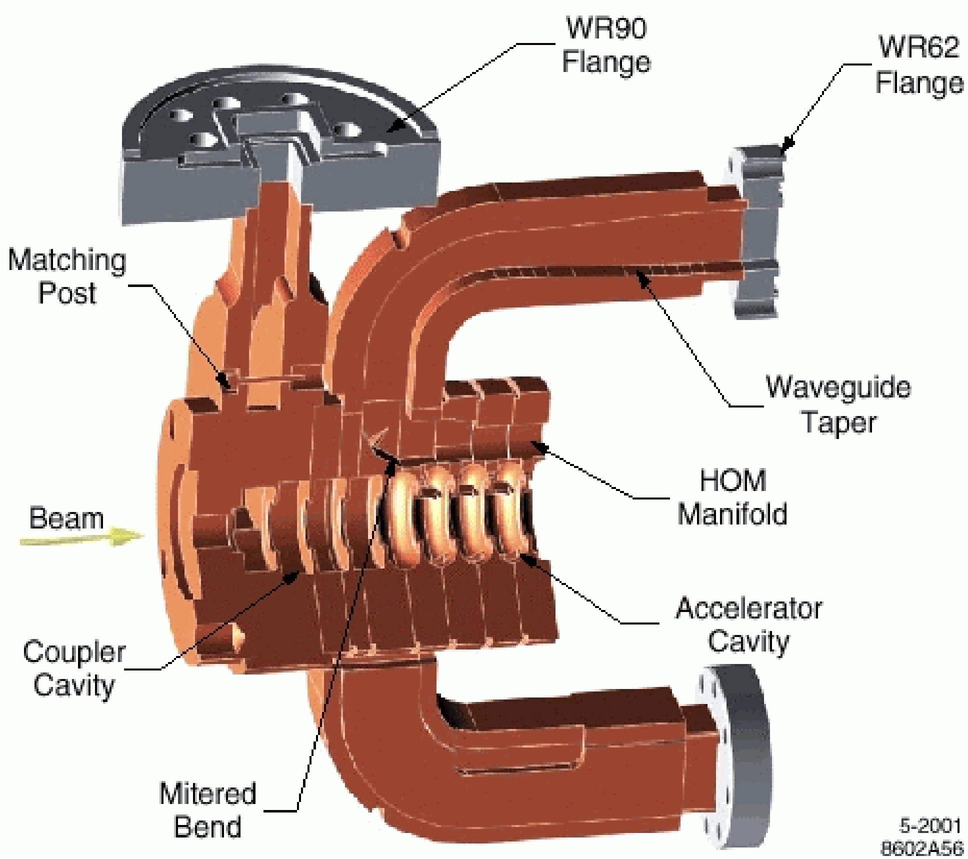
- Phase-sensitive detection
- Position jitter or dithering measures phase of position signal
- Quadrature part of signal is tilt + background
  - One phase of residual common mode
  - RF interference/leakage
- The higher the frequency the better!
- Tiltmeter also sensitive to beam tilt / cavity tilt

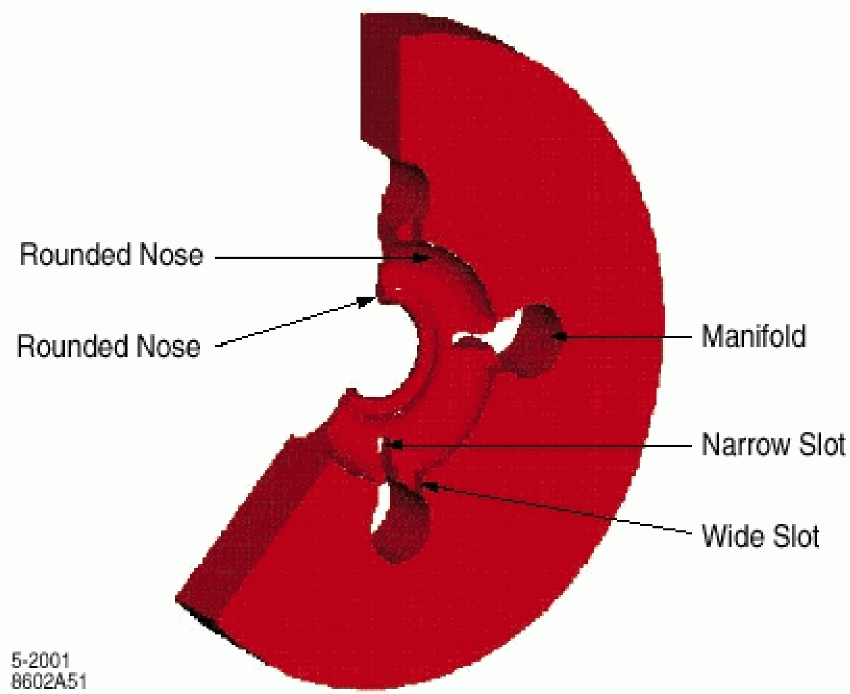
Tiltmeter R&D Plans

- Test with C-Band cavity BPMs at ATF (KEK)
  - First test done, cavity tilt dominates
  - Put more cavities on goniometers

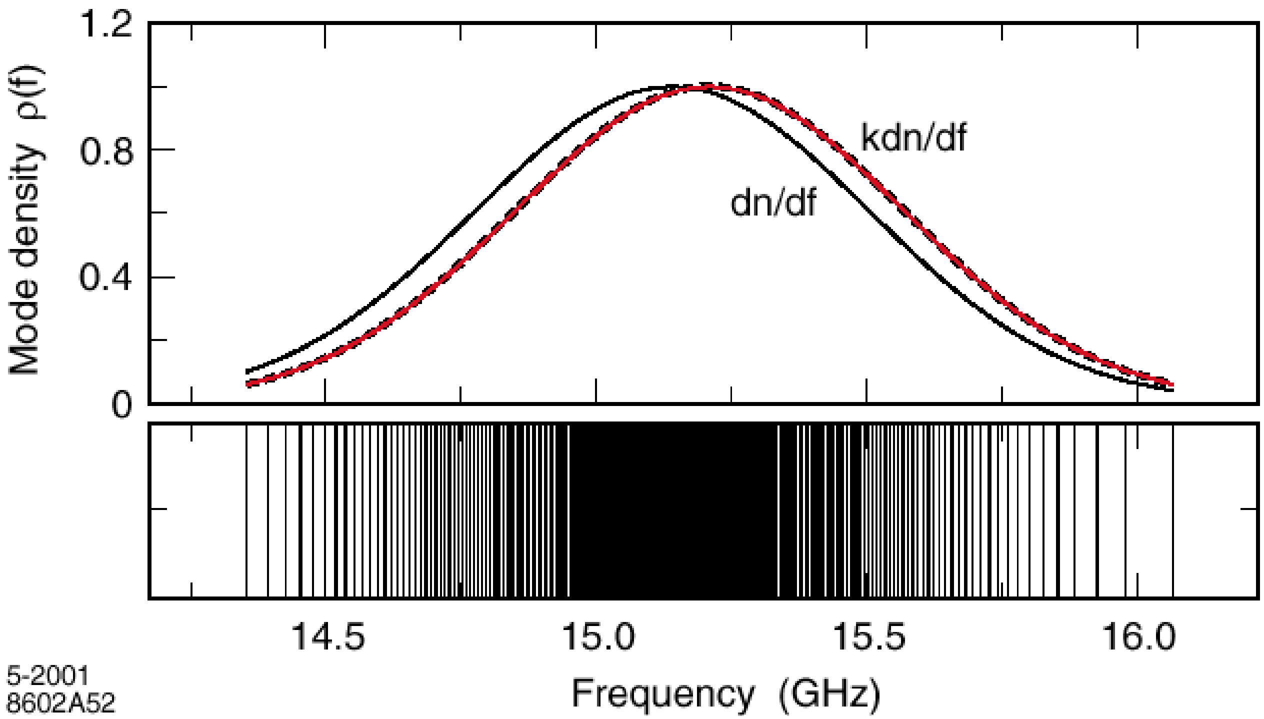
NLC RF Structure

- Use dipole modes in accelerating cavities to measure beam position.
- Align each RF structure to the beam
- Minimize transverse wakefields





Transverse Modes in Structure



RDDS1 dipole mode frequency distributions: dn/d*f* is the mode density and *k*dn/d*f* is the density weighted by the mode kick factors (*k*).

- Transverse modes contain position information
- Modes associated with z position along structure.
- Tunable receiver can measure position along structure.

Structure Position Monitor

- Damped, Detuned RF structures (DDS)
  - Damped: 4 HOM manifolds conduct transverse modes to load
  - Detuned: HOM mode frequency depends on z-position in structure
  - Two of the manifolds, have coax couplers which sample a fraction of the HOM power
- BPM measures amplitude and phase of transverse modes at load.
- Tune over 14 – 16 GHz to see position from one end to the other.
- Use to align structures to beam.

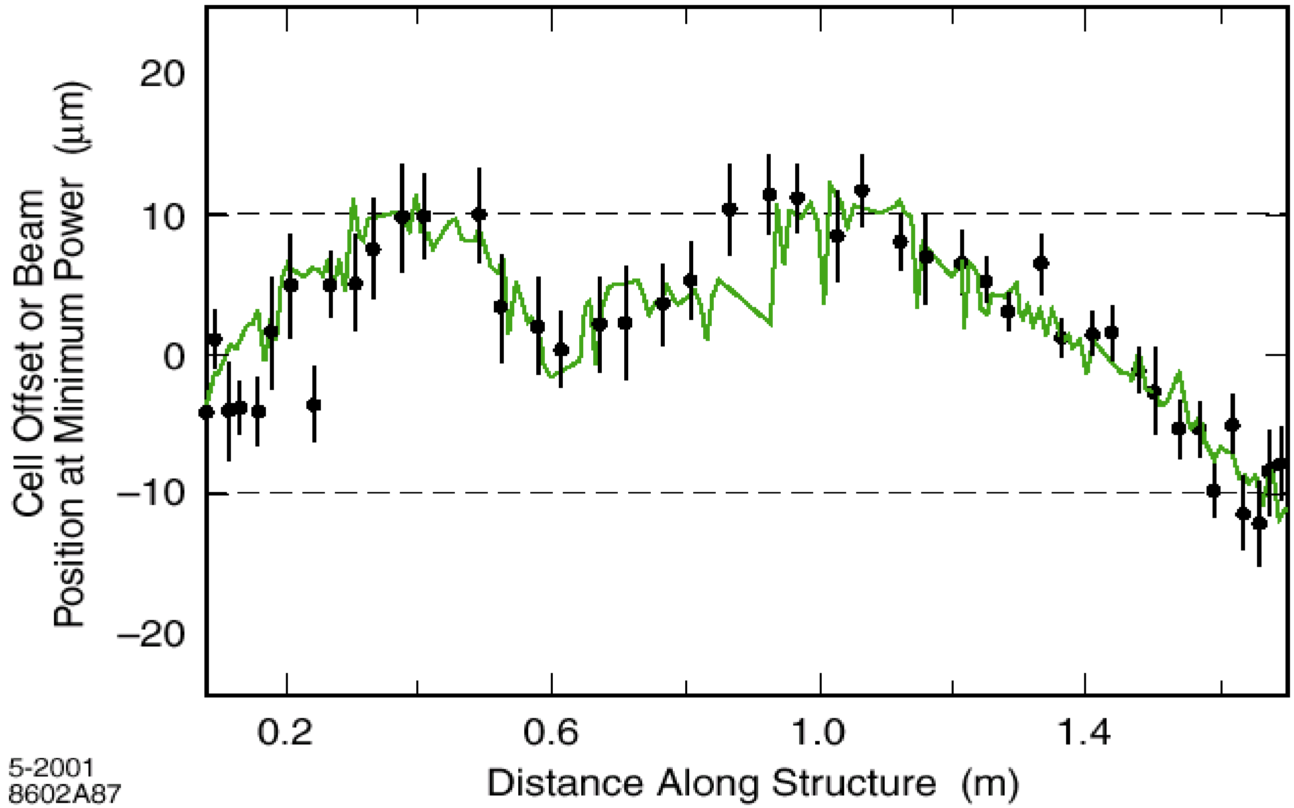
SPM Receiver

- Tunable across dipole band
  - Frequency selects z-coordinate of position measurement
- Receiver is phase-sensitive :
  - Reduces noise
  - Provides sign of offset.
- Beam phase reference provided by nearby cavity BPM
  - needs phase accuracy of only ± 90° in order to extract the sign of the beam direction.
  - Noise performance improves slightly with better phase reference
  - Low-level RF system requires beam phase accuracy of a few degrees, which will be from the same source.

SPM Requirements

Parameter	Requirement	Comments
Quantity	~22,000 X,Y BPM's ~ 700 X,Y BPM's	in X-band linacs in S-band linacs
Resolution	rms = 5 μm or 10% of beam position, whichever is greater	single bunch of 3×10^9 e^-, for at least one mode near each end
Position Dynamic Range	R < 3 mm R < 0.5 mm	single bunch or low current multibunch full current, multibunch
Stability of Center	<1 μm over 30 minutes	
Survival	90 bunches @ 1.5×10^{10} at 3 mm radius	Must not damage receiver

Cell Offset vs. HOM Minimum



Comparison of rf structure relative cell positions measured by dipole-mode BPM (points) and Coordinate Measuring Machine (line). Dashed lines show NLC rms structure alignment tolerance.

Structure Position Monitor

- Looks promising
- Have not developed even prototype electronics
- R&D needed on integrated RF module
- Large system, it must be:
  - high performance
  - reliable
  - cheap

Multi-Bunch BPMs

- Bandwidth frontier (300 MHz bandwidth)
- Stripline pickups
- Report position of every bunch in bunch train
- Used to program broadband kickers to straighten out bunch train

Parameter	Value	Conditions & Comments
Resolution	300 nm rms At 0.6 x 10^{10} e^- / bunch	for bunch-bunch diplacement frequencies below 300 MHz
Position Range	±2 mm	
Bunch spacing	2.8 ns or 1.4 ns	
Number of Bunches	1 - 190	@ 1.4 ns
Beam current dynamic range	1×10^9 to 1.4×10^{10}	Particles / bunch
Number of BPMs	278	

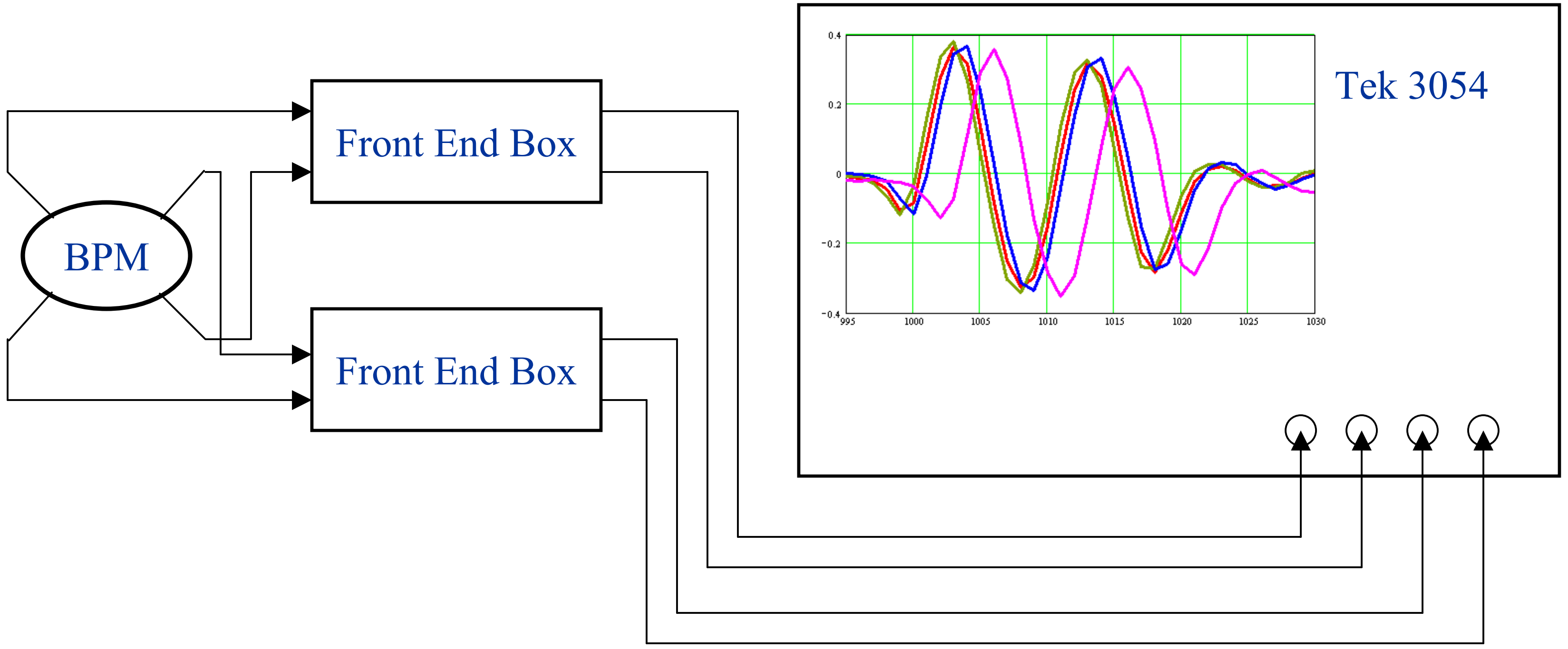
Multi-Bunch BPM Electronics

- Model
  - Preprocess using matched filters, sum-difference hybrids
  - Digitize waveform from stripline using either
    - fast ADC's
    - Sampling chip followed by slow ADC
  - Deconvolute bunch-bunch response from multibunch using impulse response measured with single bunch
- R&D
  - Demonstrate concept
  - Develop switched capacitor analog memory chip
    - Save
      - cost
      - space
      - power

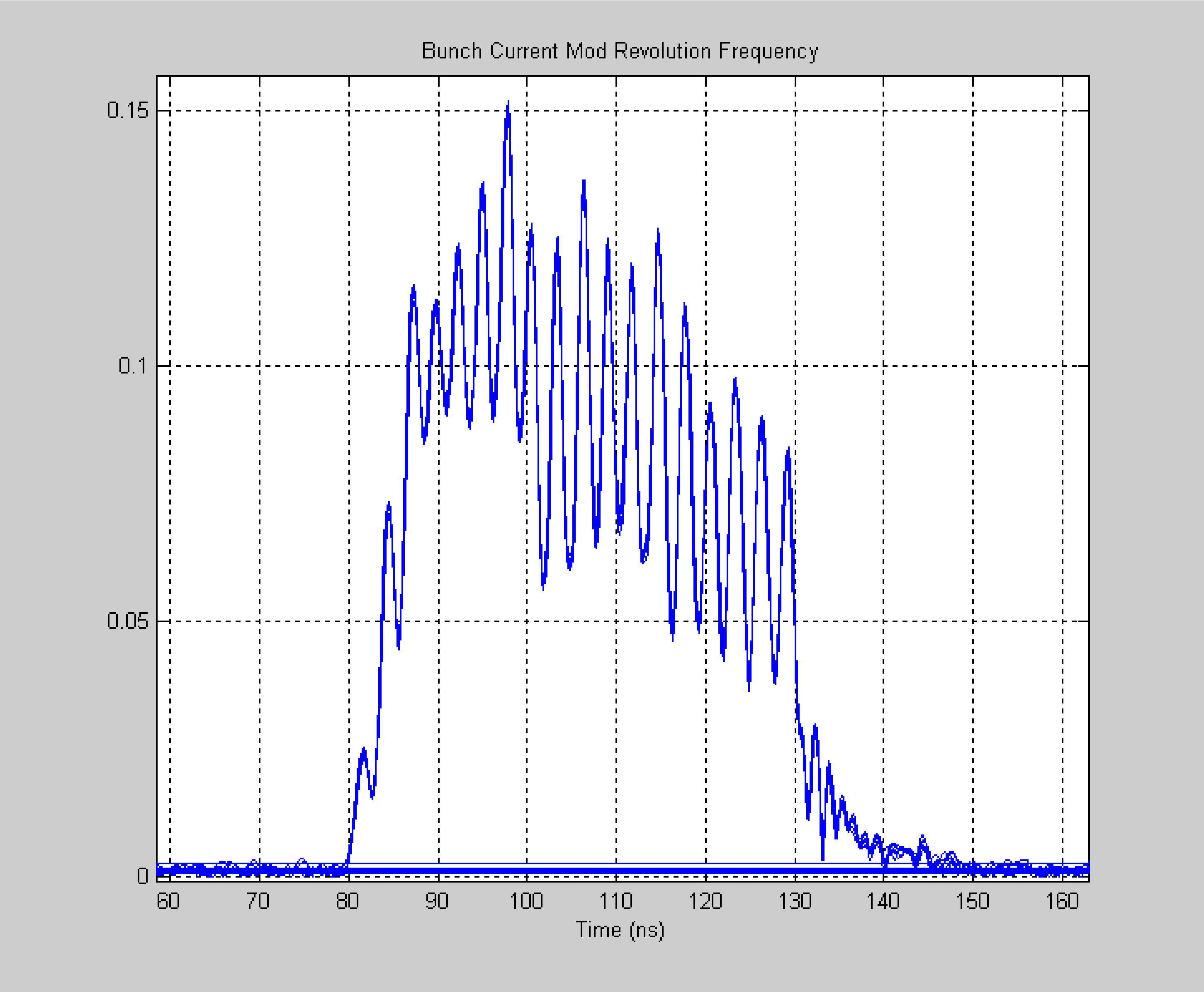
R&D

- Sampling Chip development
  - In house
  - Ohio State
- Proofs of Principle
  - Measuring bunchtrains at KEK-ATF
  - Digital receiver algorithm for Q-BPM, DR-BPM
    - test in linac, PEP-II
- Test promising parts on eval boards
- Prototype

Block Diagram



ATF Bunch Current



Damping Ring BPMs

- Button pickups in rings
- Cables to holes in tunnel wall
- Quantity 486 total in three rings
  - Two main damping rings & e^+ Pre-damping ring
- Process signals in digital receiver
  - Measure amplitude in ~10 MHz bandwidth about 714 MHz
- Differences from PEP BPM:
  - Slightly higher resolution
    - smaller signal
    - smaller beam duct
  - High peak readout rate (once per turn ~MHz)

DR-BPM Requirements

Parameter	Requirement	Conditions & Comments
Duct radius	17.5 mm in arcs up to 31 mm in straights	PEP-II is 33 mm in arcs, 45 mm in straights
Button Diameter	8 mm	PEP-II is 15 mm
Button Transfer Impedance	~ 0.2 Ohm	@ 714 MHz
Time resolution	Average over 20 bunches	Can we average over train?
Measurement Rate	Read every turn (1.4 MHz in preDR)	PEP-II ADC runs at 136 kHz Several 14-bit ADCs @ 65 MHz
Onboard processing	Multi-turn logging Multi-turn averaging Sine fit to turn-by-turn data	
Resolution for train of > 20 bunches	$\sigma_x \leq 1\mu m \bullet \sqrt{1+\left(\frac{500mA}{I_{train}}\right)^2}$	
Resolution for single bunch	$\sigma_{Single} \leq 5 \cdot \mu m$	For $Q_b > 10^{10}$ electrons
Initial accuracy	TBD	Before beam-based-alignment
Stability wrt time	1μm 10μm	over a few hours over 24 hours
Stability wrt fill pattern	<10μm shift, single bunch to full train	

Ground Motion at NLC IP

- Differential ground motion between opposing final lenses may be comparable to the beam sizes
- Several solutions possible:
  - Optical anchor stabilization
  - Inertial stabilization (geophone feedback)
  - Pulse-to-pulse beam-beam alignment feedback
- Can we use beam-beam deflection within the crossing time a single bunch train?

NLC Interaction Point Parameters

High E IP Parameters (2/00)		
	Stage 1	**Stage 2**
CMS Energy (GeV)	490	888
Luminosity (10^{33})	**22**	**34**
Repetition Rate (Hz)	120	120
Bunch Charge (10^{10})	**0.75**	**0.75**
Bunches/RF Pulse	190	190
Bunch Separation (ns)	1.4	1.4
Eff. Gradient (MV/m)	**50.2**	**50.2**
Injected $\gamma\varepsilon_x$ / $\gamma\varepsilon_y$ (10^{-8})	300 / 2	300 / 2
$\gamma\varepsilon_x$ at IP (10^{-8} m-rad)	360	360
$\gamma\varepsilon_y$ at IP (10^{-8} m-rad)	**3.5**	**3.5**
β_x / β_y at IP (mm)	8 / 0.10	10 / 0.12
σ_x / σ_y at IP (nm)	**245 / 2.7**	**200 / 2.2**
σ_z at IP (um)	110	110
Yave	0.11	0.26
Pinch Enhancement	1.43	1.49
Beamstrahlung δB (%)	4.6	8.8
Photons per e+/e-	1.17	1.33
Two Linac Length (km)	5.4	9.9

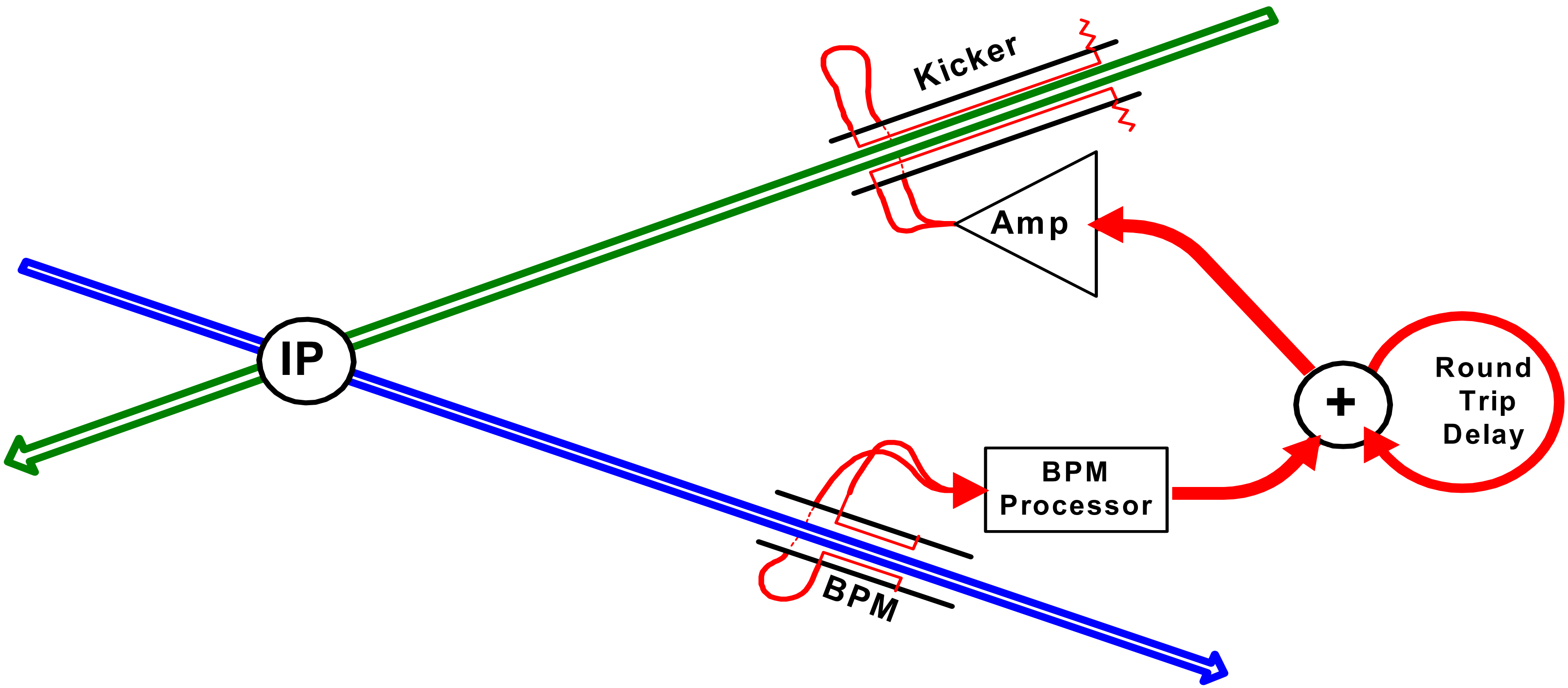
Beam-Beam Parameters

Parameter	Value	Comments
σ_y	2.65 nm	(!)
σ_x	245 nm	
σ_z	110 μm	
Disruption Parameter	14	
Deflection slope	25 μradian / nm	At origin
Displacement slope	100 μm/nm	At BPM

Intra-pulse Feedback

- Fix interaction point jitter within the crossing time of a single bunch train (266 ns)
- BPM measures beam-beam deflection on outgoing beam
  - Fast (few ns rise time)
  - Precise (~micron resolution ⇒ << 1nm beam offset resolution)
  - Close (~4 meters from IP)
- Kicker steers incoming beam
  - Close to IP (~4 meters)
  - Close to BPM (minimal cable delay)
  - Fast rise-time amplifier
- Feedback algorithm is complicated by:
  - round-trip propagation delay to interaction point in the feedback loop.
  - transfer function non-linearity

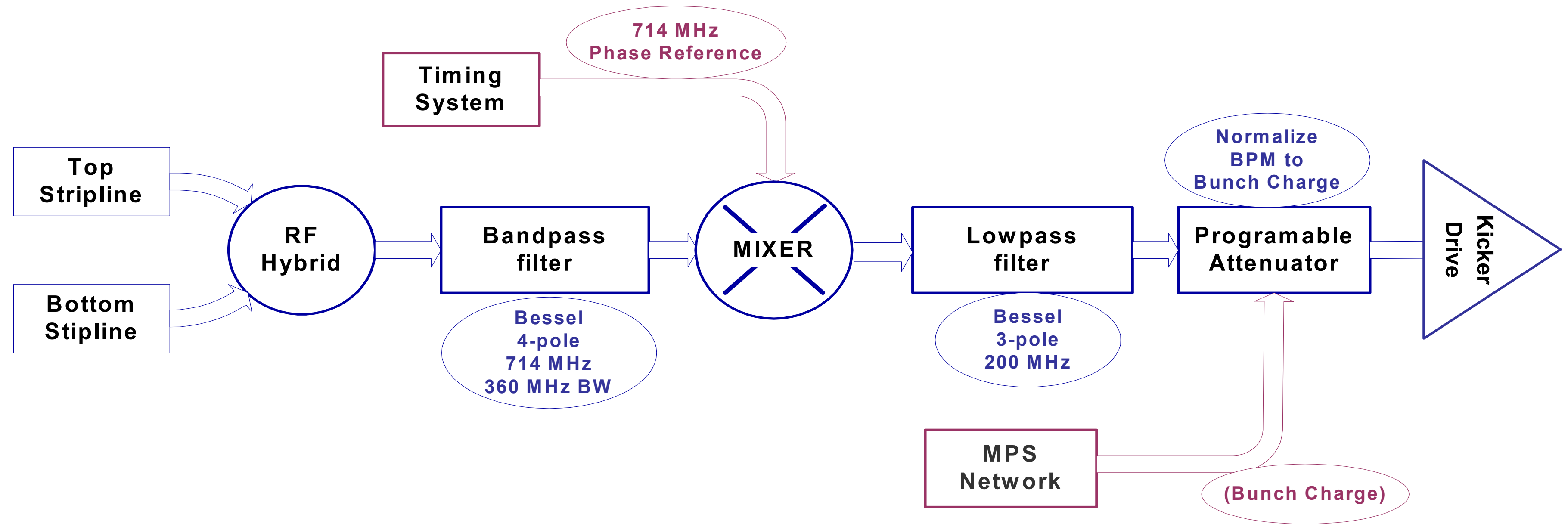
Intra-Pulse Feedback



Beam Position Monitor

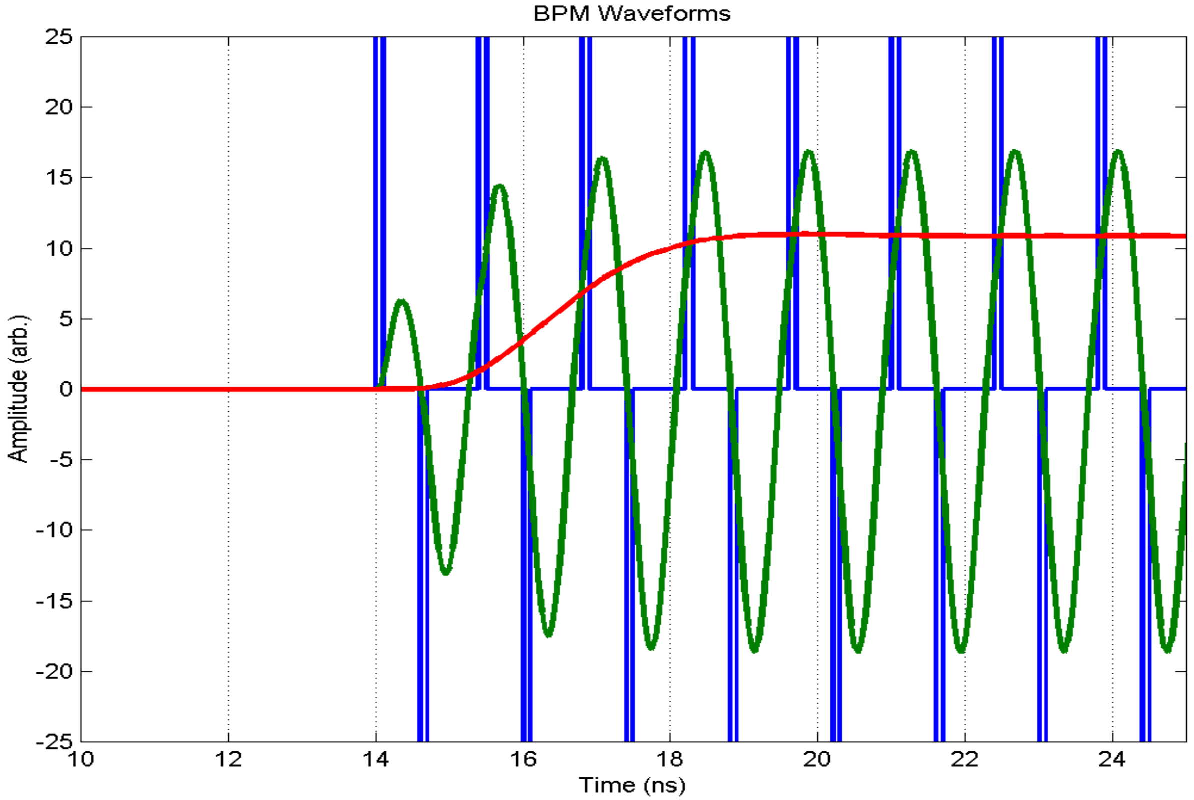
- Stripline BPM
  - 50 Ohm
  - 6 mm radius
  - 10 cm long
  - 7% angular coverage
  - 4 m from IP
  - Process at 714 MHz
    - Downconvert to baseband
    - need to phase BPM
    - Wideband: 200 MHz at baseband
    - Analog response with < 3ns propagation delay (plus cable lengths)

Fast BPM Processor



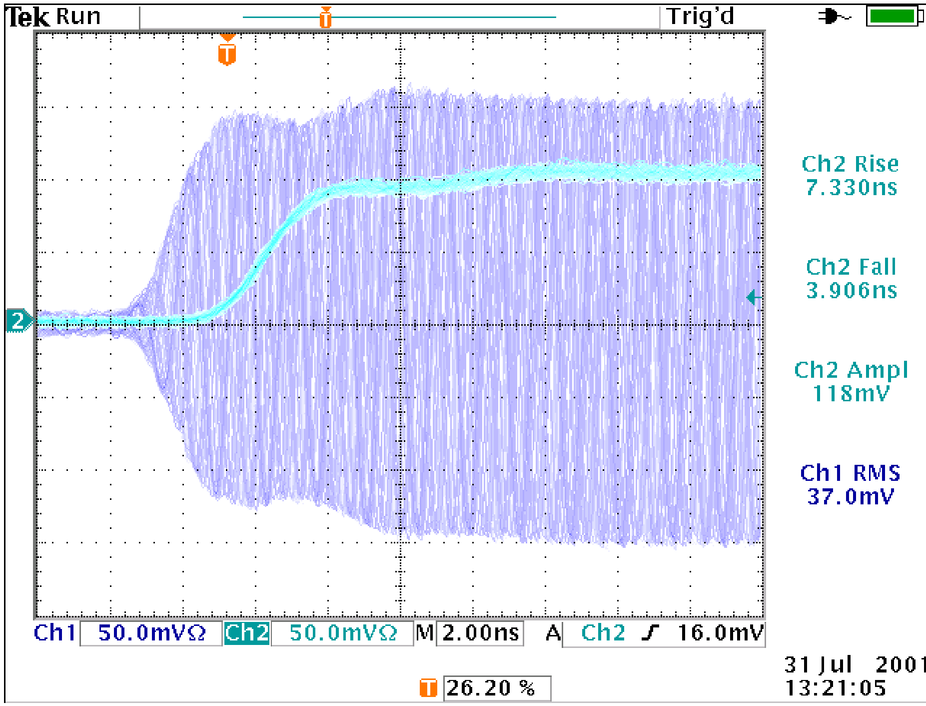
Fast BPM Processor Block Diagram

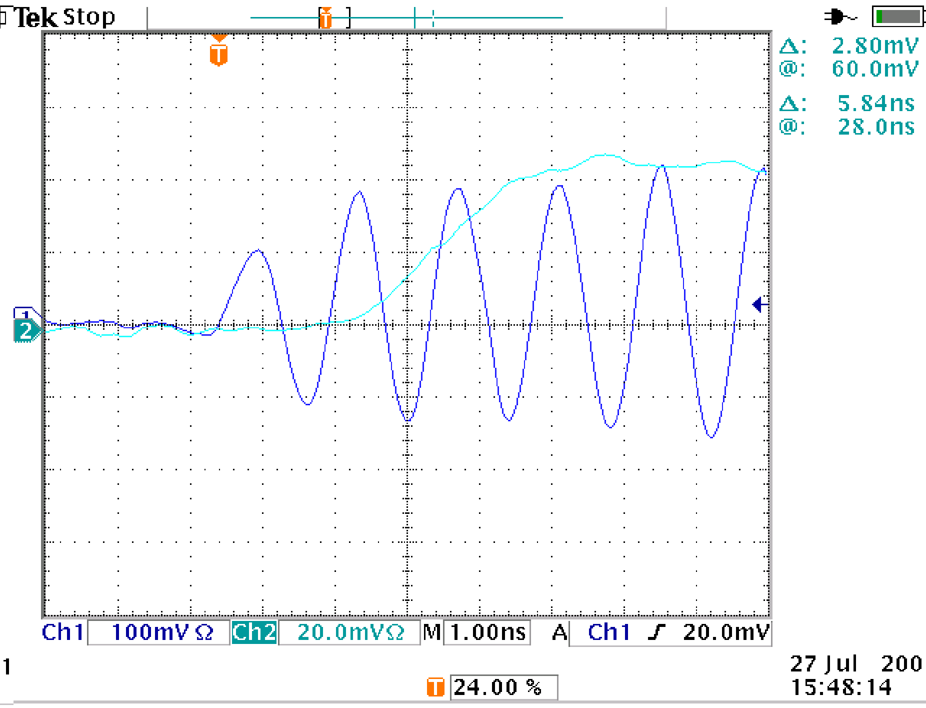
Simulated BPM Processor Signals



BPM Pickup (blue)
Bandpass filter (green)
and BPM analog output (red)

Prototype Hardware



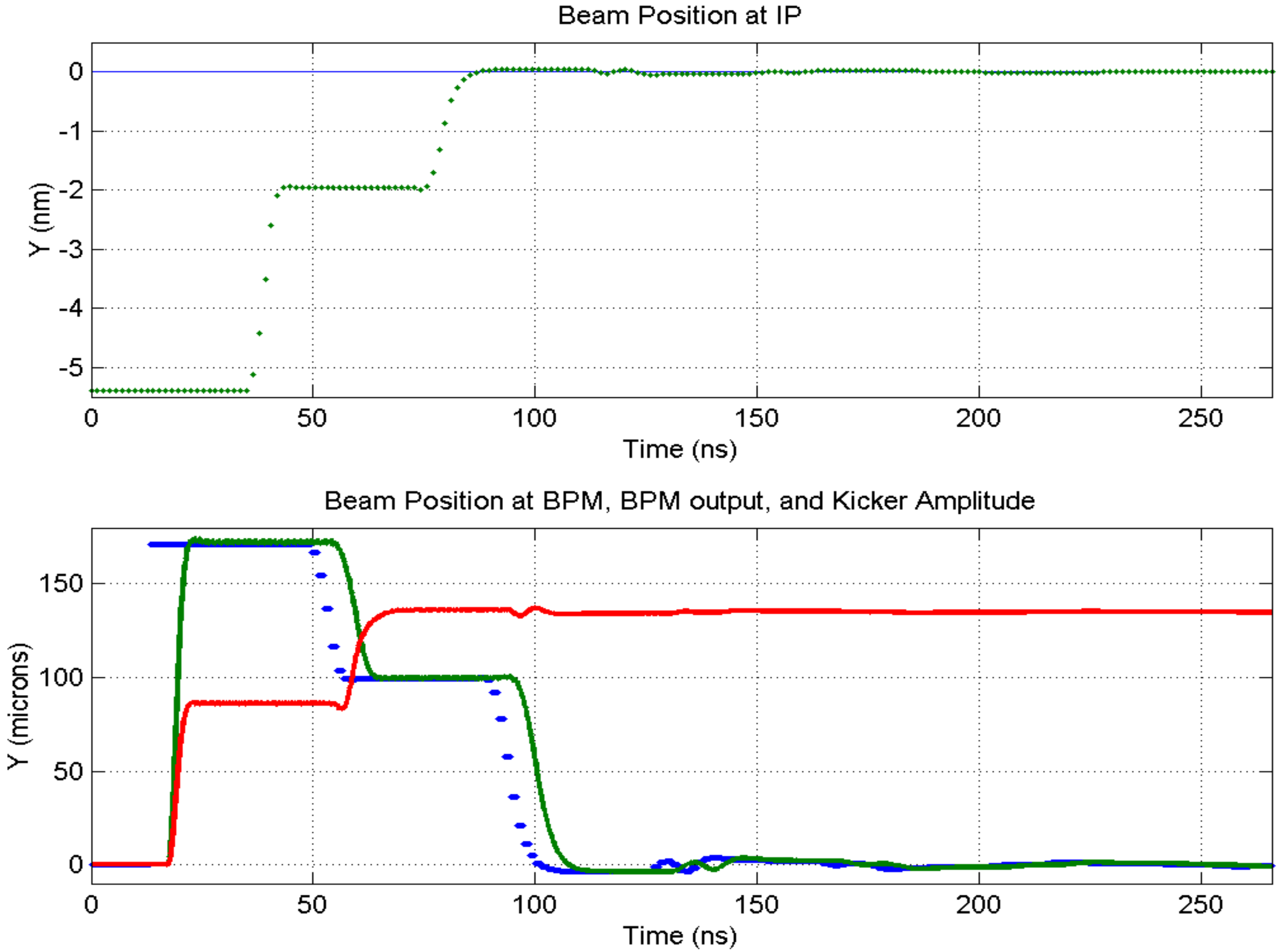


- Position monitor processor looks like the simulation

Stripline Kicker

- Baseband Kicker
  - Parallel plate approximation $\Theta = 2eVL/pwc$
    - (half the kick comes from electric field, half from magnetic)
  - 2 strips
  - 75 cm long
  - 50 Ohm / strip
  - 6 mm half-gap
  - 4 m from IP
  - Deflection angle $\Theta = eVL/pwc = 1$ nr/volt
  - Displacement at IP $d = 4$ nm/volt
  - Voltage required to move beam 1 σ (3 nm) 0.75 volts (10 mW)
  - 100 nm correction requires 12.5 Watts drive per strip
  - Drive amp needs bandwidth from 100 kHz to 100 MHz

Capture Transient

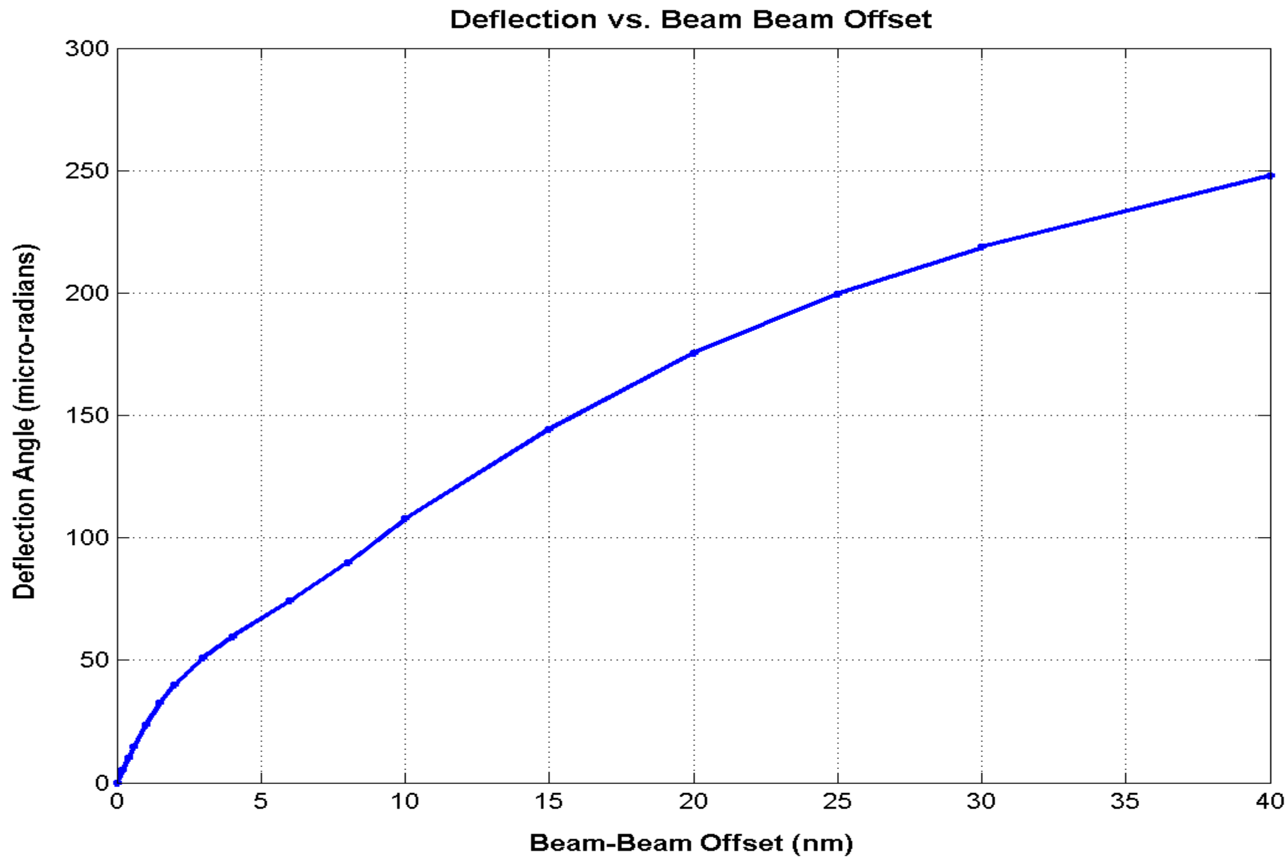


Capture transient from 2 σ initial offset

Limits to Beam-Beam Feedback

- Must close loop <u>fast</u>
  - Propagation delays are painful
- Beam-Beam deflection response is non-linear
  - slope flattens within 1 σ
- Linear feedback converges too slowly beyond ~ 10 σ to recover most of lost luminosity.
- Should be able to fix misalignments of 100 nm with modest kicker amplifiers.
  - Amplifier power goes like square of misalignment.

Non-linear Response Challenges Feedback



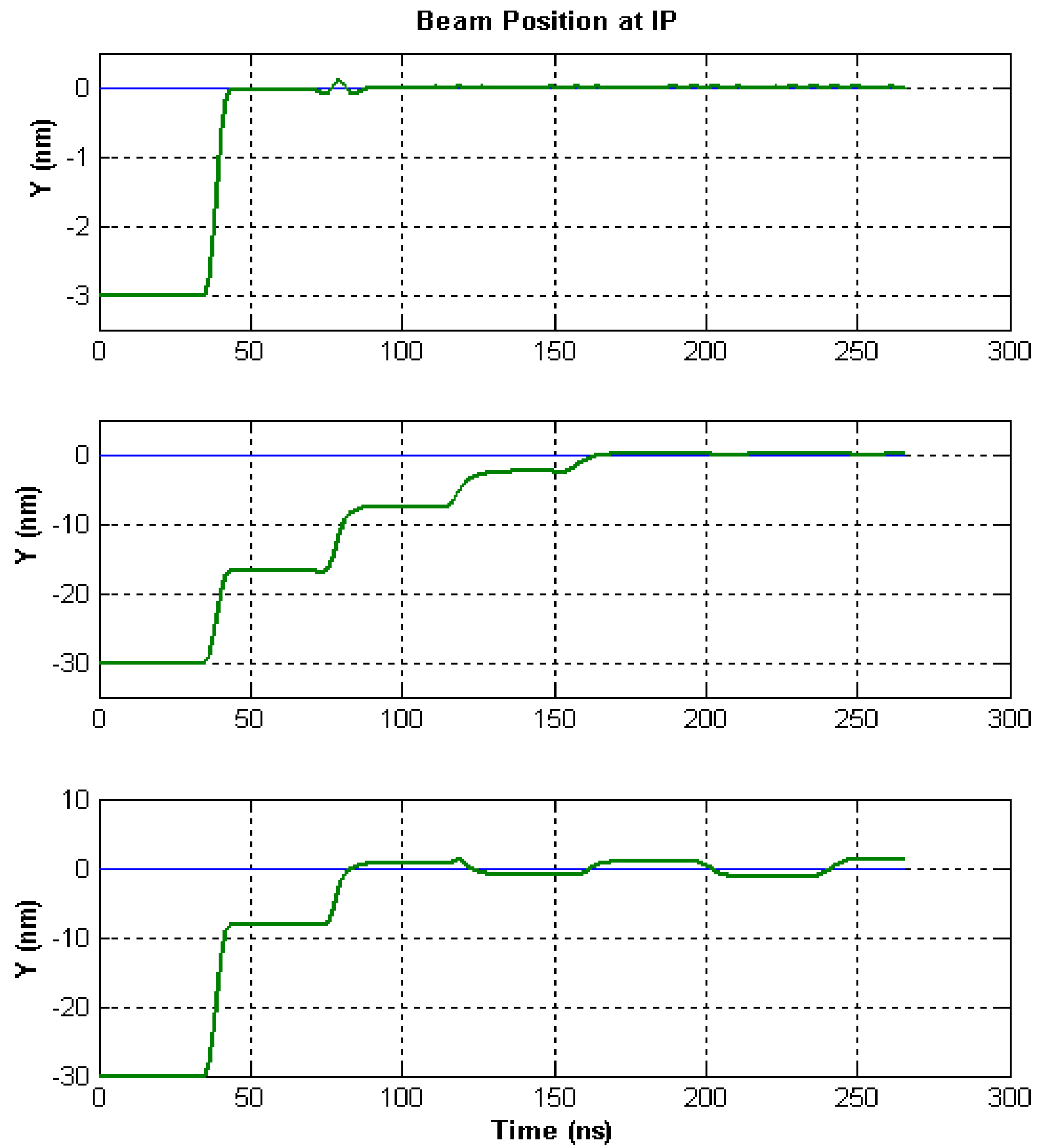
- Beam-beam deflection non-linearity limits:
  - Limits useful (timely) range of convergence
  - Limits stability in collision

Non-linear Response Challenges Feedback

Optimize gain for small initial offset:

Then convergence is poor from far out:

Set gain for good convergence, then high gain at origin causes oscillation when near center:



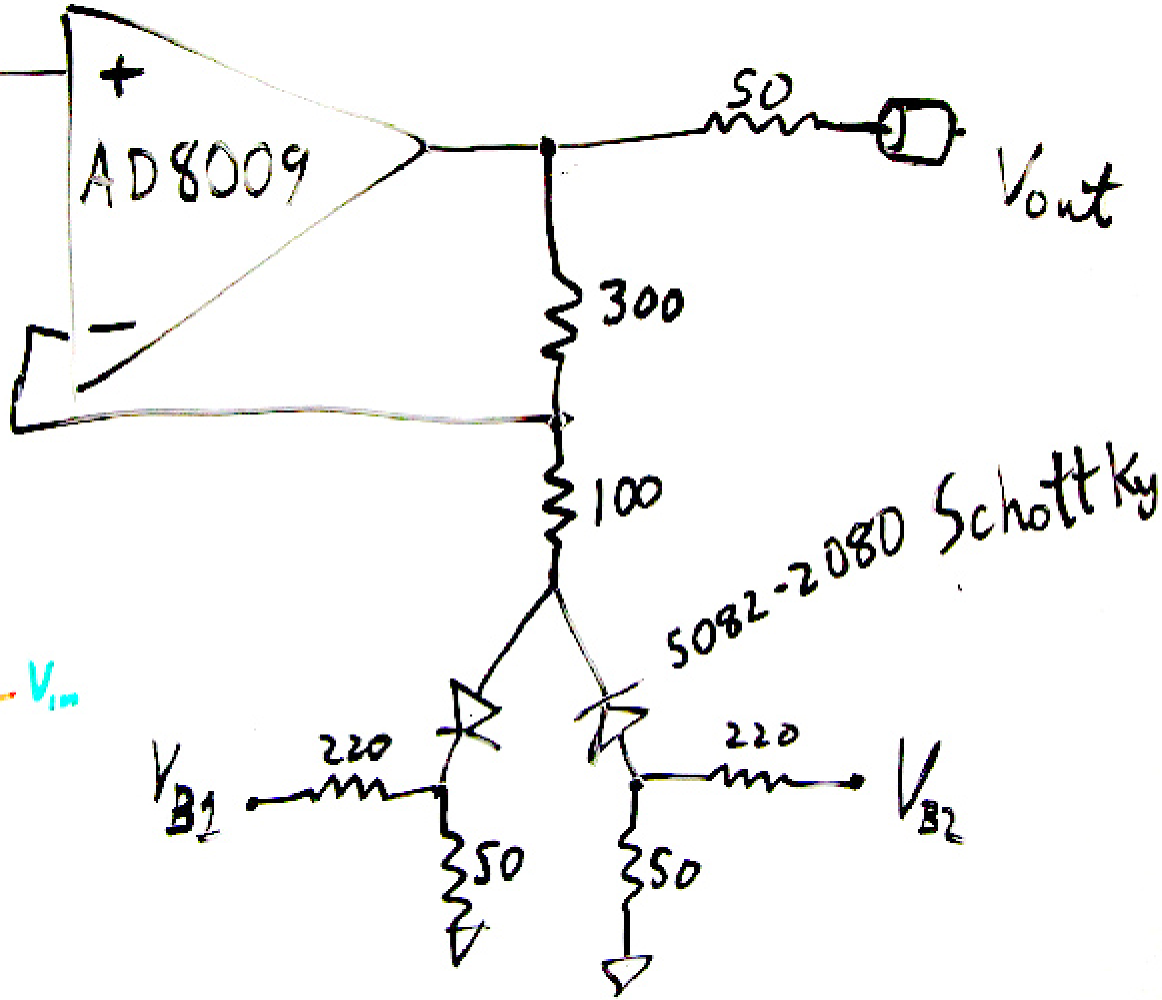
Linearize Feedback

- Can we compensate non-linearity?
  - Fast?
    - Bandwidth
    - propagation delay
  - Accurately?

- Yes!

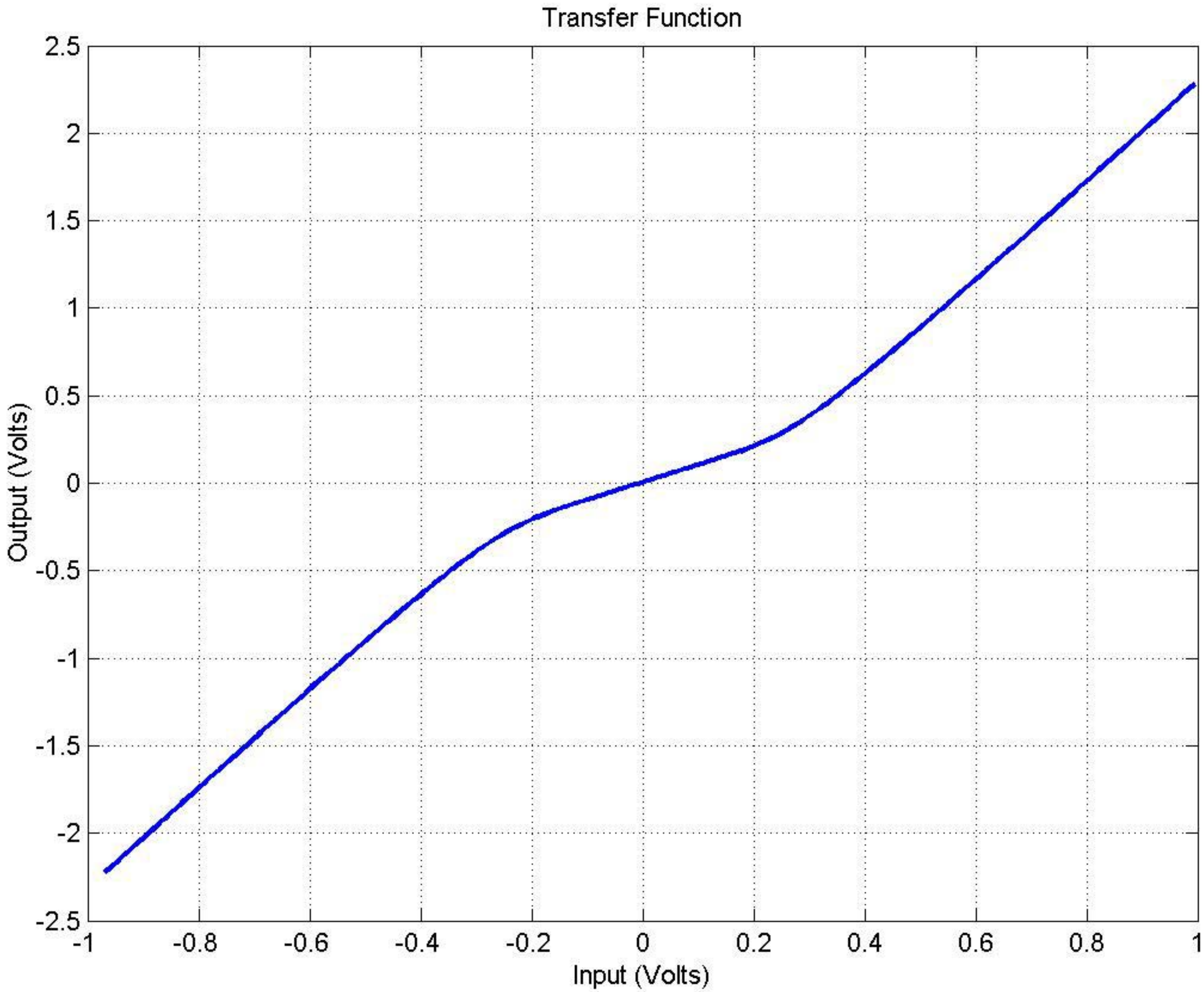
- Add compensation amplifier
  - Op-amp
  - Diodes to introduce desired non-linearity.
  - Bias adjust (knee or breakpoint)

Schematic

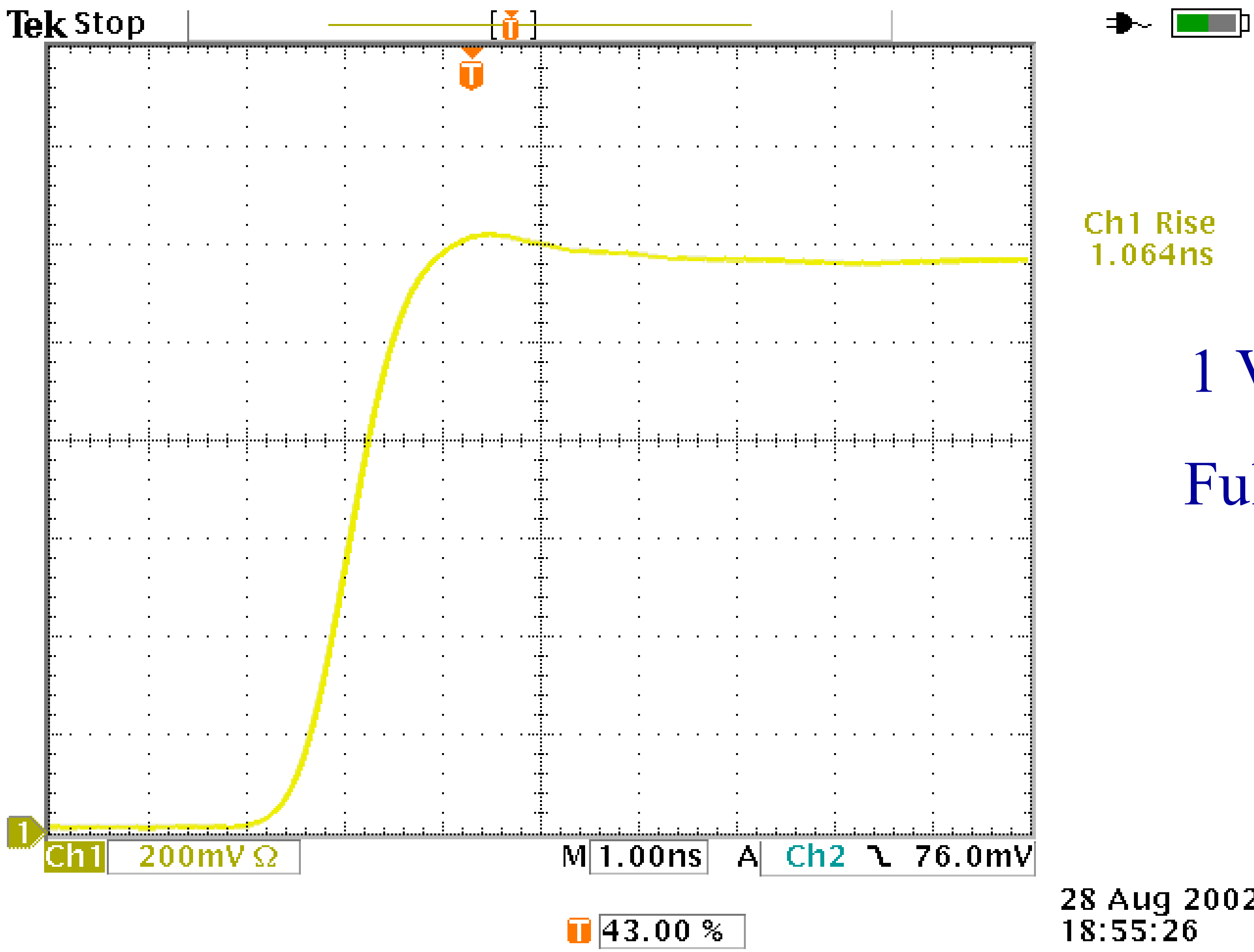

Vin
50
+
AD8009
−
50
Vout
300
100
5082-2080 Schottky
VB1
220
50
220
VB2
50


Vout
Vin
1:3

Measured Transfer Function



Large Signal Waveform

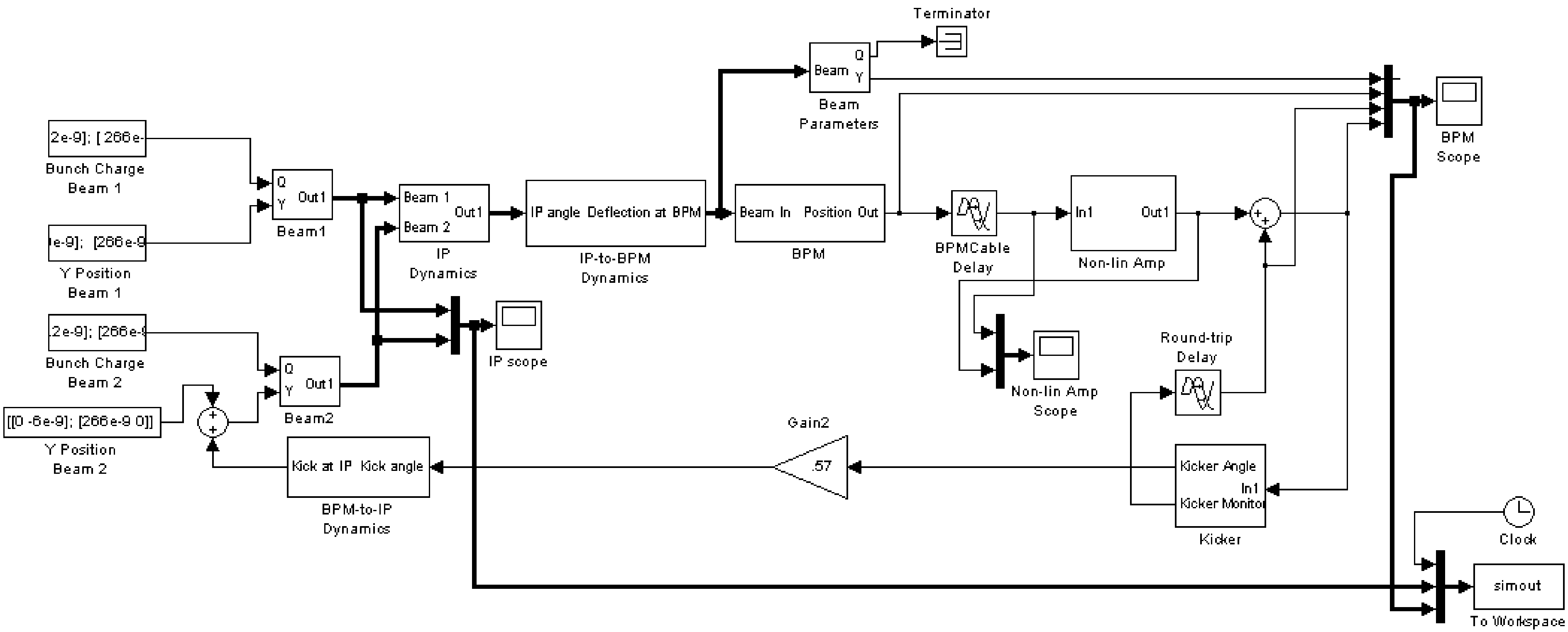


1 V step

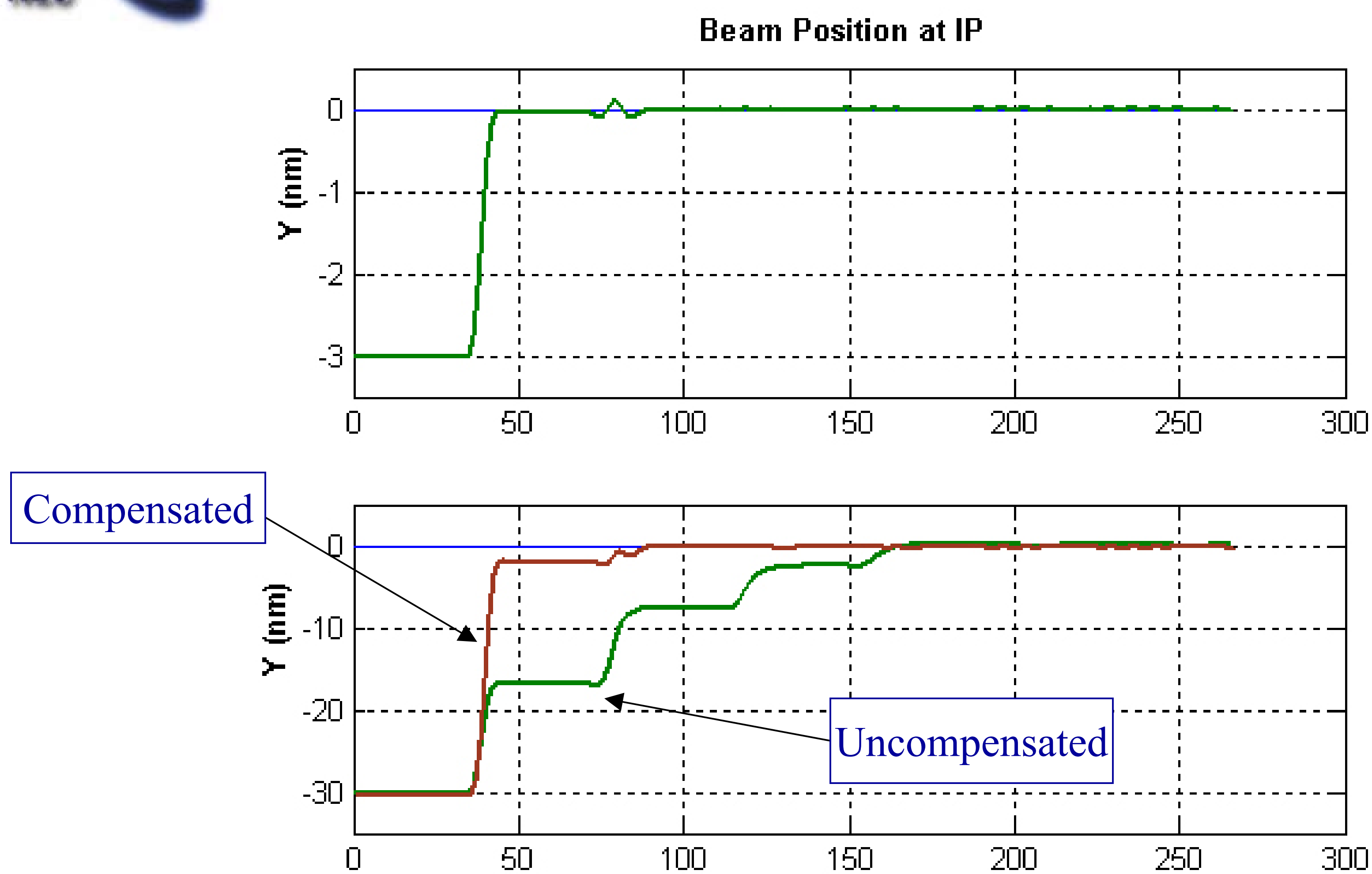
Full BW

Settles to DC response in several ns

Simulink Model



Non-Linear Feedback Simulation



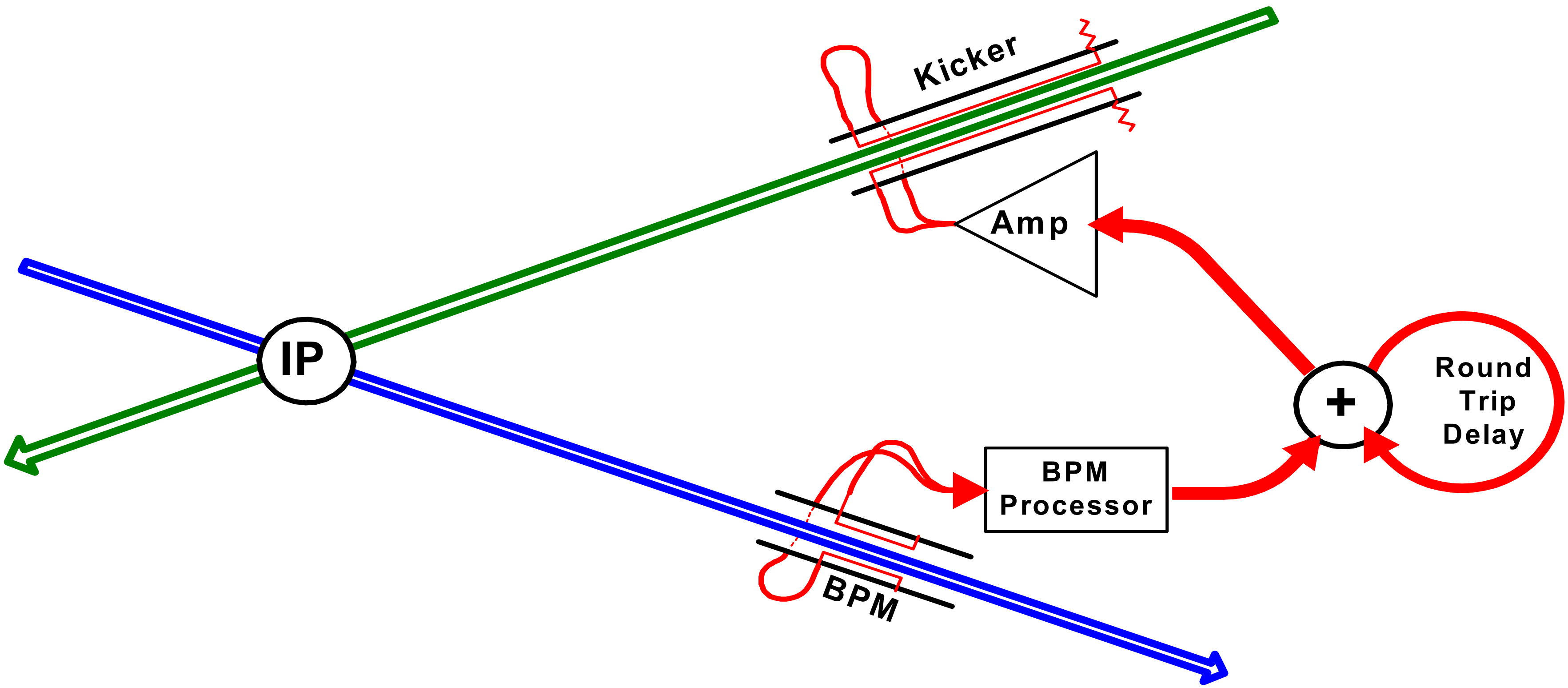
Full luminosity recovered in one round-trip time

for 10 σ initial offset.

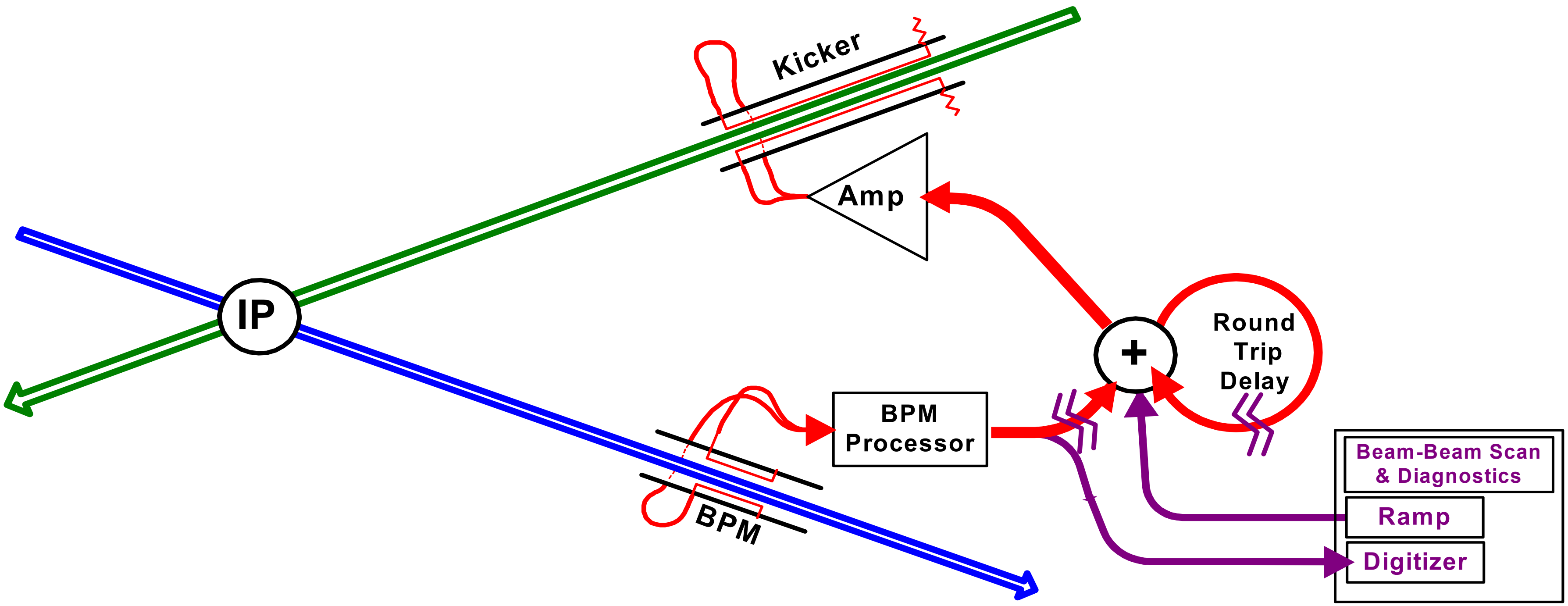
Linearizer Conclusions

- Simple op-amp based non-linear amp is sufficient to improve:
  - Stability
  - Convergence speed ⇔ capture range
  - Programmable linearity compensation
- Low propagation delay: ~ 1 ns
- High bandwidth > 200 MHz
- Sufficient to achieve:
  - Single round-trip convergence to $< 1\ \sigma$ from $10\ \sigma$ initial offset.
  - Two-cycle convergence to $< 0.1\ \sigma$ from $10\ \sigma$ initial offset.
    - Limited by dynamic range of present op-amp, not by accuracy of compensation
      - Fix with another amplifier or tune diode bias
- Breadboard prototype slightly peaky for small signals
  - Likely to be fixed with chip diodes in real layout
  - Ideally would make large signal response as peaky as small-signal response
  - (to compensate kicker fill time)

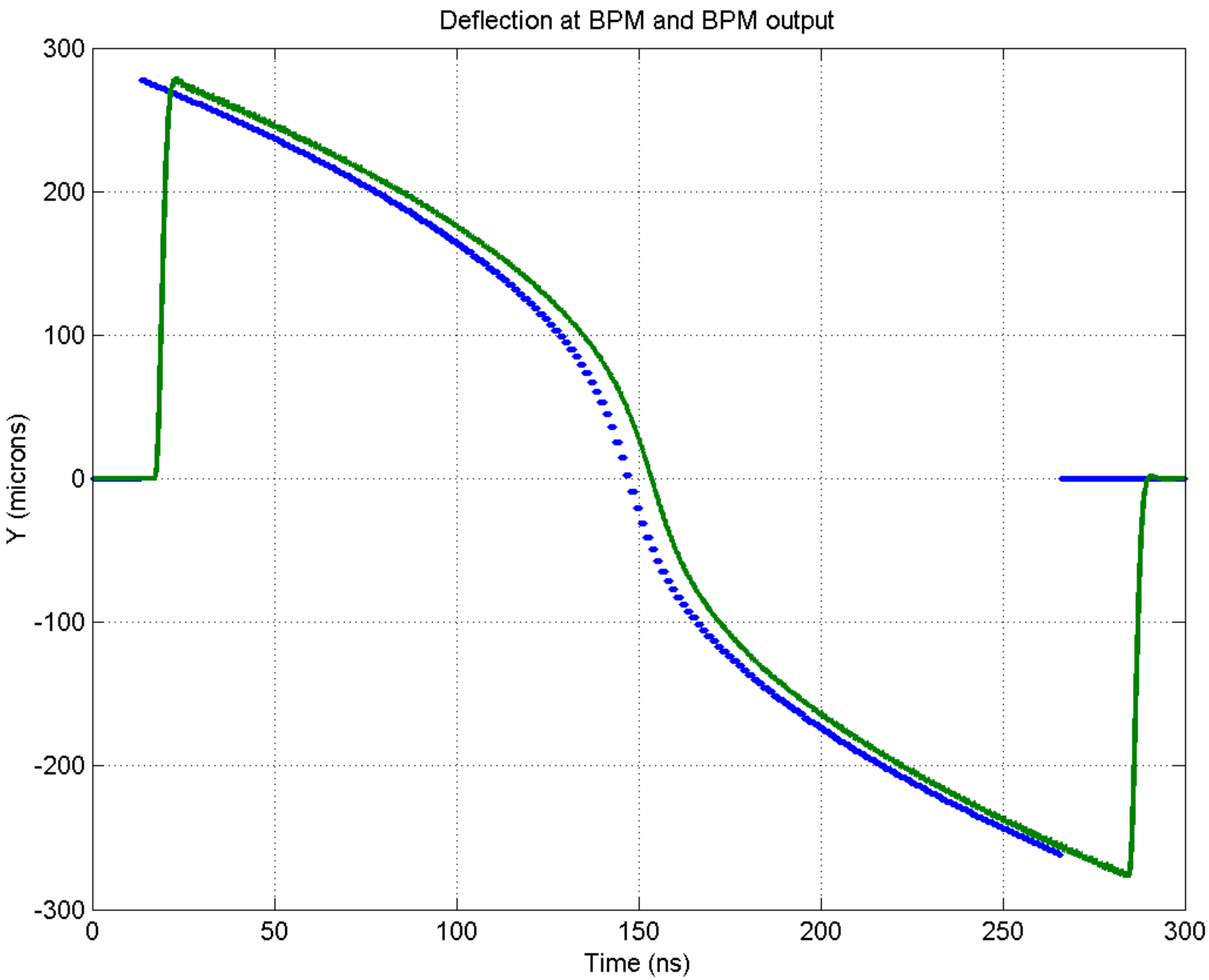
Intra-Pulse Feedback



Intra-Pulse Feedback
(with Beam-Beam Scan & Diagnostics)



Beam-Beam Scan



Beam bunches at IP: blue points

BPM analog response: green line

Conclusions

- Q BPMs
  - Need cavity BPMs
    - Accuracy
    - Stability
    - Compact
- Damping Ring BPM
  - Small evolution of current practice
- Structure Position Monitors
  - Electronically more like Direct Sattelite TV receiver
  - New to us, but similar objects are commercially available
- Multi-Bunch BPMs
  - High resolution
  - High bandwidth
  - Beyond state of the art
  - Achievable based on reasonable extrapolation of technology

Extensions

- Beyond NLC machine requirements:
- Bunch tiltmeter
- Nanometer resolution BPM's