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Some Numi Instrumentation

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Outline

- Commodities (few weeks of work – xerox job)
  - 2 toroid integrators - Aisha Ibrahim
  - 60 beam loss monitors (BLM) - Marv Olson
    - plus 4 total loss monitors
  - 4 total loss monitors (TLM) – Gianni Tassotto
  - 32 temperature/humidity sensors - John Seraphin
- Recent addition (small xerox job)
  - 1 resistive wall monitor (RWM) - Brian Fellenz
- Status
- Schedule

- Separate out BPM's
  - Larger task involving several people
  - Some components require design/development

Toroids

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- ±3% accuracy required
- Pearson 3100 current transformer   0.5V/amp 10Hz to 25MHz
- Fermilab toroid integrator
  - Full scale output 10V/4e13 particles
  - RMS noise 1.2mV or 5e9   (0.01% of full scale)
    - 16 bit A/D on board - direct digital reading
  - Long term drift (few %/month)
    - Within 3% accuracy specification but not well understood
    - Integrator -0.011%/degF temp sensitivity
    - Integrator has negligible change with ps voltage
    - Toroid +0.018%/degF temp sensitivity
    - Toroid has 0.01% or 6e9/gauss sensitivity to magnetic fields
- Improvements that affect long term drift:
  - New integrator (optimized to exploit new lower noise op-amps)
  - Trumpeter cable (better shielding and CMRR)
  - Transformer shielding (reduce effect of environmental noise)

FNAL Gas Ionization BLM's

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- <u>±30% accuracy required</u>
- 110 cm^3 Argon filled, 2KV bias voltage
  - Coaxial geometry 4" long, 1.5" ID outer, .25" OD center conductor
  - ~1 usec electron drift time ~2 msec ion drift time
- 80±4 nC/rad (6/19/00)
  - 80 to 88 nC/rad (different batches over the years ~10% accuracy)
- Max signal 1 rad in 1 usec (80 mAmps)
- Leakage current 1 pA
  - 8e10 dynamic range
- Integrator
  - 1 msec decaying integrator with logarithmic response and S/H
    - 1e6 dynamic range
    - 1 rad full scale
    - Error ±0.4% of output, ±3% of reading

BLM log amplifier

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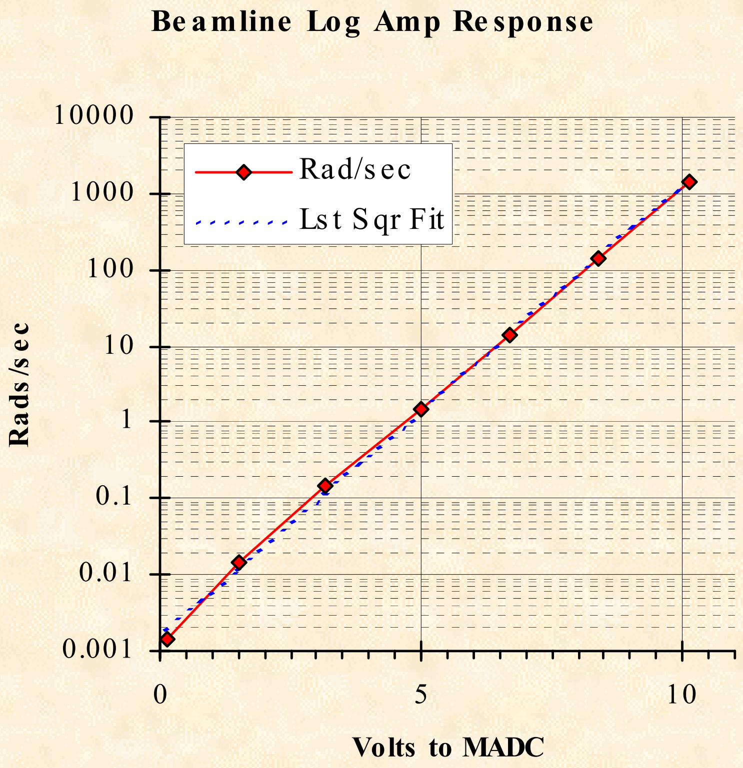
- 6 decades of dynamic range
- 1 msec decaying integrator
  - (160Hz low pass filter)
- 1 rad instantaneous or 1000 rads/sec continuous will produce full scale output



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BLM chassis

- BLM chassis holds 12 BLM channels and HV supply
  - 60 BLM tubes will be used requiring 5 chassis
- 2 chassis MI60 - 24 BLM's
- 1 chassis MI62 - 12 BLM's
  - additional chassis required for 4 total loss monitor channels
- 2 chassis MI65 - 24 BLM's
- Each channel has S/H output
  - MADC not embraced by controls because of latency issues
  - Have 40 channel multiplexed 12 bit A/D daughter cards from old RR BPM system that would allow reading BLM's through the BPM front end
    - programmer is familiar with them
    - Requires hold gate (PMC timing card)
  - Would require additional VME crate and 2434 power pc at MI62

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BLM list

- MI60 chassis 1
  - LMHV10 HV
  - LMHV1R HV
  - LMNKMA
  - LMNKMB
  - LMNKMC
  - LML60
  - LML61A
  - LML61B
  - LMV100
  - LMQ101
  - LM1011
  - LM1012
  - LM1C11
  - LM1C12
- MI60 chassis 2
  - LMHV20 HV
  - LMHV2R HV
  - LMQ102
  - LM1013
  - LM1014
  - LM1015
  - LM1016
  - LMQ104
  - LMH104
  - LMQ105
  - LMQ106
  - LMQ107
  - LM2C11
  - LM2C12
- MI62 chassis 1
  - LMHV30 HV
  - LMHV3R HV
  - LMQ108
  - LM1081
  - LM1082
  - LMQ109
  - LM1083
  - LM1084
  - LMQ110
  - LM1085
  - LM1086
  - LMQ111
  - LMQ112
  - LM3C12
- MI65 chassis 1
  - LMHV40 HV
  - LMHV4R HV
  - LMQ113
  - LMQ114
  - LMQ115
  - LMQ116
  - LMQ117
  - LMH117
  - LMQ118
  - LM1181
  - LM1182
  - LMQ119
  - LM4C11
  - LM4C12
- MI65 chassis 2
  - LMHV50 HV
  - LMHV5R HV
  - LM1183
  - LM1184
  - LMQ120
  - LMQ121
  - LM5C5
  - LM5C6
  - LM5C7
  - LM5C8
  - LM5C9
  - LM5C10
  - LM5C11
  - LM5C12

Total loss monitors (TLM's)

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- ±30% accuracy required
- 7/8" air dielectric cable HJ5-50
  - 80% Argon, 20% CO_2
  - E:TLMNS 193ft long
  - E:TLMCTU 220ft
  - E:TLMCTD 194ft
  - E:TLMPT 182ft
  - Total 789ft (beam-line is about 1200 feet)
  - Very upstream end in MI60 region is not covered by a TLM
  - 200ft of 7/8" cable will hold 20,000 cm^3 of gas (~180 BLM tubes)
- Pressure and purity will both depend on flow rate and affect response
  - considering online monitoring with a radioactive source on a short isolated section of cable at the end (Americium 1mR/Hr is reasonable)
- Use BLM chassis with 4 daughter cards to measure loss and 4 to monitor source

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Temperature and Humidity sensors

- Require
  - 9 modules
  - 16 temperature and 16 humidity channels
- Standard Temp/Humidity module
  - 3 temperatures and 2 humidity measurements per module
  - Usually tunnel air inlets/outlets with one in between
  - Each service building room
  - Read through MADC channels
  - Can be data logged

Temp/Humidity sensor locations

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- MI62 - 7 locations
  - Numi stub
  - (upper hobbit)
  - Lower hobbit
  - Pre-target
  - Target hall
  - Target hall Power supply room
  - Target hall Raw skid room
- MI65 - 9 locations
  - Absorber hall
  - Upper absorber access tunnel
  - Muon alcove 2
  - Muon alcove 3
  - Target hall 1
  - Target hall 2
  - MI65 electrical room
  - MI65 electronics room
  - Minos electrical room

Resistive Wall Monitor - addition

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- Wide band 3KHz to 3GHz beam current monitor
  - $10.4k for monitor
  - ~$8k cable + installation
  - $20k fast digitizing oscilloscope
    - Need software (possibly front end) to read/display/analyze results
  - Low end limited by ferrite
  - High end limited by beam pipe cutoff frequency
    - For 4” pipe TE11 1.7GHz TM01 2.3GHz
  - 7/8” Heliax cable LDF5-50A (~10db @ 1GHz for 700ft)
    - Cable dispersion is important
- Sharing MI RWM may not be possible
  - MI RWM – doesn’t see extraction problems
  - Allowing others to make connections can be problematic
  - Cost of scope and software is significant
    - MI scope cannot be dedicated to Numi purposes

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Status

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Toroid status

- Toroids
  - Pearson 3100's have been delivered
- Need to:
  - order ceramic gaps
  - build stand / electrical bypass
    - Jim Klen has built them before
  - Assemble 2 integrators
  - Identify 2 wide NIM slots at MI60 and MI65
    - Share NIM chassis with temp/humidity?
  - Requires Camac 184 digital I/O cards and 377 Tclk decoders

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BLM status

- All 6 BLM chassis are built
  - 4 are installed
  - 1 is at Argonne being tested
- All BLM tubes have been ordered (1 year ago)
  - Still waiting for delivery
    - Have received 24
    - Vendor has recently promised 8 tubes/week
    - Need to monitor this
- Need to evaluate reading BLM's through BPM front end

Temp/Humidity status

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- Need to order parts and assemble 9 temp/humidity NIM modules 16 temp and 16 humidity sensors
- Need 2 NIM chassis
- Need cables identified and pulled
- (Building batch of modules for Booster soon)

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RWM status

- Need decision
- procurement
  - 16 weeks to get ferrite
  - 12 weeks to get ceramic vacuum break
- Cable installation

- Estimate ~$20k to purchase digital scope
- Need application program (possibly front end) to process and display data

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Schedule

- BPM, BLM, toroid, temp/hum cables are specified
  - Some cables are being installed this shutdown
- Remaining tunnel work will be completed as access is allowed
- 6 week shutdown in July/August 2004
- Beam January 2005

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Numi BPM's

Jim Crisp

BPM pickups

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- 4 Qualifying BPM's in MI ring (installed)
- 26 MI8bpm's in beamline (built)
  - 49.2mm radius
  - 5.25" long split electrodes
  - 4.3±0.03mm/db (sample of 60 MI8bpm's)
  - Electrical center ±0.4mm rms
  - 0.5Vpk/1e10ppb 53MHz, 2ns sigma t, (.8011 factor)
- 4 target BPM's (building more)
  - 25.4mm radius
  - 5.25" long split electrodes
  - 1.8mm/db
  - 0.5Vpk/1e10ppb 53MHz, 2ns sigma t, (.8011 factor)
- MI 60 cables are <670ft (4.9db @ 50MHz)
  - LDF2RN-50 heliax cable

Main Injector ring qualifying BPM's

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- Need to specify functionality of qualifying BPM's
  - Assume position for N turns leading up to extraction is desired
  - How much time is allowed for processing results?
- 4 qualifying BPM's in MI
  - Large aperture BPM at Q608 has 4 plates rotated by 45º
  - 4 plates 60deg wide
  - 58.8mm radius
  - 4" long
  - 2.3mm/db rotated 45deg (1.8mm/db hor/ver plates)
  - 0.13Vpk/1e10ppb 53MHz, 2ns sigma t, (.8011 factor)
- Need to identify other 2 BPM's

BPM list

- MI ring (4)
  - VP608
  - HP608
  - VP?
  - HP?
- MI60 (13)
  - VP101
  - HP101
  - HP102
  - VP103
  - HP104
  - HP105
  - VP106
  - HP107
  - VP108
  - HP109
  - VP110
  - VP111
  - HP112
- MI65 (11)
  - VP113
  - HP114
  - HP115
  - VP116
  - HP117
  - VP118
  - HP119
  - HP121
  - VP121
  - HPTGT
  - VPTGT

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Numi Beam

- 4e11 in 1 batch to 4e13 in 5 batches of 84 bunches
  - ~0.5e10 to 10e10 / bunch
  - (6 batches possible without pbar stacking)
- 3 to 8 nsec bunch lengths
  - Assume this includes 90% of a gaussian shaped bunch?
  - 0.9 to 2.4 nsec σ_t (53 MHz component 0.96 to 0.73)

- <u>±3% accuracy required</u> for BPM intensity measurements
- BPM's measure the amplitude of the 53MHz component and do not know the bunch length or the number of bunches
  - BPM system will measure the average bunch intensity over one batch
  - Measured bunch intensity will depend on bunch length
    - 8 nsec bunch reads 23% lower than 3 nsec bunch
  - Relative measurements between BPM's are better
    - Expect few % (limited by cable errors, terminating impedance, reflections)

Single gaussian bunch – time domain

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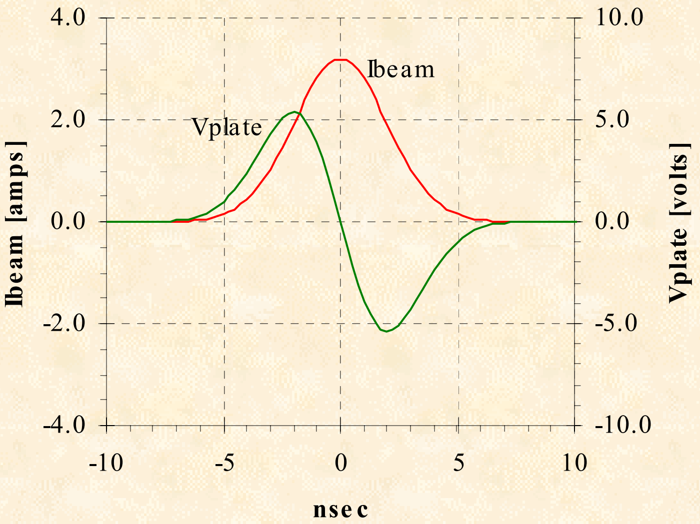
- Single gaussian bunch
  - 2ns σt, 10e10, 25Ω plate
  - Plate length 5.25" (dt = 0.44nsec)
  - Ibeam = 3.2Amps peak, Vplate = 5.4Volts peak
    - Max cable loss 4.9db (factor of 1.8)
    - GC814 max input 1.1Vpk

$$I = \frac{Ne}{\sigma_t\sqrt{2\pi}} \exp^{-\frac{1}{2}\left(\frac{t}{\sigma_t}\right)^2}$$

$$\frac{dI}{dt} = \frac{Ne}{\sigma_t\sqrt{2\pi}} \exp^{-\frac{1}{2}\left(\frac{t}{\sigma_t}\right)^2} \frac{t}{\sigma_t^2}$$

$$V_{plate} = Z_o\, I(t) \frac{t}{\sigma_t^2}\, dt$$



Frequency spectrum of BPM signal

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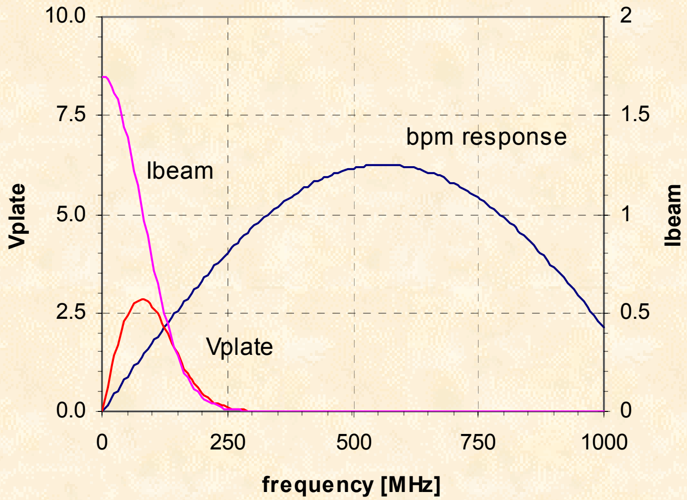
- 2 nsec σ_t bunch length
- 5.25" long BPM electrode
- 10e10 protons/bunch
  - 1.7 Amps peak @ 53MHz
  - 2.4 V peak @ 53MHz
    - Max cable loss 4.9db (factor of 1.8)
    - GC814 max input 1.1Vpk



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Planned BPM system

- VME system
  - 2434 power pc
    - PMC UCD Tclk decoder
  - Carrier card
    - IP UCD Tclk decoder
    - IP TSG timing generator
    - Digital I/O daughter card
    - 1 BLM mulitplexed A/D
  - Echotek A/D clock generator
  - Arbitrary waveform generator
  - 4 Echotek GC814 digital receiver cards
    - 8 A/D channels or 4 positions per module
- 19” rack modules
  - Clock fanout
    - 1 output for each GC814 module
  - BPM attenuator/filter
    - Handle type N to SMA conversion
    - Get signals to front of rack
    - Band pass or low pass filters
    - Attenuate signal for optimum range
    - (Possible test port/switches)

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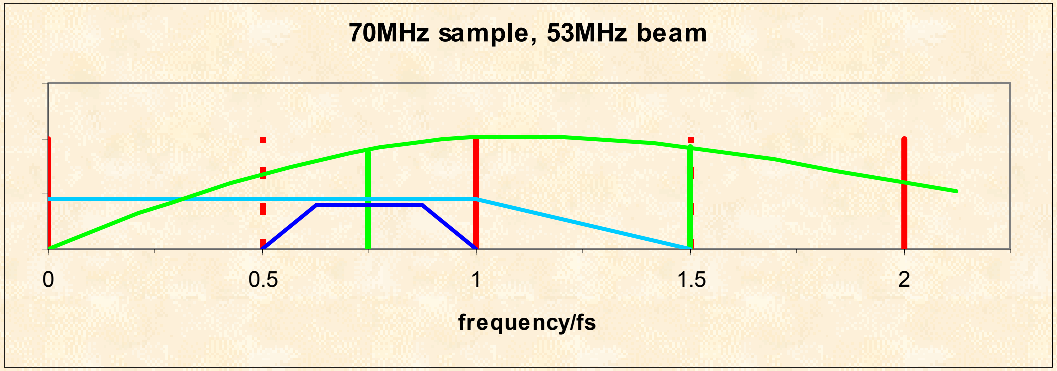
14 bit 80MHz A/D



- Envelope of the MI8bpm frequency response and the first and second bunch frequency harmonics are shown
- Sample frequency 70.6MHz (4/3 of 53MHz)
- Use bandpass filter to eliminate signals <fs/2 and >fs
  - Low pass filter will work if the only undesirable component is at 106MHz

Echotek GC814 frequency response

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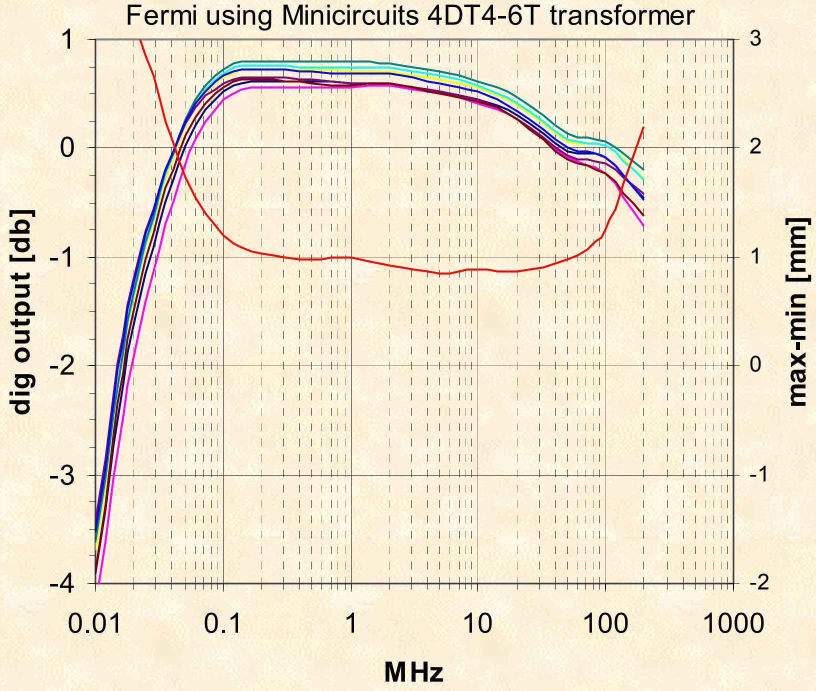
- Undersampling should be ok
  - Measure fixed sinewave at 14 frequencies from 0.01 to 200MHz with 70.6MHz clock frequency
  - All 8 channels are shown
  - Normalized to response at 53MHz
- Red trace shows position error from using largest and smallest channel
  - 4.3mm/db



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Echotek/Boone BPM test

- Vic Scarpine and Warren Schappert measured positions from all 4 Boone target BPM's (1.8mm/db)
- Obtained resolution of 20 to 40 um RMS
  - Measured single position for each batch of 84 bunches
  - 1.7 to 4.8e10/bunch

- The low pass filter allowed some second harmonic (106MHz) through
- This, coupled with small phase differences between the A and B signals, produced ±100um errors that depended on the phase between the A/D clock and the beam

Position noise with 84 bunch train

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- MI8bpm 4.3*20log(A/B) or 75(A-B)/(A+B)

- For a signal that just reaches full scale input
  - 70MHz sample rate
  - 84 - 53MHz bunches (111 samples)
  - 74db/20log2 = 12.4bits ENOB (effective number of bits)

$$X_{noise} = 75mm \frac{1}{\sqrt{2}} \frac{1}{\sqrt{111}} \frac{1}{2^{12.4}} = 0.93\mu m\ Rms \qquad at\ \ 10e10/bunch$$

- Position noise is inversely proportional to the beam intensity and the square root of the number of samples
  - (~20um rms at 0.5e10/bunch)

Measured Echotek BPM response

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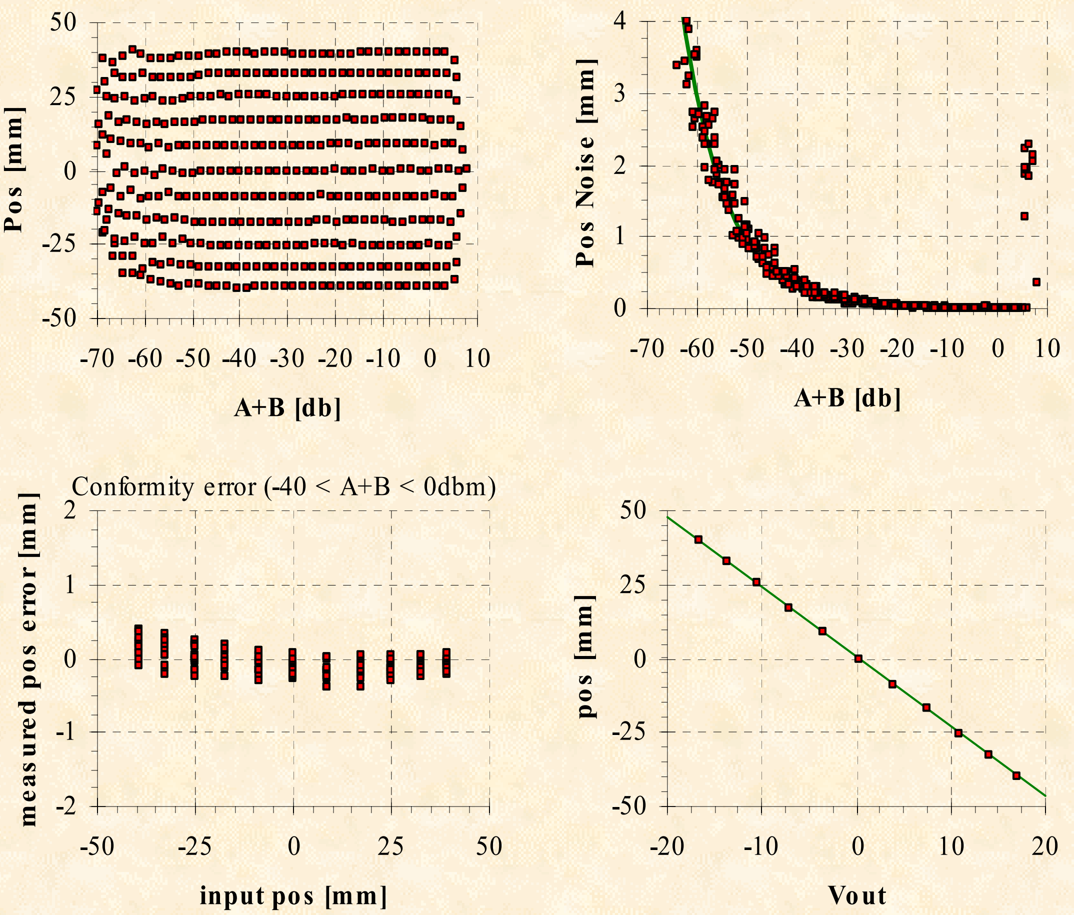
- 1mm rms @ -50dbm
  - -92.3 db fs noise
  - 15.3 bits
- A/D 12.4 ENOB
- Processing gain
  - 2.9 bits
  - Equivalent to 57 samples
- 84 bunches @ 70MHz
  - 111 samples
- Using gaussian window to reduce timing sensitivity



Intensity sensitivity

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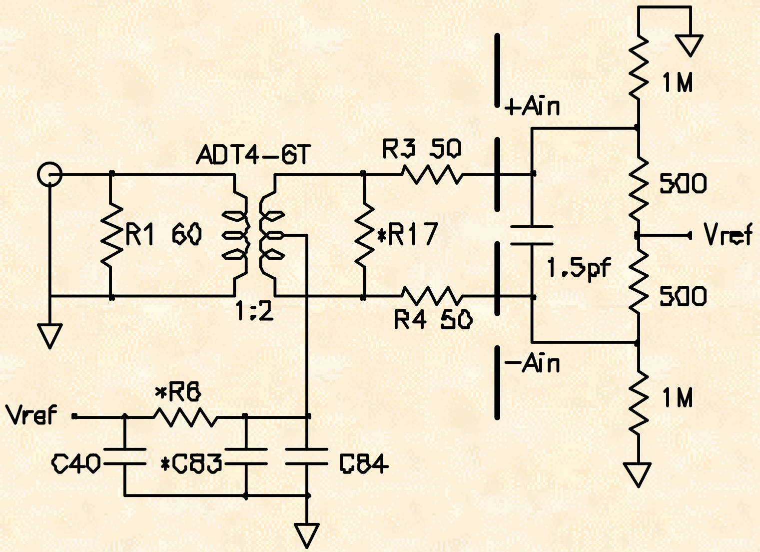
- Measured position depends on intensity
  - Used splitter to simulate A=B
  - Changed fixed attenuators in front of splitter to scan A+B
  - A/D linearity should be good to 10um (74.5db SINAD)
  - Could it be transformers at A/D input?



Position accuracy/resolution

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- Define accuracy as position with respect to the design orbit
- Define resolution as the rms variation in the measurement of the same position
- Accuracy errors include:
  - Systamatic (correctable) errors
    - Survey
    - Electrical center of the BPM
    - Cable attenuation
    - Cable characteristic impedance
    - Terminating impedance
    - Echotek channel differences
  - Unpredictable errors
    - Stability of cables, terminations, filters
    - Cable reflections (VSWR)
    - A/D non linearity

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Position resolution

- Resolution concerns:
  - A/D SNR –74.5db
    - 1um at 10e10/bunch
  - Environmental noise (heliax cable should have good isolation)
    - Rf leakage from cavities
    - Ceramic breaks (toroids)
    - Return currents from beam exiting beam pipe
      - Like attaching a 3.2 amp current source between beam pipe and upstairs with exactly the same frequency being measured
    - Kicker induced ground currents
    - Power supply scr firing pulses
  - Bunch structure, bunch to bunch variations

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Position requirements

- Requirements
  - Resolution and stability over periods of hours:
    - 150 um rms at 1e10 protons/bunch averaged over full spill
    - ±20mm range
- In my opinion, this is not achievable
  - 150um == 0.035db
    - difficult even in a quiet lab using a $35K network analyzer
    - Numi requires this through 700ft cables strung between a noisy beam pipe and an equally noisy service building
- Target BPM errors will be half as large
  - sensitivity 1.8mm/db compared to 4.3mm/db for MI8bpm's

Sources of position error

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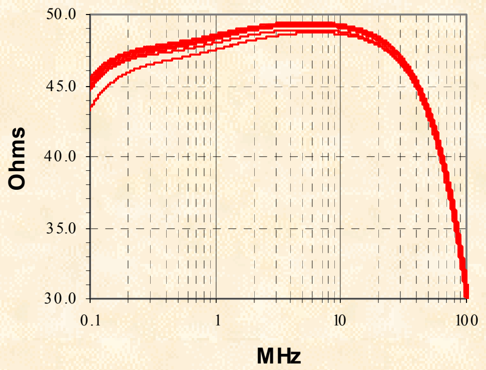

- Cable and terminating impedance mismatch
  - LDF2-50 50±1Ω
  - GC814 40-41Ω @ 53MHz
    - (Match with attenuator/filter)
- MI8bpm plate 21pf to ground
  - Put 50Ω to ground on each plate (in parallel with 50Ω cable)

$$f_o = \frac{1}{2\pi\ RC} = 300MHz \quad for\ R = 25\Omega \quad C = 21pf$$

- Cable reflections
  - Cables are .2 to .8 usec long
  - Signals are 1.6 usec/batch
  - Multiple reflections will build up a VSWR in the spill

Impedance matching error

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- Assuming kr << 1 and that A ≈ B

$$k_r = \frac{Z - Z_O}{Z + Z_O} \qquad A' = A\left(1 + k_r\right)$$

$$x \approx 75mm \frac{A\left(1 + k_r\right) - B}{A + B}$$

$$X_{error} \approx 75mm \frac{k_r}{2}$$

- For Z-Zo = 1Ω, kr = .01
  - error = 0.38mm

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VSWR

- VSWR – voltage standing wave ratio (not necessarily from terminations!)
  - Ratio of the max to the min voltage along a cable that is not properly terminated

$$vswr = \rho = \frac{1+|k_r|}{1-|k_r|} \qquad k_r = \frac{Z - Z_O}{Z + Z_O}$$

$$\rho = larger\ of \quad \frac{Z}{Z_O}\ or\ \frac{Z_O}{Z} \qquad (always\ greater\ than\ 1)$$

- Assume both cables have the same vswr but max and min's probably don't align at the receiver
  - Use the square root of the vswr to estimate position error

$$X = 4.3\left[\frac{mm}{db}\right]20\log\left(\frac{A}{B}\sqrt{\rho}\right)$$

$$X_{error} = 4.3\left[\frac{mm}{db}\right]20\log\left(\sqrt{\rho}\right) = 0.37mm\ for\ \rho = 1.02$$

- Measured beam position will vary through the spill as reflections add up

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Cable attenuation

- The percentage change in attenuation is probably about the same as the percentage change in characteristic impedance

$$\alpha\left[\frac{Np}{m}\right]=\frac{R}{2Z_O}$$

- 1Ω or 2% variation in Zo will provide a 1% variation in attenuation
- 700ft of LDF2RN-50 is 4.9db
  - .01(4.9)(4.3mm/db) = .2mm error

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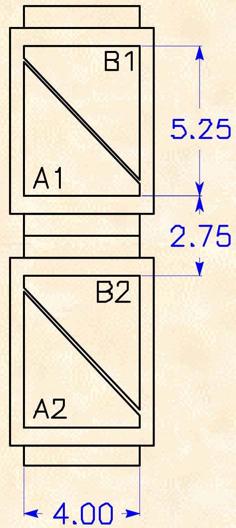
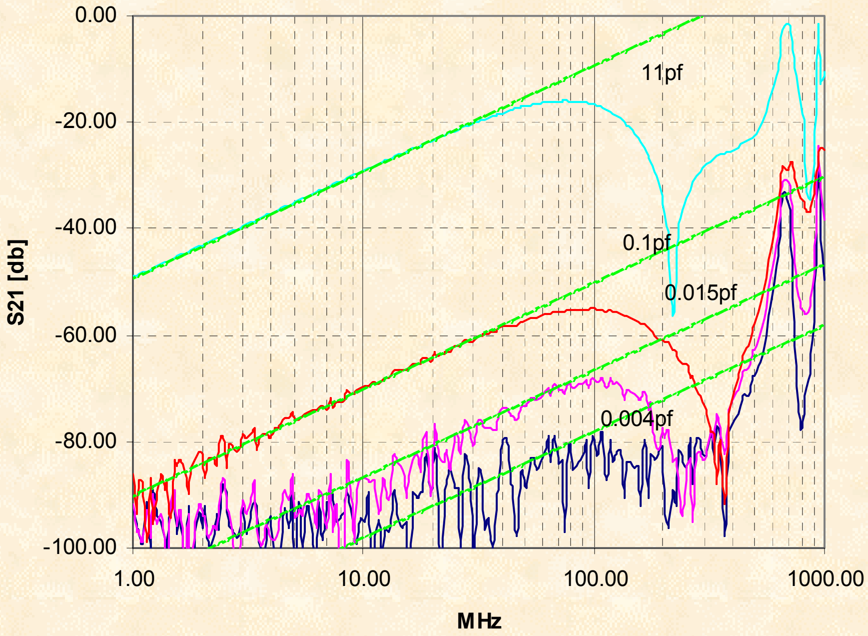
Coupling between neighboring BPM's





- 11pf plate to plate in same BPM
- 0.1pf between near plates
- 0.015pf between near/far plates
- 0.004pf between far plates

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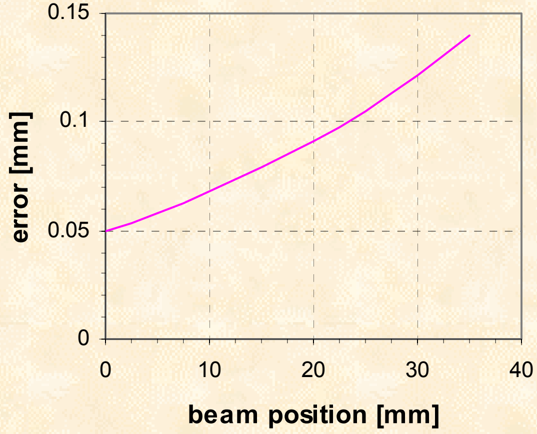
Position error from nearby BPM

- Position error caused by nearby BPM depends on beam position
- Offset at center from difference in coupling to A and B plates



- Too small to worry about

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BPM cost

- Major components (neglecting cables and detectors)
  - 3 VME crates $10k
  - 3 2434 power pc cards $10k
  - 11 Echotek GC814 cards $134k
  - 3 Echotek clock generator cards $7k
  - 3 PMC UCD cards $1k
  - 3 digital I/O cards $5k
  - 3 arbitrary waveform generators $15k
  - 3 clock fanout $3k
  - 3 attenuator filter chassis $3k
  - Total $188k

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BPM status

- Digital receiver modules and clock generators have been ordered
  - Expected delivery December
  - Have IP TSG's
  - Have BLM multiplexed A/D's
- PO's submitted for
  - VME crates
  - 2434 power pc's
  - PMC UCD timing card
  - Echotek clock generator (need module with 2 – 4 way splitters)
  - Industry pack carrier
- Need to order
  - Digital I/O card
  - Arbitrary waveform generator for test system

BPM schedule

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name	task	Oct	Nov	Dec	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Nov	Dec	Jan
	6 week shutdown										x x x	x x x				
	Numi beam															x
Crisp	Numi internal instrumentaion review	x														
Childress	specify functionality of qualifying bpm's															
Crisp	specify/document functionality/performance of beamline bpm's		x x x x													
"	specify 53MHz filter		x x	x x x x												
"	Consider self trigger or hardwire trigger			x x x x												
"	specify test system			x x x x	x x x x											
Prieto	select/order VME chassis			x x												
"	select/order AWG and digital I/O IP				x x											
	assemble first system for testing/development				x x											
Prieto	design/build atten/filter chassis					x x x x										
Prieto	build clock fanout chassis					x x x x										
McClure	program/test PMC UCD, IP UCD, and trigger cards					x x										
Briegel	program Echotek cards and AWG					x x x x			x x x x							
Voy	program 2401 power pc card					x x x x			x x x x							
Hendricks	ACNET interface									x x x x						
Winterowd	application program (R39)									x	x x x					
Bob West	test/control application (R33)									x	x x x					
Marc Mengel	test system application									x	x x x					
	phase match and terminate cables										x x					
	install systems										x x					
	test/calibrate bpm's in place											x x x				

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Numi BPM summary

- Numi BPM's will follow the Recycler Ring BPM design very closely
- This system has obtained high quality positions from the Boone beamline
- Position algorithms, Acnet interface, and applications programs require small modifications
  - People involved are estimating a month or so to modify their part
  - Beamline BPM system has much less data flow
- Design, implementation, operation, and maintenance of the Recycler and Numi systems will have synergy