Feedback Control of Particle Beam Instabilties

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Talk Outline

Background - Accelerator Instabilities, Feedback control

- Feedback basics
- Requirements for beam instability control

Possible Solutions and Technical Challenges - State of the Art Review

- Example systems from around the world
- parallel processing DSP structures, flexible reconfigurable architectures
- Kicker antennas and power structures

Accelerator Diagnostics via transient domain techniques

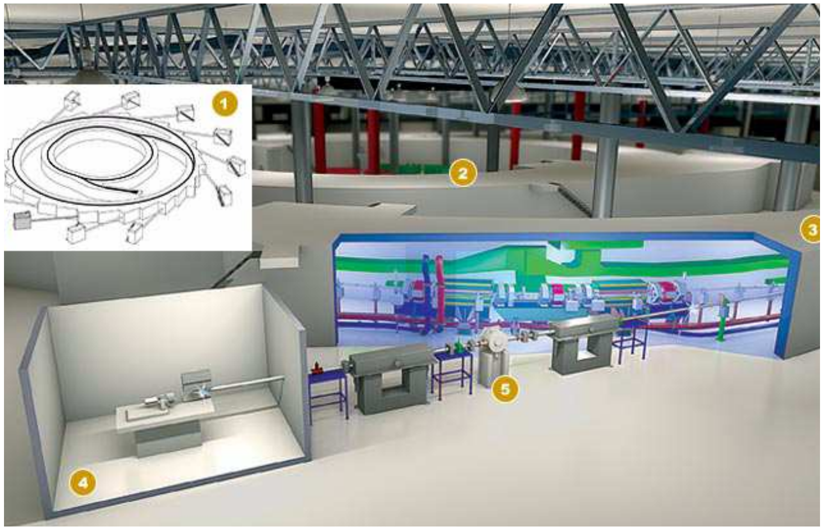
- Modal Growth/damping rates
- Impedances, noise driven motion
- Ion and Electron Cloud diagnostics

Fundamental limits to performance and Promising R&D Opportunities

Interesting new directions - ecloud instabilties in the SPS and LHC

Summary

Motivation



Applications of charged-particle circular accelerators

- Colliders
- Light sources

Coupled-bunch instabilities cause beam loss or reduced performance affecting the intensity of light sources and the luminosity of colliders.

In the past circular machines were designed to operate below the instability threshold.

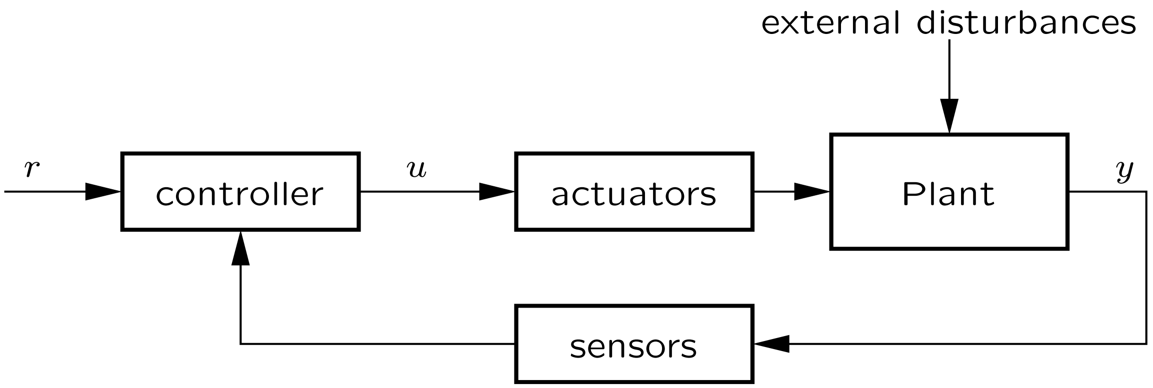
However modern high-current accelerators are routinely run above the instability threshold. For example the Advanced Light Source has 400 mA design current and 40 mA instability threshold.

Active feedback is needed for design performance!

Feedback Control provides Stability - AND Accelerator Diagnostics

Feedback basics

The objective is to make the output y of a dynamic system (plant) behave in a desired way by manipulating input or inputs of the plant.



Regulator problem - keep y small or constant

Servomechanism problem - make y follow a reference signal r

Feedback controller acts to reject the external disturbances.

The error between y and the desired value is the measure of feedback system performance. There are many ways to define the numerical performance metric

- RMS or maximum errors in steady-state operation
- Step response performance such as rise time, settling time, overshoot.

An additional measure of feedback performance is the average or peak actuator effort. Peak actuator effort is almost always important due to the finite actuator range.

Feedback system robustness - how does the performance change if the plant parameters or dynamics change? How do the changes in sensors and actuators affect the system?

Coupled-Bunch Feedback Principles - General Overview

Principle of Operation-Feedback can be used to change the dynamics of a system

Longitudinal - measure $\delta\phi$ - correct E

Transverse - measure$(\delta X, \delta Y)$ - kick in X', Y'

Technical issues

Loop Stability? Bandwidth?

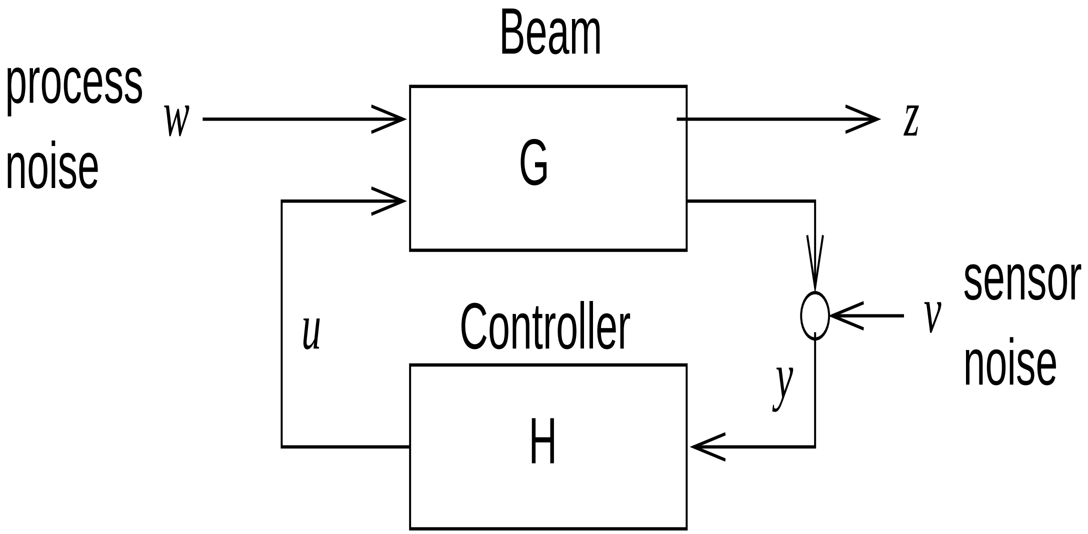
Pickup, Kicker technologies? Required output power?

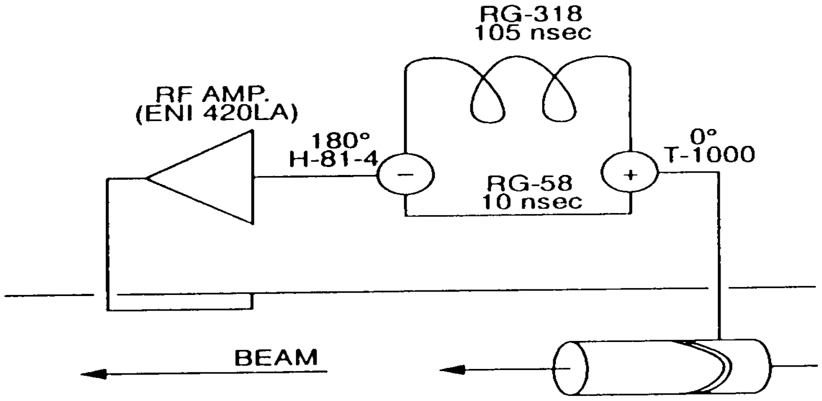
Processing filter? DC removal? Saturation effects?

Noise? Diagnostics (system and beam)?

Example - the simplest transverse feedback idea (from Galayda, NSLS)

all analog, cable delay for 1 turn

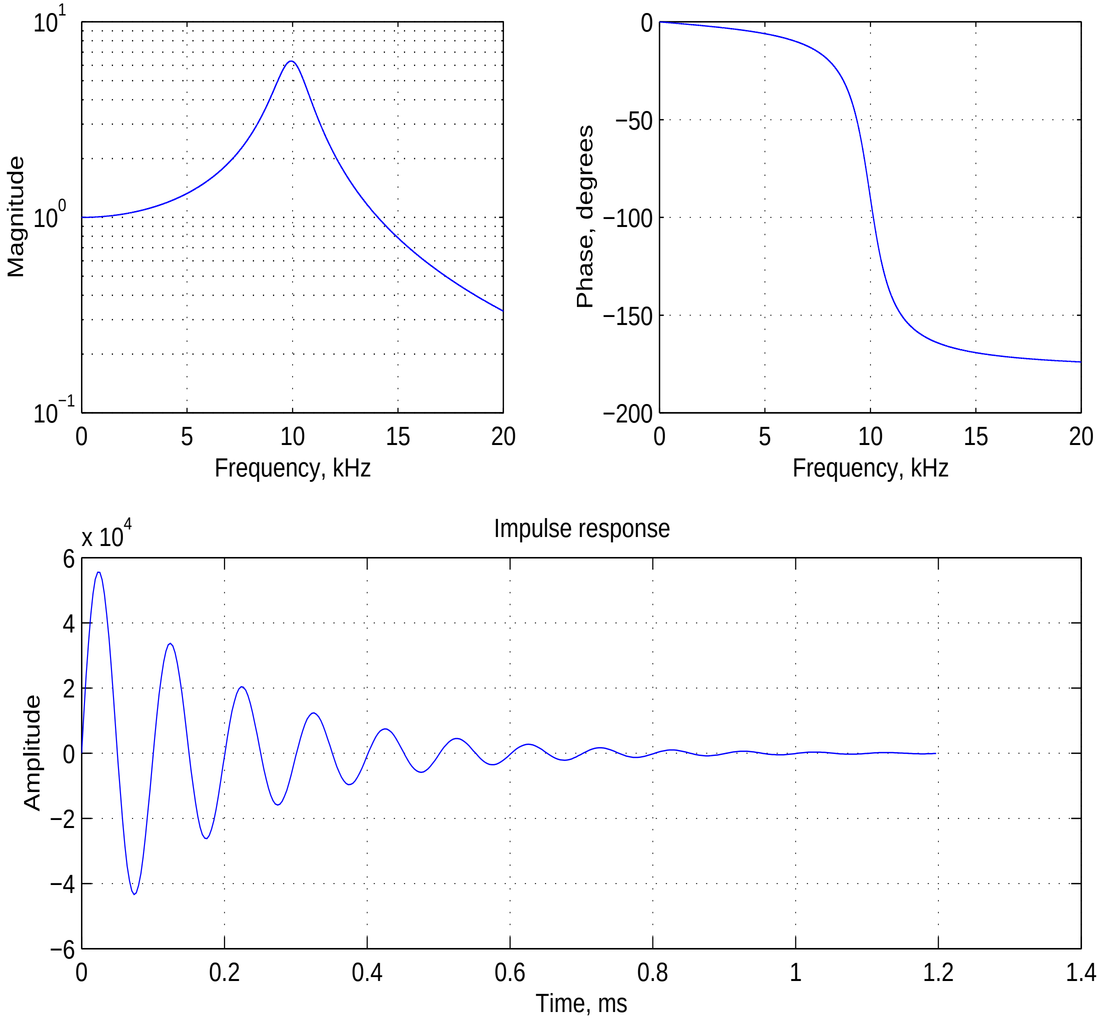




Harmonic Oscillators, Revisited

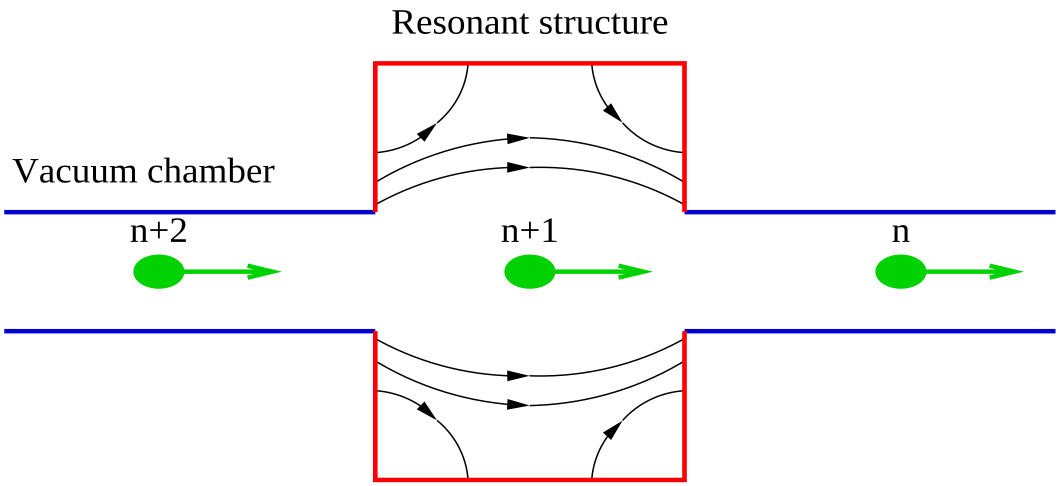
Equation of motion $\ddot{x} + \gamma\dot{x} + \omega_0^2 = f(t)$ where $\omega_0 = \sqrt{\frac{k}{m}}$

Damping term γ proportional to $\dot{x}$ - use feedback to ensure negative damping

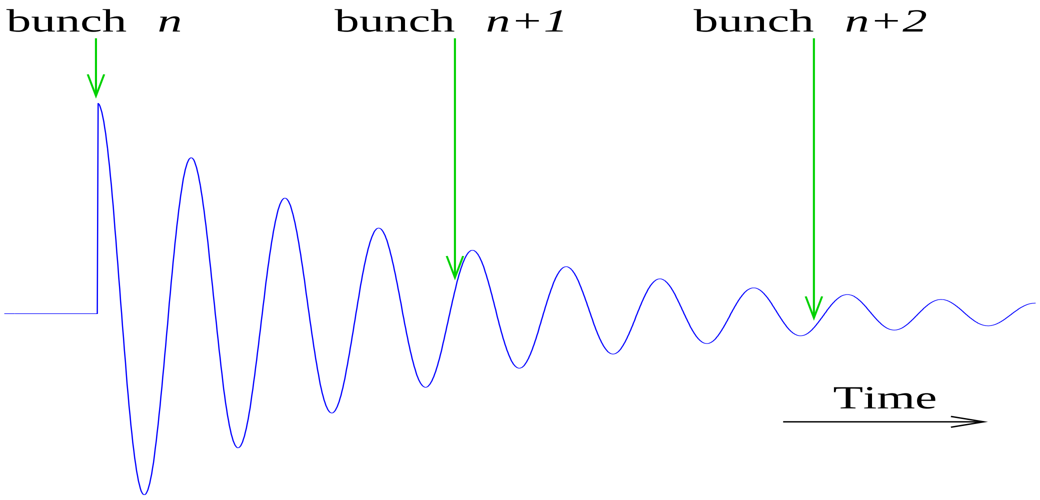


Coupled dynamics: multiple bunches

Bunch passing through a resonant structure excites a wakefield which is sampled by the following bunches - a coupling mechanism



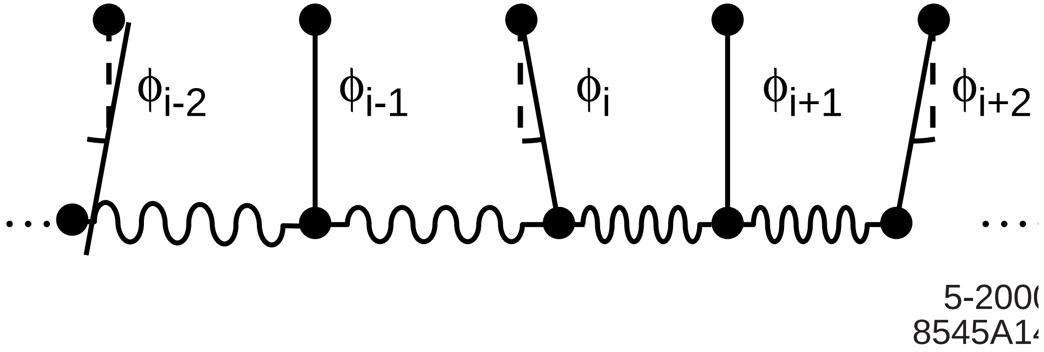
Longitudinal bunch oscillation translates into a phase modulation of the wakefield - slope of the wake voltage sampled by the following bunches determines the coupling.



Transverse Oscillations excite transverse “kicks” - magnitude proportional to transverse displacement*current

For certain combinations of wakefield amplitudes and frequencies the overall system becomes unstable. (In practice the wakefields have much longer damping times than shown)

Normal Modes, Revisited



N coupled Oscillators, N Normal Modes (so thousands of modes in large machines)

Driving term provides coupling

Broadband (all-mode) vs. Narrowband Feedback

Time Domain vs. Frequency Domain formalism

- Pickup, Kicker signals the same
- Bandwidth Constraints identical

An all-mode frequency domain system (with uniform gain) is formally equivalent to a bunch-by-bunch time domain system - identical transfer functions

Eigenmodes and impedances

For an even fill pattern the bunch motion can be easily projected into the even-fill eigenmode (EFEM) basis. For N coupled harmonic oscillators (bunches) there are N normal modes.

Longigtudinal Modal eigenvalues are given by

$$\Lambda_m = -d_r + i\omega_s + \overbrace{\frac{\alpha e f_{\mathrm{rf}}}{2E_0\nu_s}}^{\text{Accelerator parameters}} \overset{\text{Beam current}}{I_0}\, \overset{\text{Aliased impedance}}{Z^{\mathrm{eff}}}(m\omega_{\mathrm{rev}} + \omega_s)$$

$$Z^{\mathrm{eff}}(\omega) = \frac{1}{\omega_{\mathrm{rf}}} \sum_{p=-\infty}^{\infty} (p\omega_{\mathrm{rf}} + \omega) Z(p\omega_{\mathrm{rf}} + \omega)$$

Real part of the eigenvalue - exponential growth rate, Imaginary part - undamped natural frequency

The growth rate is proportional to beam current. Above some threshold current system is unstable.

Two ways to fight the instabilities: lower the impedance or use feedback damping

Lowering the impedance is achieved with RF cavity design (for HOM’s) or Direct RF feedback

Active Feedback techniques require signal processing and act as a negative real impedance

Processing Requirements

For instability control, the processing channel must

- extract (filter) information at the appropriate synchrotron or betatron frequency,
- amplify it (a net loop gain must be generated, large enough to cause net damping for a given impedance)
- generate an output signal at an appropriate phase (nominally 90 degrees, but arbitrary if the system and cable delays, pickup and kicker locations are considered)

Some technical issues

- Bandwidth/sampling rate (500 MHz RF (the bunch separation), or more?)
- DC offset removal from the processing channel (e.g. from DC synchronous phase position, or static orbit offset)
- Saturation on large input errors (injection, or driven motion)
- Noise in the input channel (e.g. bandwidth reduction via processing filter)
- Maximum supportable gain - limits from noise as well as loop stability
- Diagnostics (processing system and beam dynamics)

Technical Challenges

Short interbunch Interval

- KEK-B, ALS, BESSY, PLS, etc. 2 ns, DAFNE 2.7 ns, PEP-II 4.2 ns
- requires wideband pickups, kickers (from required bunch isolation, kicker filling times)
- sets required processing bandwidths
- Resolution - Longitudinal damped oscillation rms 0.6 picosecond
- - Transverse damped oscillation ~microns

Many Bunches (many unstable modes)

- KEK-B 5120, PEP-II 1746
- Need to compactly implement bunch by bunch filters

Ratio of Frev to Fosc

- Nyquist limit Fosc< 1/2 Frev
- Betatron Oscillations grossly undersampled
- Synchrotron oscillations typically oversampled
- low synchrotron frequency sets scale of required filter memory (Delay-bandwidth product)

Block diagram of a longitudinal feedback system

First Generation DSP, programmable system installed in:

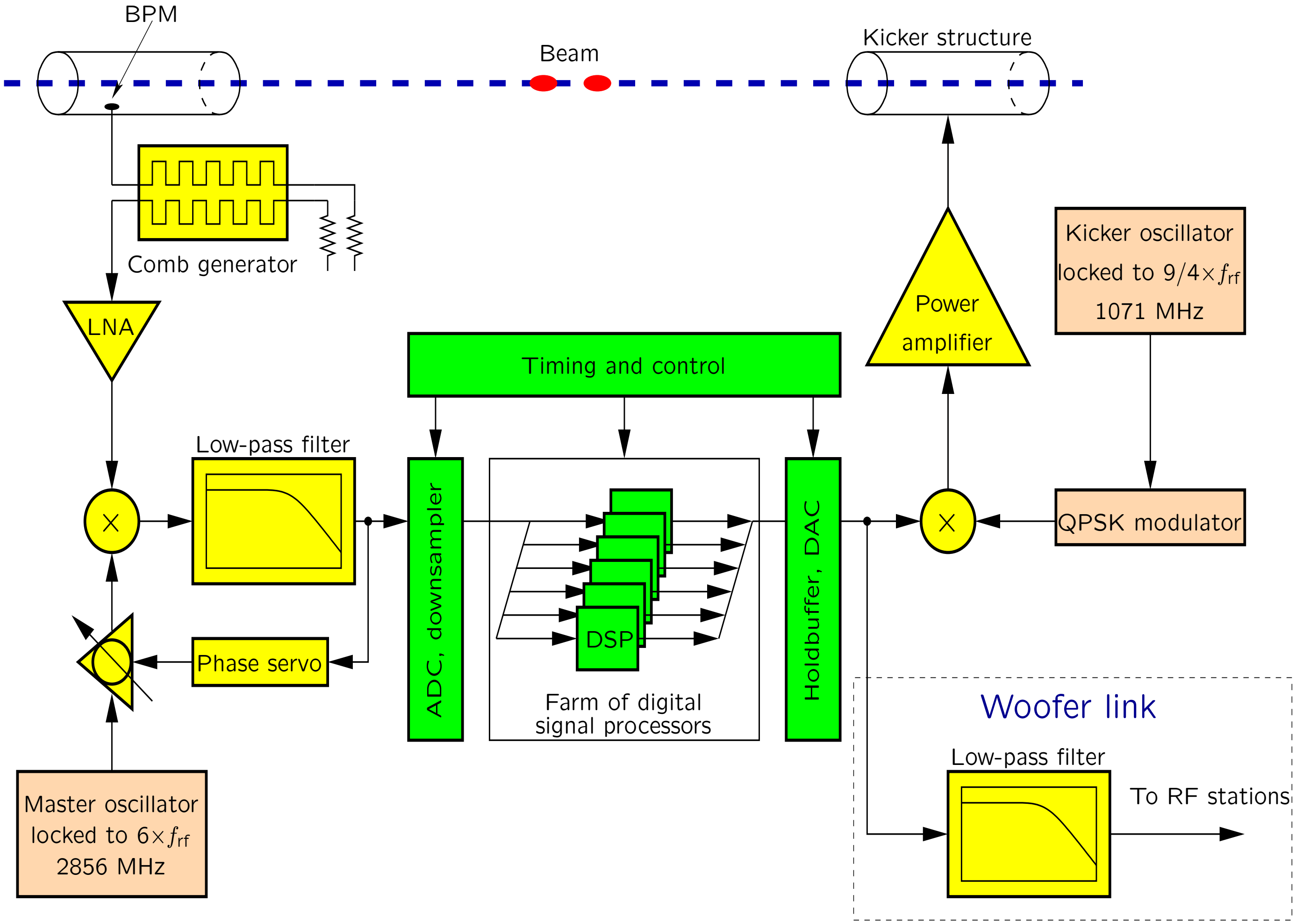
PEP-II, ALS, BESSY-II, PLS, DAΦNE and demonstrated at SPEAR

Detection at $6 \times F_{RF}$, correction at 9/4 RF (options 11/4, 13/4)

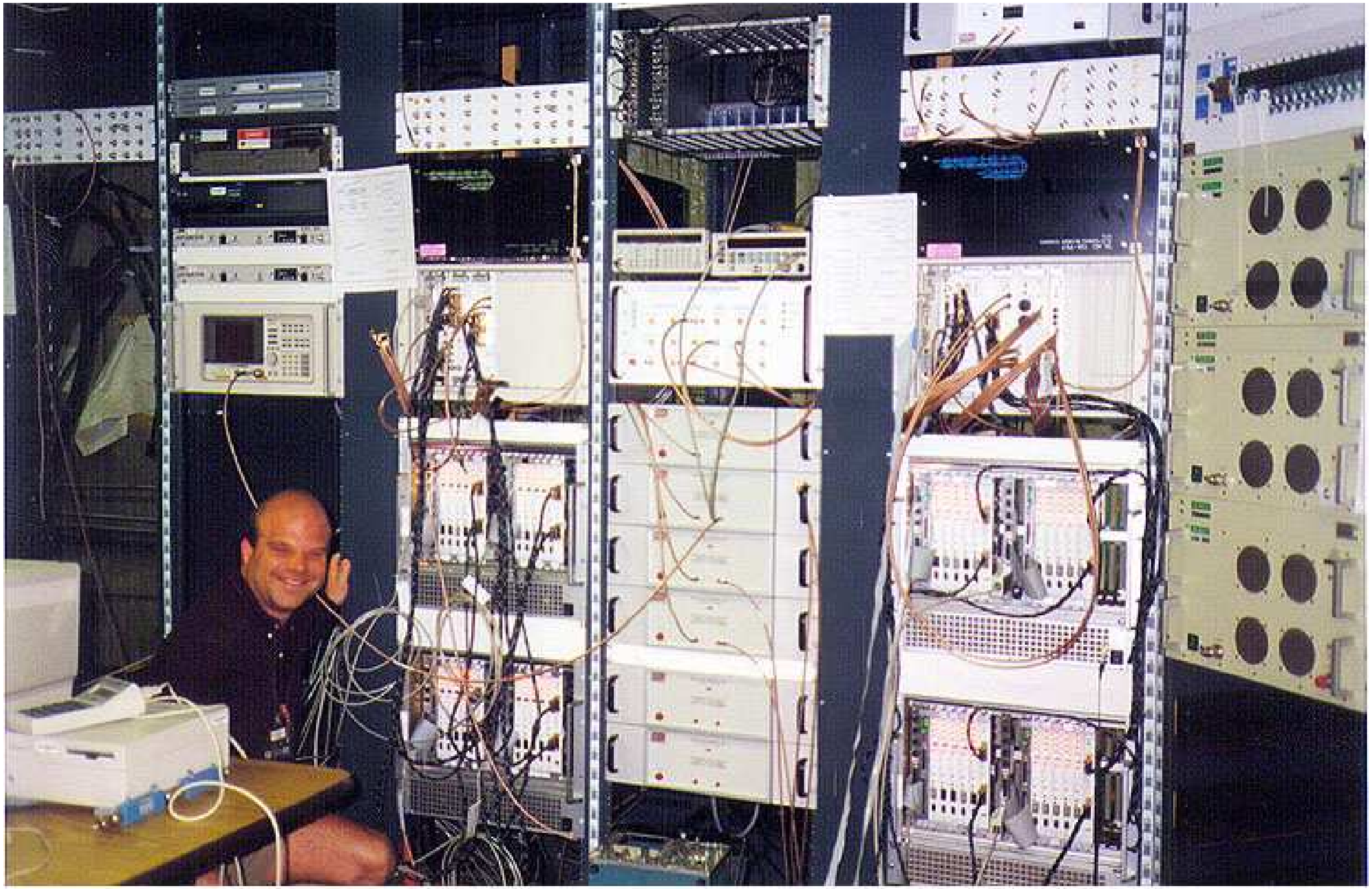
Scalable processing array, up to $3.2 \cdot 10^9$ MAC/sec.

Sampling at 500 MHz

May want Downsampling to reduce computational load (match processing rate to synchrotron oscillation frequency)



HER and LER Systems at PEP-II



AY_008 HER and LER Electronics 10-4-97

Filter Implementation Options

Terminology

- Time domain - bandpass bunch by bunch filters
- frequency domain - modal selection, notch at Frev

Sampling process suggests discrete time filter (filter generates correct output phase, limits noise, controls saturation)

General form of IIR filter (infinite impulse response)

$$y_n = \sum_{k=1}^{N} a_k y_{n-k} + \sum_{k=0}^{M} b_k x_{n-k}$$

General form of FIR filter (finite impulse response)

$$y_n = \sum_{k=0}^{M} b_k x_{n-k}$$

wide bandwidth filter - insensitive to variations in machine tune

narrow bandwidth filter - helps reject detector noise

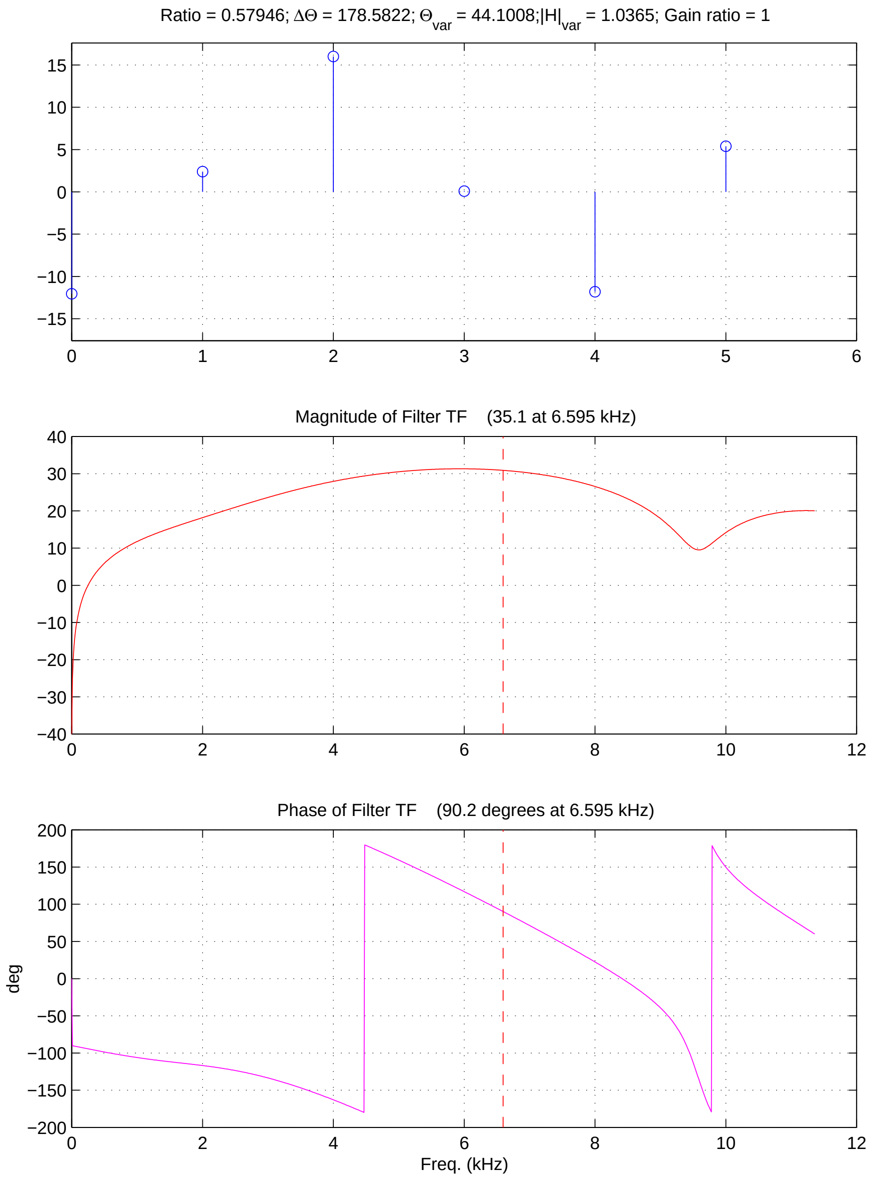
Maximum gain - when noise in front-end saturates DSP processing

Example FIR filters

Each bunch gets an independent controller

The example 6 tap filter (longitudinal, PEP) has broad bandwidth - longer filter would have narrower bandwidth, but comcomitant longer group delay

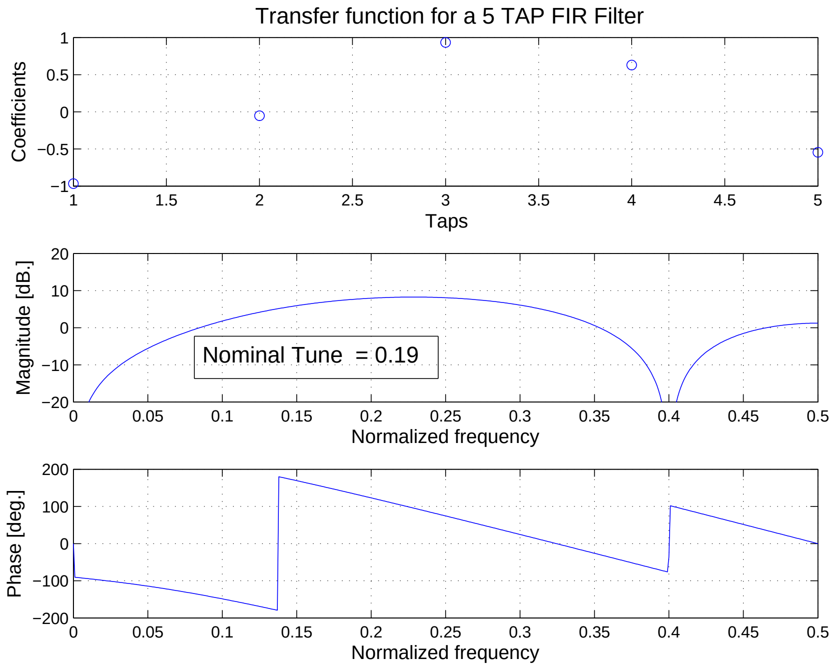
Example 5-tap transverse filter for tune 0.19



Ratio = 0.57946; ΔΘ = 178.5822; Θ_{var} = 44.1008;$|H|_{var}$ = 1.0365; Gain ratio = 1

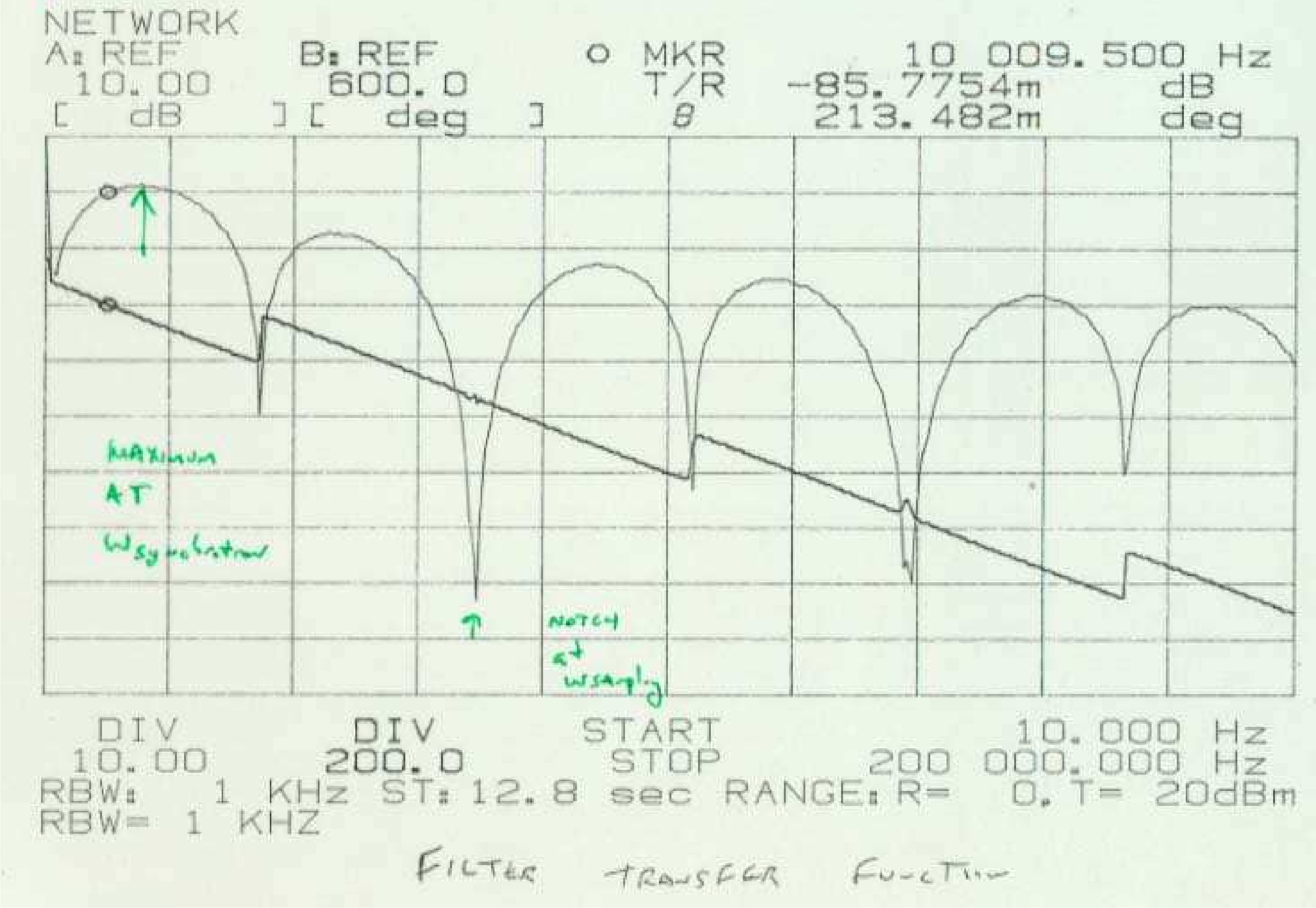
Magnitude of Filter TF (35.1 at 6.595 kHz)

Phase of Filter TF (90.2 degrees at 6.595 kHz)



Transfer function for a 5 TAP FIR Filter

Baseband transfer Function

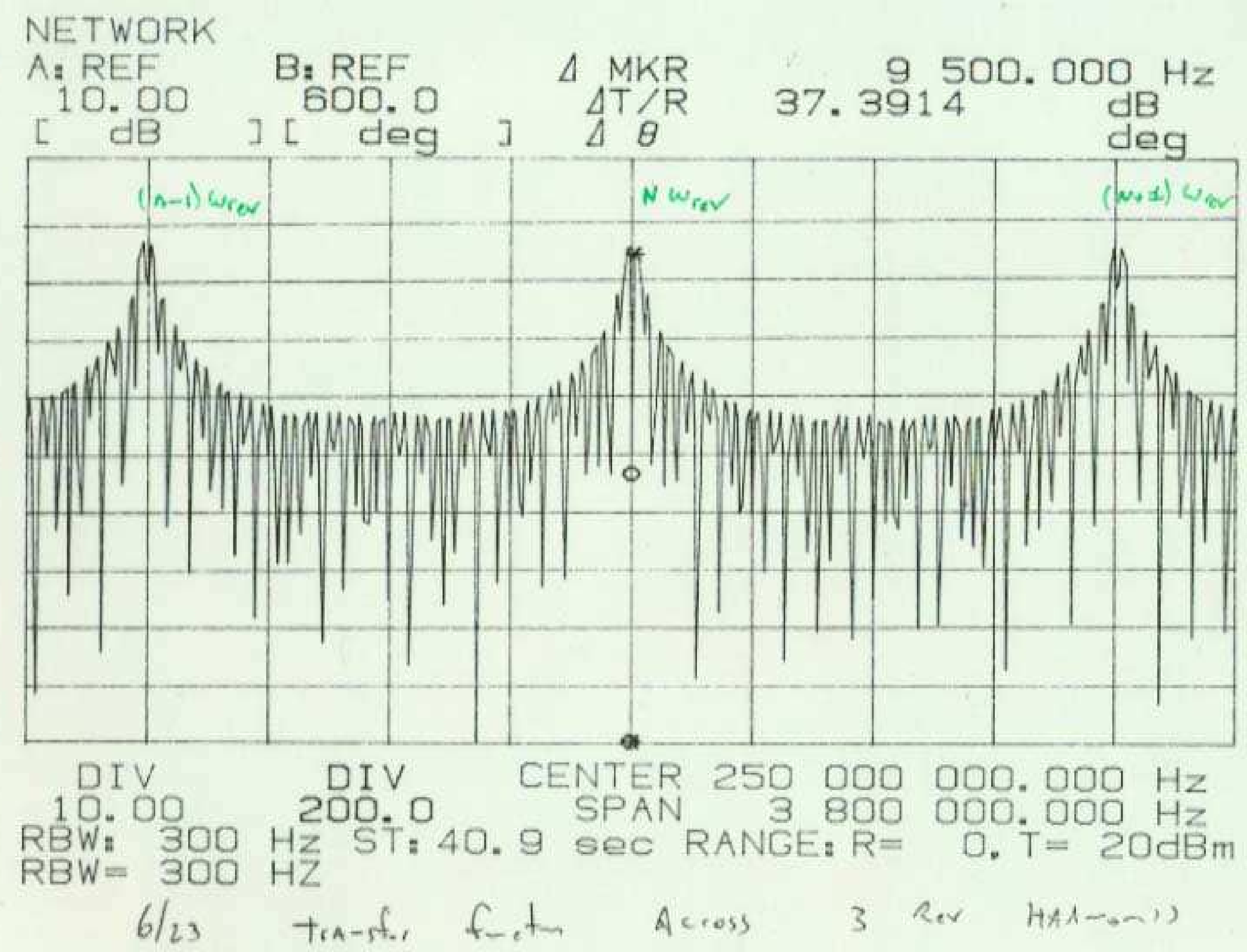


```
NETWORK
A: REF          B: REF          o MKR       10 009.500 Hz
  10.00           600.0           T/R     -85.7754m     dB
[   dB    ][   deg    ]            B       213.482m     deg

    DIV            DIV          START           10.000 Hz
   10.00          200.0          STOP      200 000.000 Hz
RBW:    1 KHz  ST: 12.8  sec  RANGE: R=   0. T=  20dBm
RBW=  1 KHZ
```

FILTER TRANSFER FUNCTION

RF Transfer Function



```
NETWORK
A: REF          B: REF          Δ MKR             9 500.000 Hz
 10.00           600.0          ΔT/R    37.3914         dB
[  dB    ][  deg    ]           Δ θ                     deg
```

```
  DIV           DIV         CENTER 250 000 000.000 Hz
 10.00         200.0          SPAN   3 800 000.000 Hz
RBW:  300 Hz  ST: 40.9 sec  RANGE: R=   0, T=  20dBm
RBW=  300 HZ
```

6/23 transfer function Across 3 Rev Harmonics

Existing/Example Coupled-Bunch Feedback Systems

NSLS - Galayda, et al (transverse)

- 2 tap analog FIR (“correlator filter”)

ALS - Barry, et al (transverse)

- 2 ns bunch spacing -2 tap analog FIR filter
- quadrature pickups, sum for phase shift

UVSOR (Japan) - Kasuga et al. (longitudinal)

- 16 bunches - 16 analog filters with multiplexing

DESY - Kohaupt et al. (transverse and longitudinal)

- 96 ns bunch spacing - 70 bunches - 3 tap digital FIR

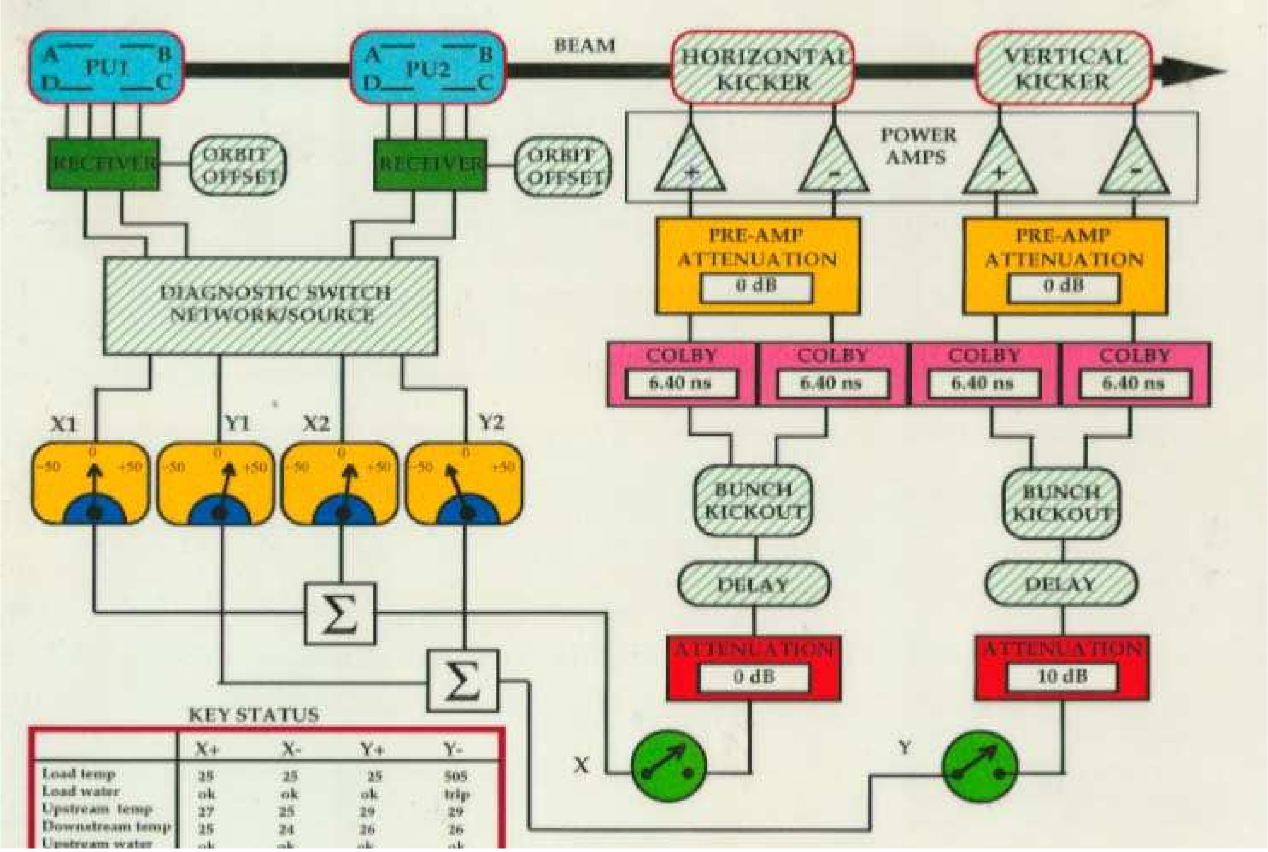
CESR - Billing, et al (transverse and longitudinal)

- 16 ns bunch spacing, digital FIR filter

Elettra, SLS- Bulfone, et al (transverse)

- 2 ns bunch spacing, mix of commercial ADC/DSP boards, custom electronics

ALS Transverse Feedback Implementation



KEY STATUS

	X+	X-	Y+	Y-
Load temp	25	25	25	505
Load water	ok	ok	ok	trip
Upstream temp	27	25	29	29
Downstream temp	25	24	26	26
Upstream water	ok	ok	ok	ok

From W. Barry

Quadrature processing via 2 pick-ups , Analog 2-tap FIR filter for DC orbit suppression

Existing/Example Coupled-Bunch Feedback Systems, cont.

PEP-II/ALS/DAFNE/BESSY/PLS - Fox, et al (longitudinal)

- 2 - 4 ns bunch spacing, 120 - 1746 bunches
- general purpose DSP processing
- Algorithms for FIR and IIR filtering

KEK-B - Tobiyama, et al (transverse, longitudinal)

- 2 ns spacing, 5120 bunches, 2 tap digital FIR with fixed +1/-1 coefficients (no multipliers)
- use of custom GaAs multiplexing chip set, 16 way muliplexed channels

SPRING-8(also TLS)Date,et al- 500 MHz,Transverse,4 way multiplexed, FPGA FIR implementation

iGp - Tetytelman, et al (general purpose, transverse, longitudinal)

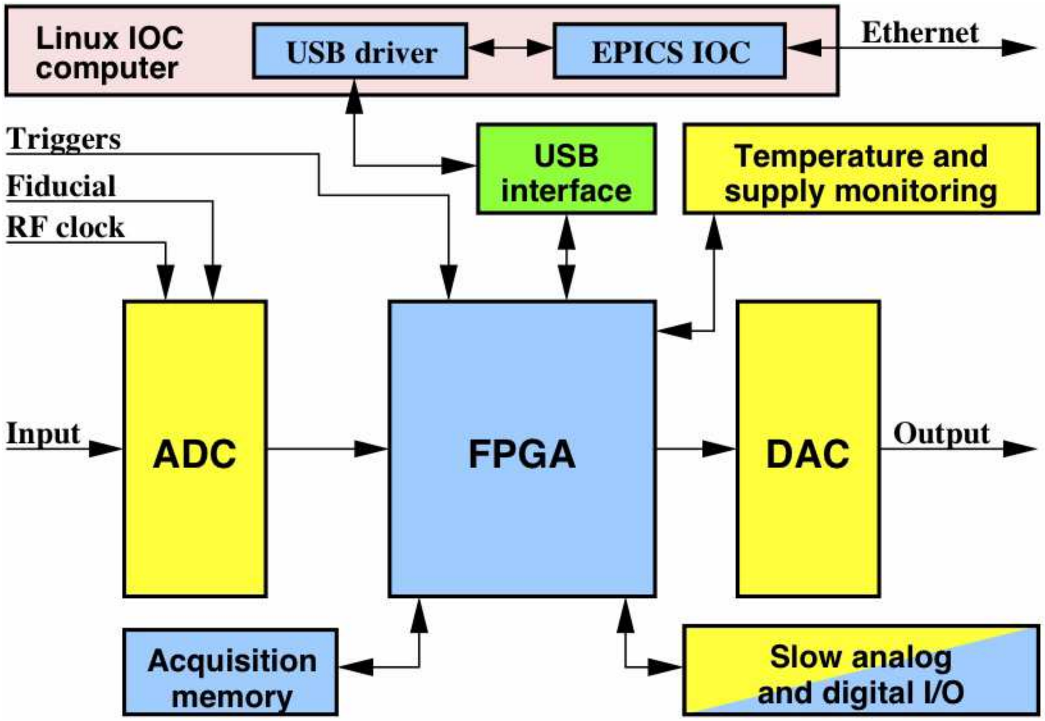
- 2nd/3rd Generation technology - reconfigurable gate arrays
- parallel processor - uneven stepping applicable to various harmonic numbers
- 2 ns spacing, 5120 bunches, 16 tap FIR,
- flexible transverse,longitudinal processor channel

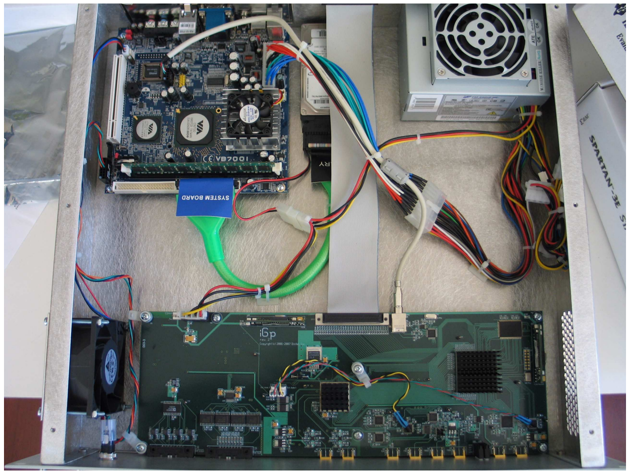
Libera Bunch-by-Bunch (Instrumentation Technologies) - Multiplexed A/D with FPGA

Example -IGP processing channel

- 3rd generation instability control technology
- Commerical product (DIMTEL) based on SLAC, KEK, LNF-INFN design collaboration -
- Transverse instability control
- Longitudinal instability control
- High-speed beam diagnostics (500MHz sampling/ throughput rate)
- Builds on program in instability control and beam diagnostics.
- Significant advance in the processing speed and density previously achieved.

Applicable to many installations

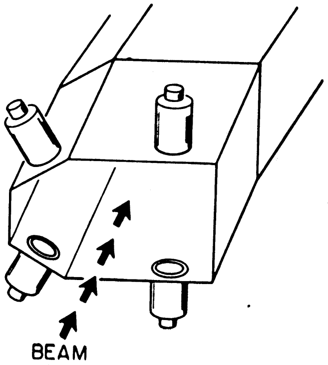


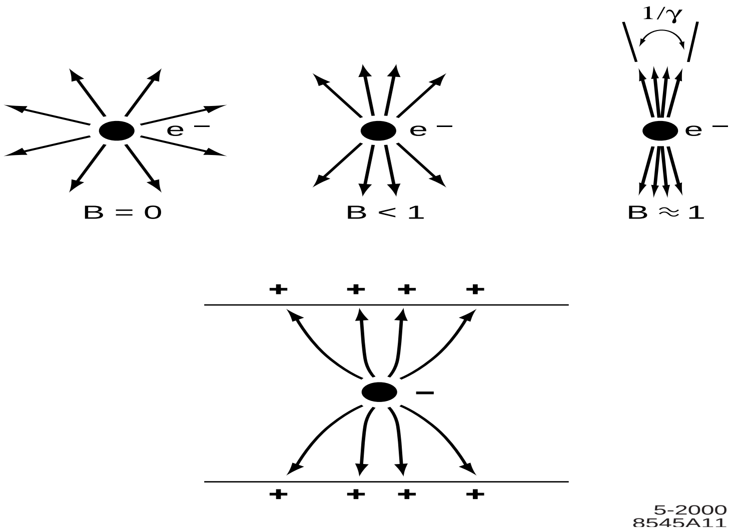


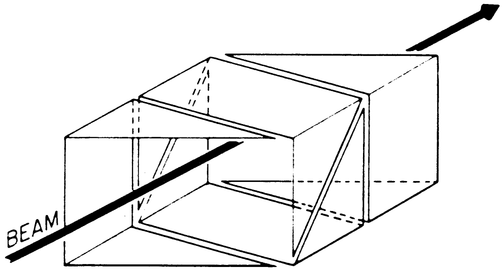
Interactions with the particle beam - pickup and kicker technologies

- How do you measure the time of arrival of a mm long particle beam, travelling the speed of light?
- You want sub-picosecond rms noise (600 fs), and you need to do it every 2 ns., without coupling one measurement to the other.
- How do you change the energy of the particle beam by kilovolts, again requiring independent control of the bunches every 2 ns?
- How do you measure the transverse position of an electron beam with micron resolution every 2 ns?

These are interesting transducer and actuator problems!

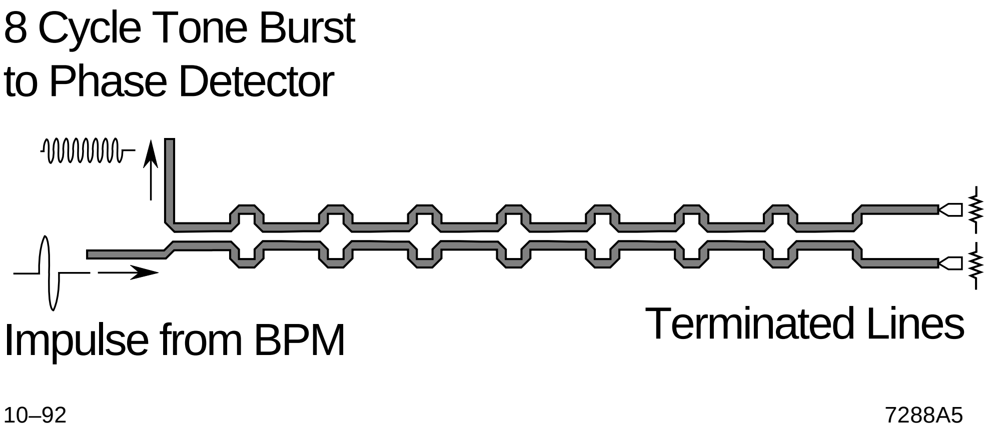




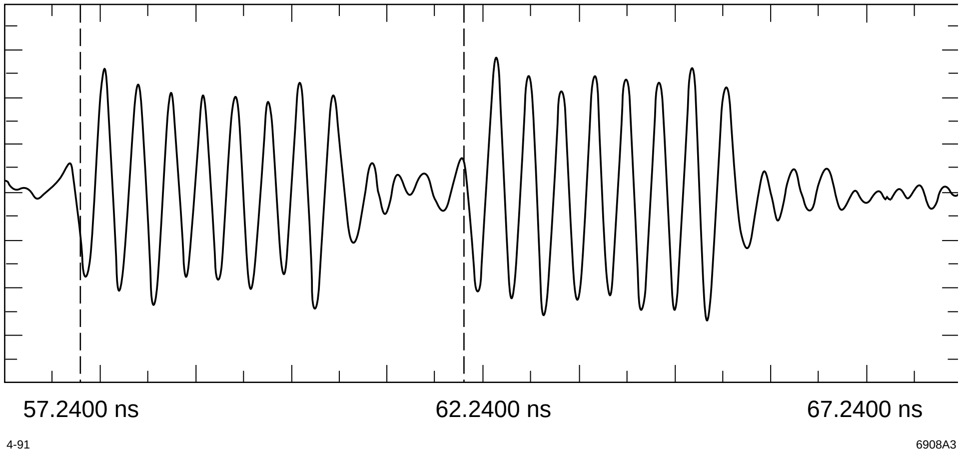


Pickup and Frontend technology

Difficult to process picosecond bunch signals - make a periodic coupler circuit which defines the number of couplers and the center frequency. BPM impulses are converted to short “tone bursts” for subseqent delta-sigma or phase detection processing, heterodyning to baseband for A/D input



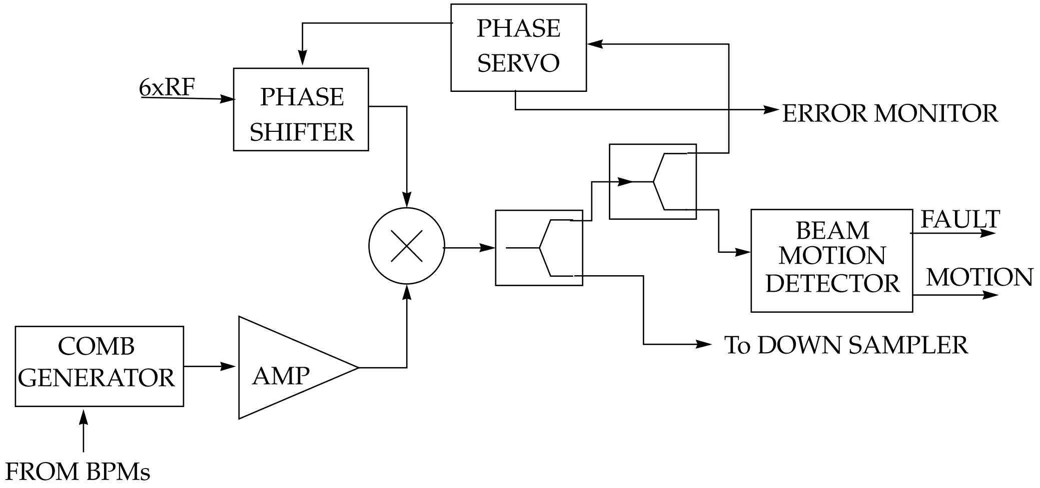
Example 3 GHz comb, the measured signal shows little coupling between the bunches. (note a resonant bandpass filter would decay exponentially)



Longitudinal signal - Phase detect against 3 Ghz RF harmonic, baseband phase error

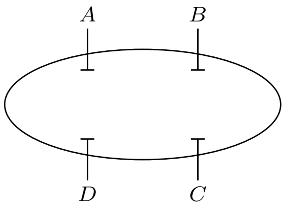
Transverse signal - needs AM detection and Delta-Sigma processing for X and Y coordinates

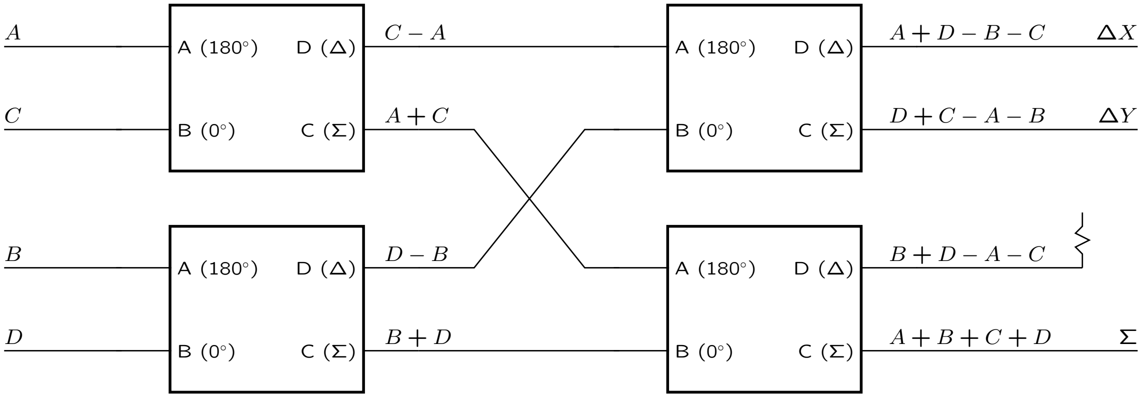
Frontend signal processing



Longitudinal - phase detection against harmonic of RF system. sensitivity scales with harmonic

Transverse - Delta/sigma processing provides sum, difference signals. Amplitude detect at harmonic of RF, or process directly at baseband



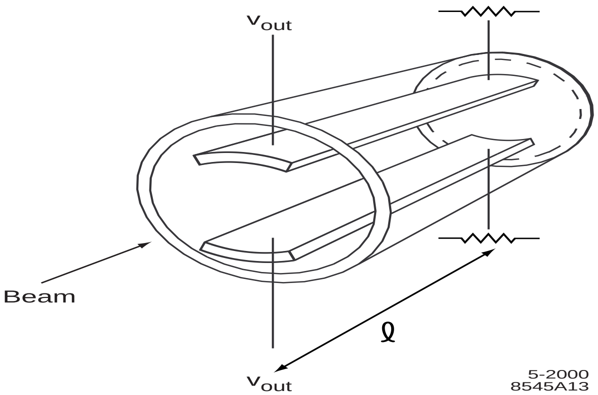


“Kicker” Technology Issues

Basic ideas - Transverse Control via Stripline Electrodes

Like a directional coupler

- Drive signal goes “upstream”
- (combines E-field and B-field kicks)
- Downstream feed - E and B cancel



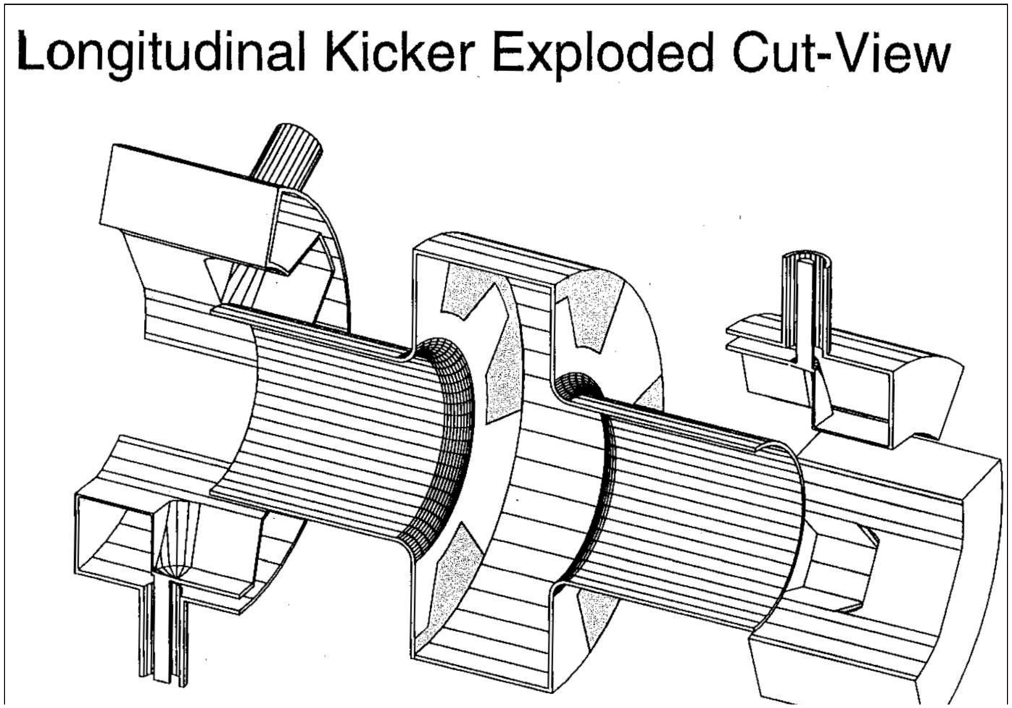
Longitudinal kick via periodic drift-tube

(a transmission line with shielding drift tubes - excitation wave counter-propagates with beam)

Over-Damped resonant cavity -

a sort of wideband RF cavity. Q must be very low (4 or 5) to kick individual bunches nanoseconds apart

Operating frequencies in the 1 - 2 GHz band.



Six Bunches and associated longitudinal kicks

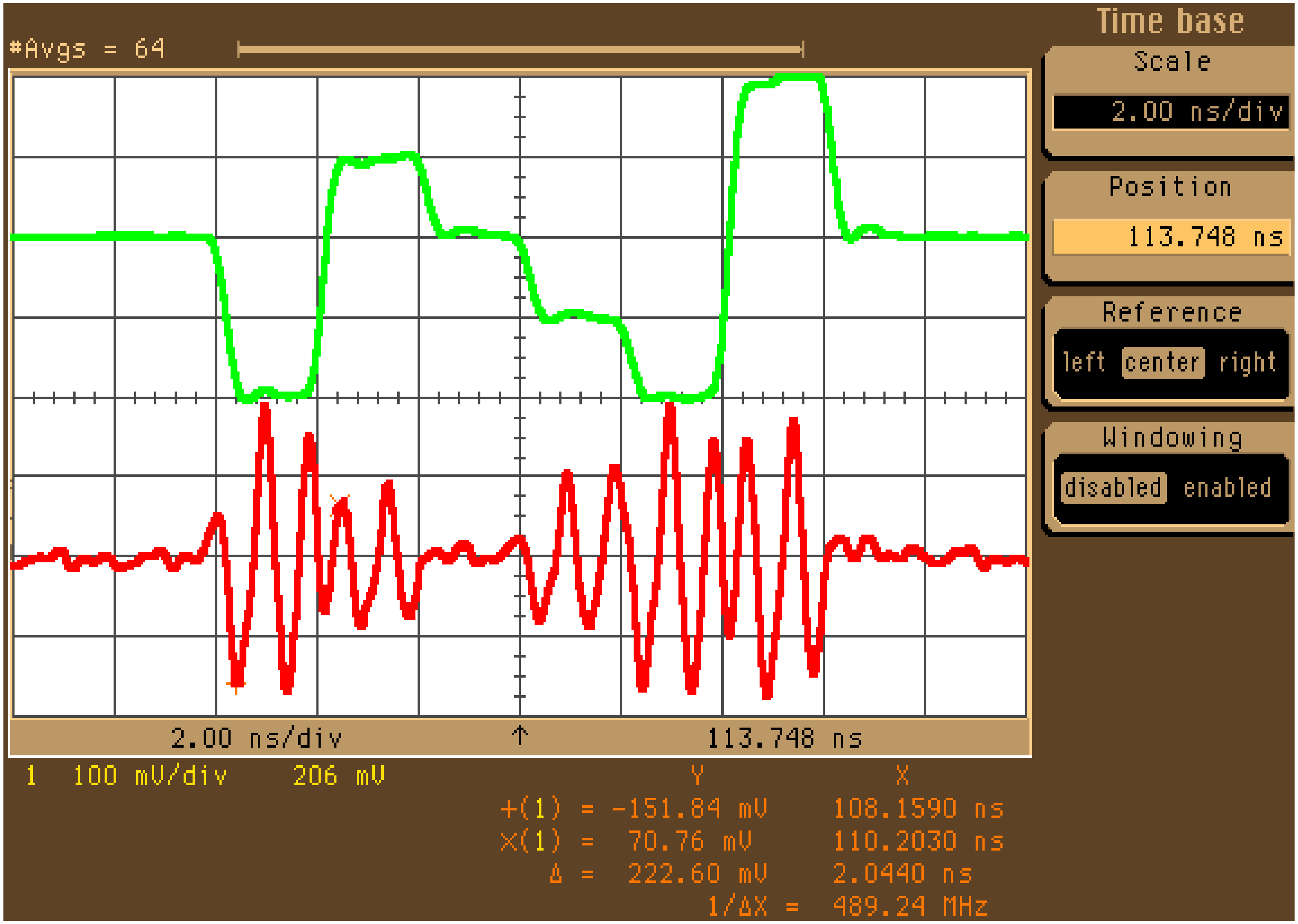
Longitudinal output amplifier control signal 2 ns bunch spacing

Baseband risetime

320 ps (2ns/div)

QPSK-AM
modulation

Signal phase inverts
carrier for
negative kick



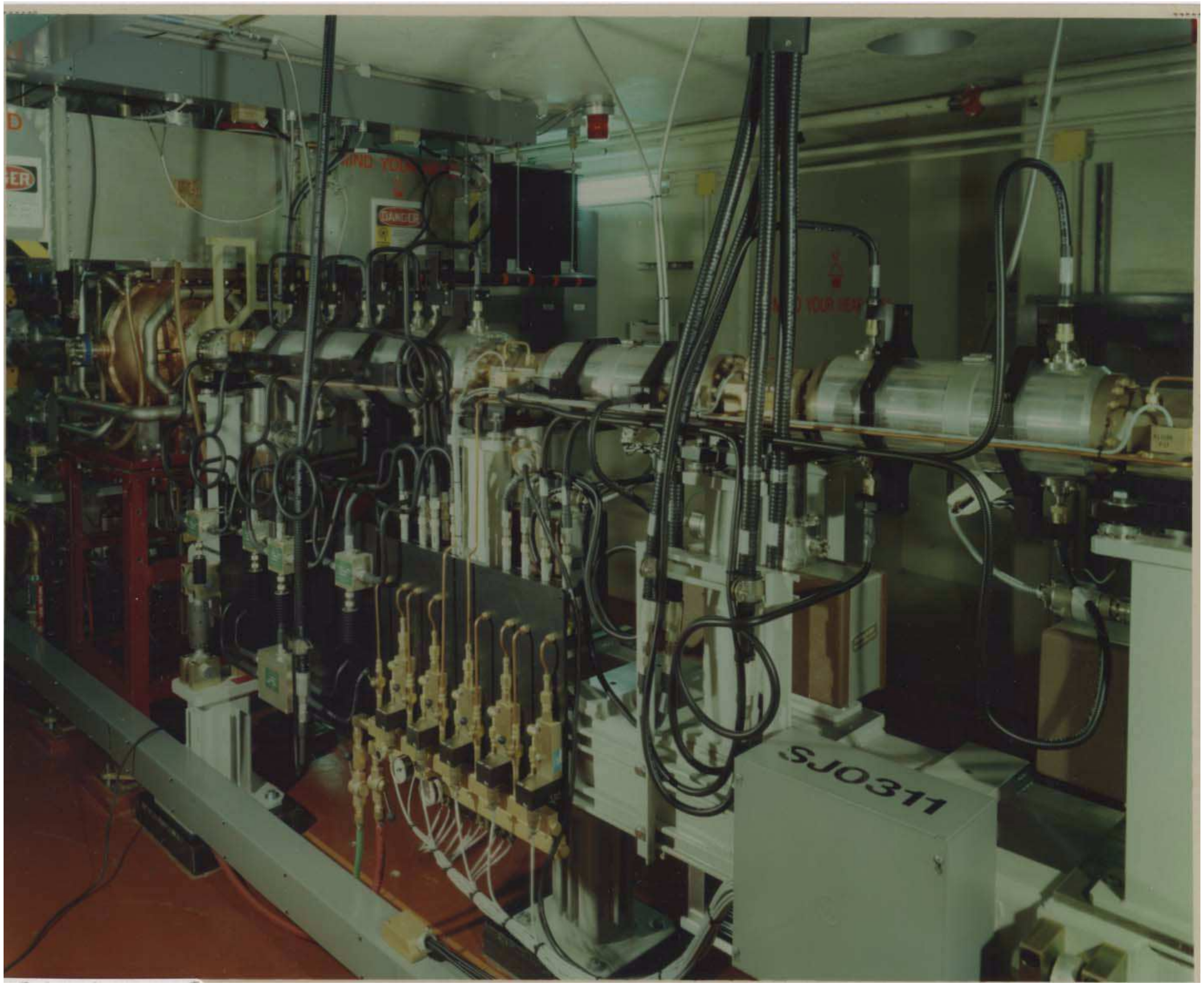
```
Scale      2.00 ns/div
Position   113.748 ns

2.00 ns/div                ↑          113.748 ns
1   100 mV/div      206 mV
                                  Y               X
                      +(1) = -151.84 mV     108.1590 ns
                      ×(1) =   70.76 mV     110.2030 ns
                         Δ =  222.60 mV       2.0440 ns
                                  1/ΔX =    489.24 MHz
```

ALS Beamline

A view of the ALS (Advanced Light Source, LBL) beamline showing Y kicker, X kicker and longitudinal kicker antennas.

The “kicker” structures allow external wideband correction fields to transversely deflect the beams or to add or subtract energy from the beam.



Kicker Implementations

Transverse -

Essentially all striplines. Length limited by bunch spacing. Operation at baseband (except for KEK-B, using two sets of kickers/amplifiers)

Cornell (CESR) has clever short-circuited design to kick counter-propagating beams. Also clever duty-cycle modulated kicker driver, as opposed to linear amplifier drive

Amplifiers - baseband (100kHz - 230 MHz)

Longitudinal - Several designs

Ceramic Gap (UVSOR) - modest shunt impedance

Loaded (damped) Cavity - Designed by LNF-INFN, used by DAFNE, BESSY (KEK-B?). Easy to cool. Needs circulator. Reasonable shunt impedance. PEP-II LER updated to this design

Drift-tube structures - designed by LBL Beam Electrodynamics Group, used by ALS, PLS, PEP-II. Useful in-band directivity. Cooling issues for ampere currents (see PEP-II LER, above)

Operating in 1 - 1.5 GHz band. GaAs power amps (200 - 500 W), also TWT power stages (200 W)

Measuring beam & system dynamics

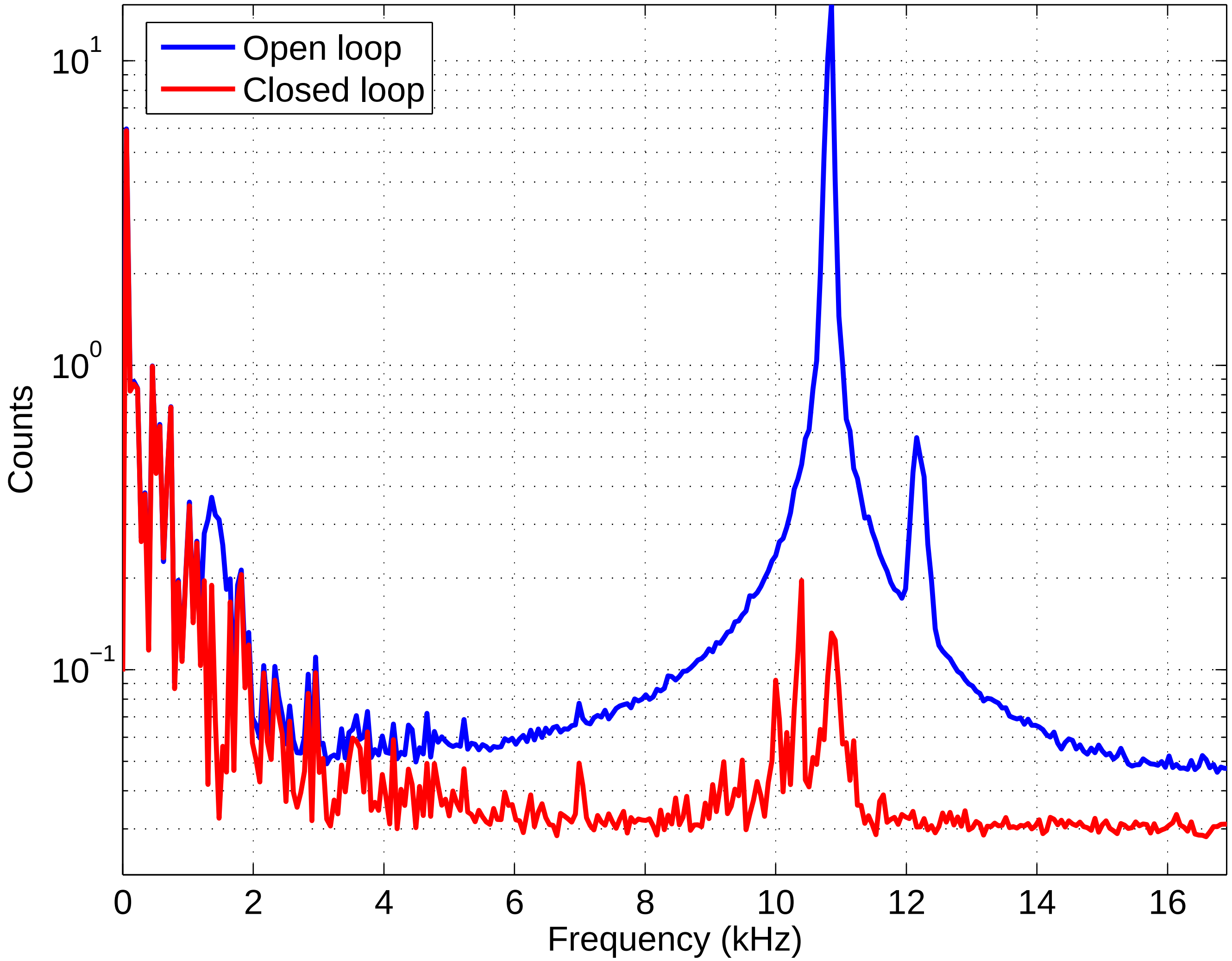
Many uses

- Controller algorithm design
- Estimation of operating margins
- Optimization of operating conditions
- Feedback hardware testing

How to characterize an unstable system? Possible approaches

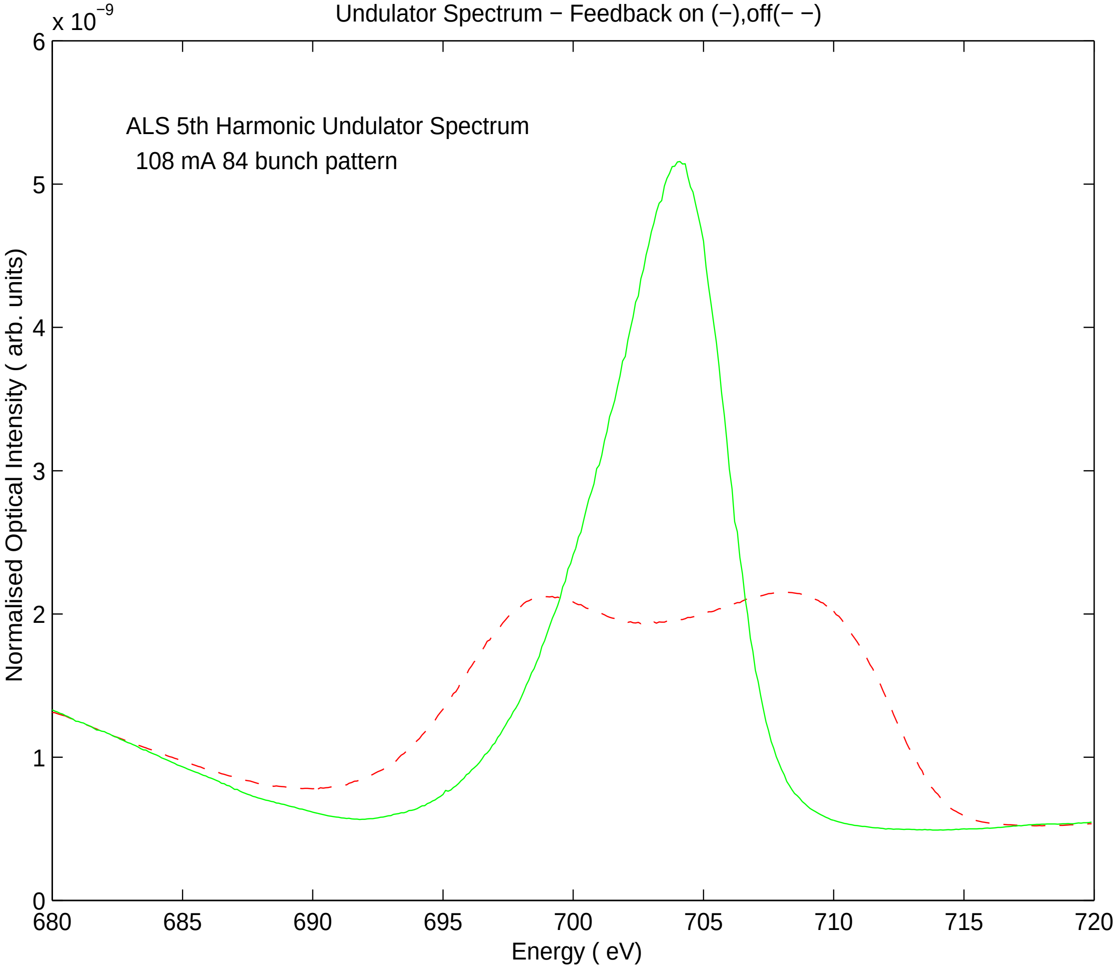
- Power Spectrum measurement - no phase information but shows frequency information
- Open-loop transfer function - measurement is only possible below instability threshold. Each mode to be quantified requires a separate network analyzer sweep.
- Closed-loop transfer function - extracting beam dynamics is complicated, depends strongly on the loop configuration.
- Transient diagnostics - allow to characterize open and closed-loop dynamics in a single 20 ms measurement. All unstable modes can be measured in a single transient.

Longitudinal Control at the ATF



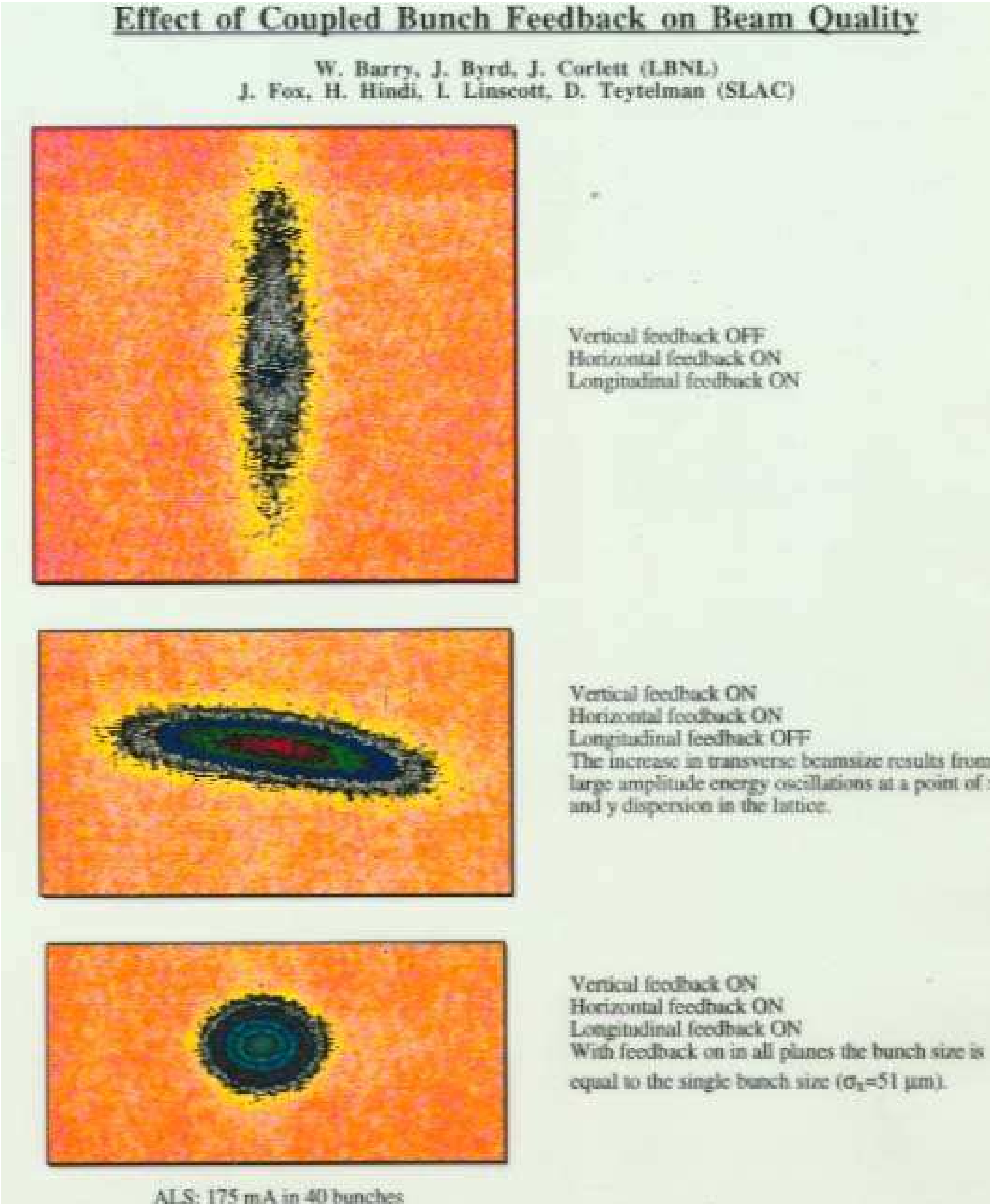
Feedback reduces the driven noise spectrum, improves energy spread in extracted bunch

Effect of Longitudinal Stability on Synchrotron Light Sources



Thanks to Tony Warwick (ALS) for Undulator Spectrum

Synchrotron Light Images



Effect of Coupled Bunch Feedback on Beam Quality

W. Barry, J. Byrd, J. Corlett (LBNL)
J. Fox, H. Hindi, I. Linscott, D. Teytelman (SLAC)

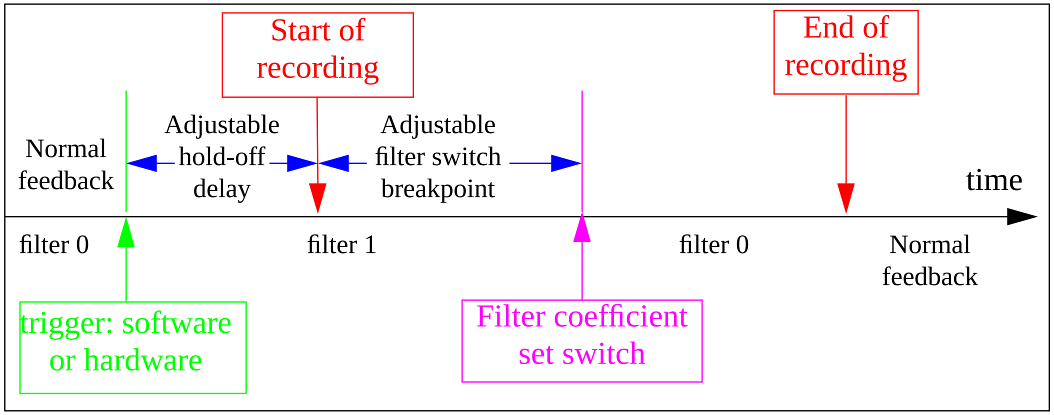
Vertical feedback OFF
Horizontal feedback ON
Longitudinal feedback ON

Vertical feedback ON
Horizontal feedback ON
Longitudinal feedback OFF
The increase in transverse beamsize results from
large amplitude energy oscillations at a point of
and y dispersion in the lattice.

Vertical feedback ON
Horizontal feedback ON
Longitudinal feedback ON
With feedback on in all planes the bunch size is
equal to the single bunch size (σ_x=51 µm).

ALS: 175 mA in 40 bunches

Grow/damp transient measurement



Start of recording

End of recording

Normal feedback

Adjustable hold-off delay

Adjustable filter switch breakpoint

time

filter 0

filter 1

filter 0

Normal feedback

trigger: software or hardware

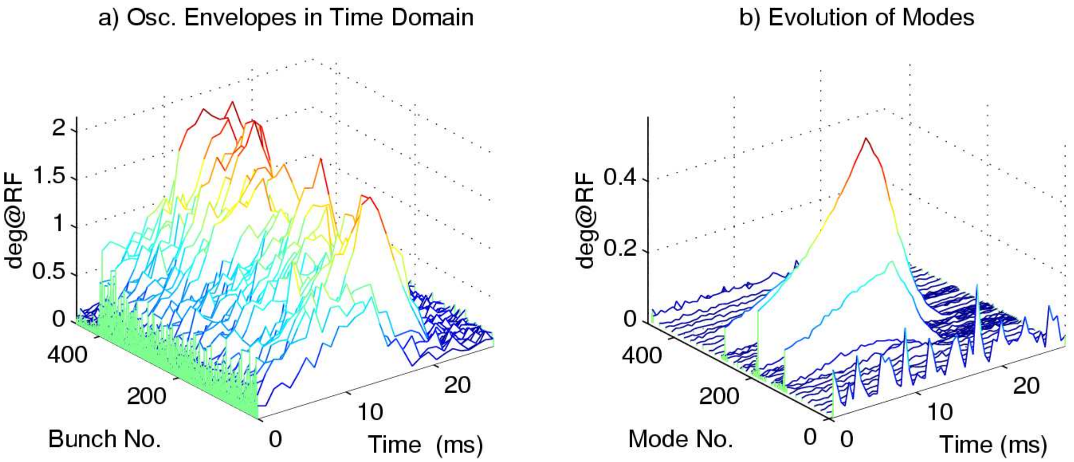
Filter coefficient set switch

A transient diagnostic technique that generates

- 1.2MB record of the motion of all bunches
- Complete modal information

Transient measurement to characterize open-loop dynamics of an unstable system.

Linear time control is difficult when making an exponentially growing measurement.



PLS:dec1599/1237: Io= 150mA, Dsamp= 15, ShifGain= 5, Nbun= 460,

Gain1= –1, Gain2= 0, Phase1= 30, Phase2= 30, Brkpt= 930, Calib= 11.02.

Grow/damp measurement example from PLS

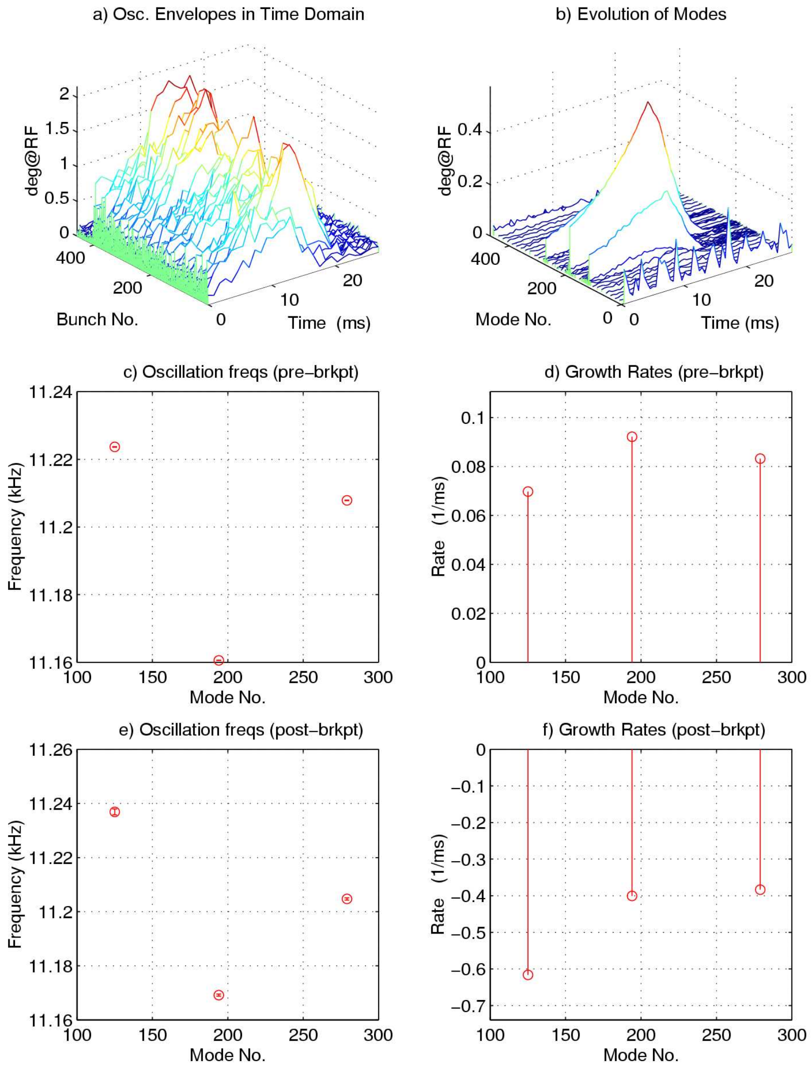
A 30 ms long data set with 15 ms open-loop section.

All filled bunches participate in the modal motion. Transformation to the even-fill eigenmode basis simplifies the picture - there are three strong eigenmodes in this transient. Fitting complex exponentials to the modal motion we extract estimates of the modal eigenvalues for both open and closed-loop parts of the transient.

A single measurement like this only characterizes the instabilities and the feedback at a single accelerator operating point.

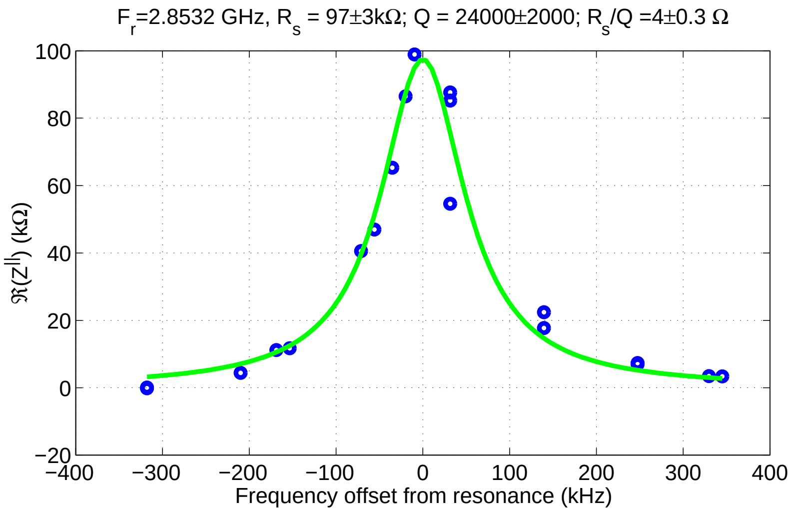
A very powerful technique - measure modal eigenvalues as a function of beam current, RF system configuration, etc. Reveals the impedances directly driving the beam

Difficulty - the “free” motion is dominated by the largest impedance(s). To study slowly-growing modes, you can excite the mode of interest before the study - it then starts at a higher (detectable) amplitude. In a while it is swamped by the fast modes.

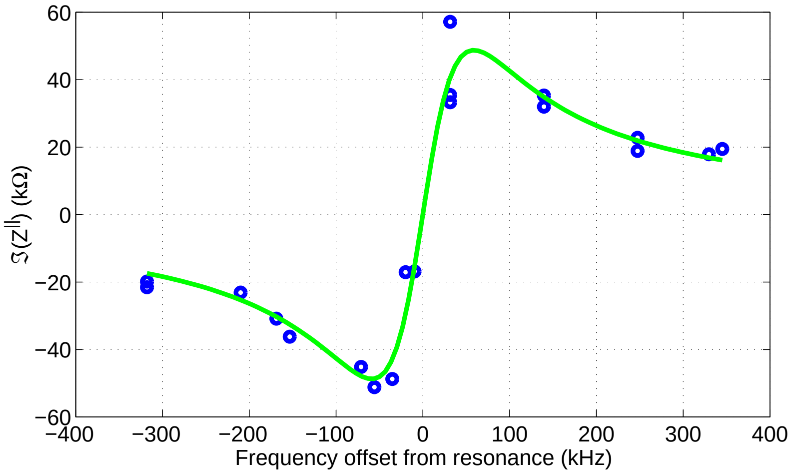


PLS:dec1599/1237: Io= 150mA, Dsamp= 15, ShifGain= 5, Nbun= 460,
Gain1= −1, Gain2= 0, Phase1= 30, Phase2= 30, Brkpt= 1100, Calib= 11.02.

ALS HOM Complex Impedance Measurement



F_r=2.8532 GHz, R_s = 97±3kΩ; Q = 24000±2000; R_s/Q =4±0.3 Ω



These techniques allow beam-based measurement of in-situ HOM impedances

The measurement is made via grow-damp transients, measuring complex frequencies, as the water temperature of the cavity structure is varied (this sweeps the HOM frequency across the sampling frequency of the beam)

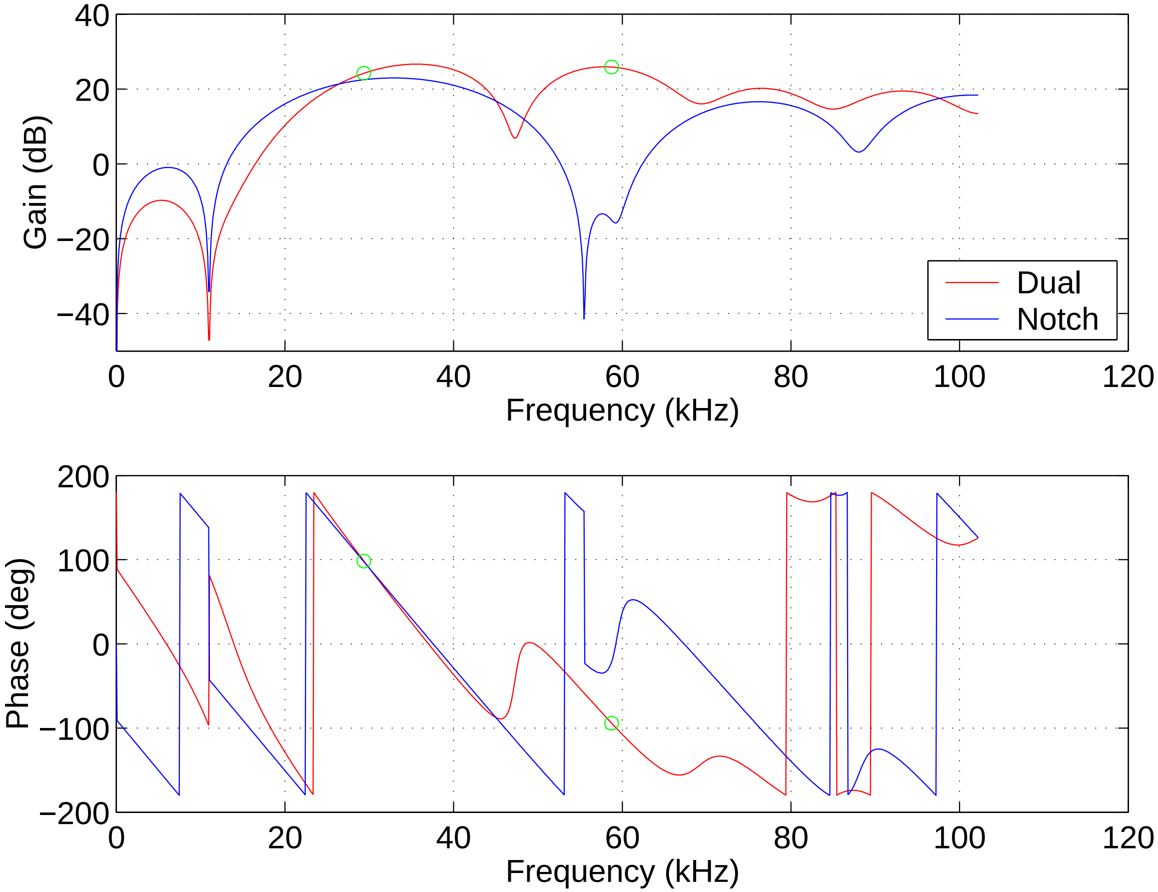
Quadrupole instability control

DAFNE e+/e-collider at LNF

- increased operating currents
- quadrupole mode longitudinal instabilities have appeared (the installed system suppresses the dipole modes).

Flexible DSP code implemented a novel quadrupole control filter

- software programmability of the DSP farm
- two parallel control paths for dipole and quadrupole modes.
- quadrupole control has been successful, allowing a 20% increase in luminosity.



Advantages and difficulties of transient analysis

Advantages

Complementary to narrowband frequency domain detection. Both approaches allow measurements of growth/damping rates.

In a transient all unstable modes are measured at once - much faster than mode-by-mode narrowband measurement when there are hundreds of unstable modes

From a transient measurement we get complex eigenvalues - not only growth rates, but also oscillation frequencies.

Large datasets - information about the motion of every bunch

Difficulties

Exponential growth rates - easy to lose control of the beam.

Large datasets

Ultimate/Practical Limits to Instability Control

What Limits the Maximum Gain (e.g. fastest growth rate, or allowed impedance)?

Several Mechanisms

I). Noise in feedback filter bandwidth, limits on noise saturation. Gain is from several stages -

Front End (BPM to baseband signal) gain limited by required oscillation dynamic range, steady-state offsets (synchronous phase transients, orbit offsets). Noise floors in the receivers typically 10 - 20 dB above A/D quantizing noise.Damped equilibrium noise floor is not set by A/D noise or DSP

Processing Block - gain limited by noise in filter bandwidth. Quantizing noise (broadband) is one system limit - noise from RF system or front-end circuitry is typically greater in contribution. Narrowband filters help with broadband noise. Broad filter bandwidths help with reduced sensitivity to machine tunes, operating point - or variations of dynamics with current

Power stages - gain scales with kicker impedance, sqrt(output power). An expensive way to increase gain (more kickers, more output power).

Output power (actually maximum kicker voltage) determines maximum oscillation amplitude from which linear (non-saturated) control is possible. Saturated behavior is complicated

Driven noise (e.g. from RF system, or from other excitations) may set limit on achievable gain

Interesting Movie - loss of Control in PEP-II from RF noise PRST 13:052802,2010

Ultimate/Practical Limits to Instability Control, part II

II) Stability of the feedback loop itself, (e.g. limits on phase shift and gain vs. control frequency)

Related to time delay between pickup, processing, and actuator

For circular machines (systems with kick signal applied on later turn than pickup)

limit set by revolution time, fastest growth rates, and filter phase slope over control band

Appropriate for optimal control theory applications

- LQR
- Robust Control
- Uncertain Systems

Negative group delay over a portion of the frequency band is possible, but for causal systems you pay the price in increased phase slope away from the negative region

Promising Areas for R&D Efforts

1 - 4 GS/sec. processing channels

General-purpose reconfigurable building blocks - based on reconfigurable FPGA architectures. Software configured for multiple longitudinal/transverse applications. SLAC/KEK/CERN collaboration has prototypes in evaluation, development of novel control filters. Allows I&Q processing streams (2X sampling)

Low Group Delay processing channels

- potential applications in Energy Recovery Linacs, IP collision point feedback in ILC
- Very low group delay (e.g. 10s of nanosecond scale) FIR/IIR filter blocks, using electronic or electro-optic technologies

Kicker structures

existing drift tube, stripline and damped cavity kickers all have issues with heating at high beam currents, residual HOM content

RF Feedback techniques to reduce impedances seen by the Beam - the existing analog and hybrid analog/digital RF feedback techniques in the LLRF systems at PEP-II (and also LHC) are nearing technology and operational limits. Efforts to develop a low group delay digital RF processing channel look very attractive

LHC/SPS Ecloud driven instability R&D Efforts

Ongoing project SLAC/LBL/CERN via US LARP

Proton machines, Ecloud driven instability - impacts upgraded LHC (and SPS injector)

- Photoelectrons from synchrotron radiation - attacted to positive beam
- Coupled-dynamics, electrons act as lens to kick transversely
- Single-bunch effect - head-tail (two-stream) instability

Research directions

- Simulations
- Machine measurements - understand required bandwidth, validate simulations
- What sort of feedback control is feasible?
- Development of 4 GS/sec. processing channel demonstrator

Kicker structures

- Research effort to investigate useful 1 - 2 Ghz bandwdith transverse kicker
- Use periodic slotline (stochastic cooling)? Array of 1/4 wave striplines? overdamped cavity?

SPS MD Studies

Ecloud studies June 2009, April 2010 July 2010. Vertical Instability develops after injection of second batch, within 100 turns. Time domain shows bunch charge, and transverse displacement 1E11 p/bunch (June2009). Roughly 25 slices (250 ps) between displacement maxima and minima

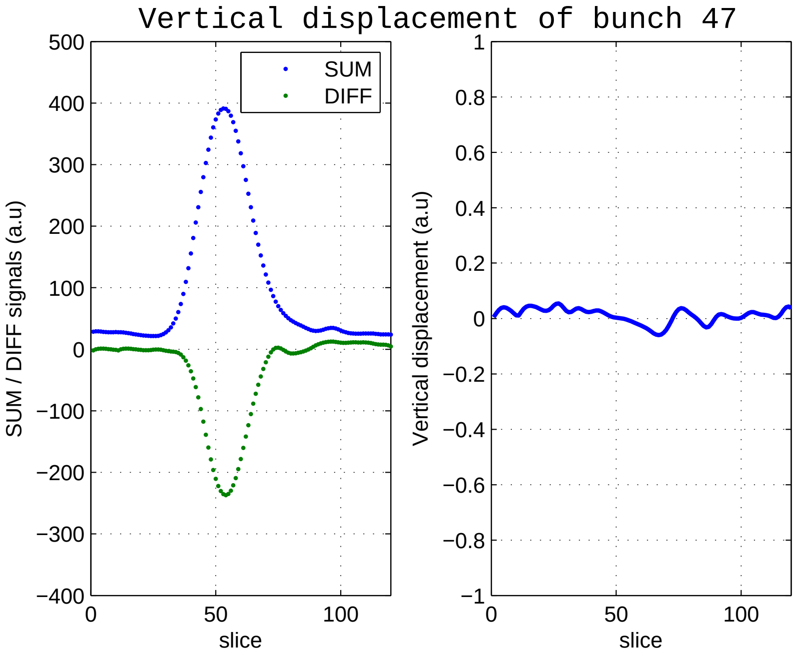
TMCI Studies July/August 2010. Single bunch injection at 1.3E11 (3E11). Vertical instability develops - time scales of 1000 turns

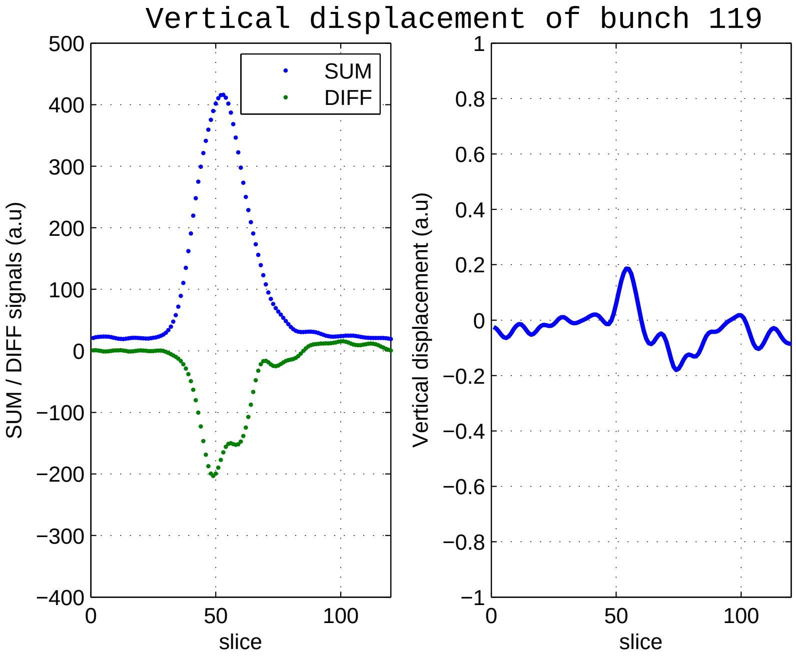
data taken via exponentially-tapered stripline pickups, delta/sigma processing at baseband. sampled 20 or 40 GS/sec.

We need MD data to compare beam simulations and dynamics models, - extract beam dynamics necessary to design feedback.

Studies of bandwidth of motion, tune shifts

pickups -Noise, transverse resolution well-quantified





Movies of June 16, 2009 SPS MD

MD data at 1E11 P/bunch, with three chromaticity values (.1,.2 and -.1), 2 RF voltages

Pre-processing includes equalization (cable response), suppression of longitudinal motion

(www.slac.stanford.edu/~rivetta/e-clouds/movies_Aug09 and

also in http://www.slac.stanford.edu/~dandvan/e-clouds/aug_09/)

1E11 P/bunch, 25 ns separation, 72 bunches/batch (June 2009 MD data)

Injection of batch 1 (stable) followed by 2nd batch (which goes unstable)

Movie 1- Vdspl_bunch_47.avi Vdisplacement for bunch 47 1st batch (stable)

Movie 2 - Vdspl_bunch_119.avi Vdisplacement for bunch 47 2nd batch (#119 e-clouds)

Movie 3 - tune_s.avi Sliding Window spectrogram of Bunch 117 vertical signal by slice

Movie 4 - centroid.avi Centroid tune shift along 620 turns

Movie 5 - rms.avi RMS of slice motion with respect to the bunch centroid

These animations help show the complexity and non-linear behavior of the system

We need to extract simpler model dynamics to use to design/estimate feedback control

Feedback Estimation- requires quantitative knowledge of ecloud/beam dynamics

Goal - develop quantitative analysis methods, normal-mode, other formalisms

- Equalization, suppression of longitudinal motion effects
- Modes within the bunch (e.g. bandwidth of feedback required)
- growth rates of modes (e.g. gain of feedback channel)
- tune shifts, nonlinear effects (e.g. Stability, robustness of feedback process)

sliding window FFT techniques - check tunes, tune shifts

- slice FFTs (tune per slice)
- vs. time (modes within a bunch)

RMS techniques - on SUM and Delta (estimation of motion of the beam, time evolution, charge loss)

Estimate impacts - injection transients, external excitations, imperfections/noise in receivers, power stages.

Recent Emphasis - System Identification methods to fit coupled-oscillator models to data

Critical to estimate - required sampling rate (bandwidth), growth rates, tune shifts, internal modes

E-cloud Feedback Channel - Complexity? Scale?

Frequency spectrograms suggest:

sampling rate of 2 - 4 GS/sec. (Nyquist limited sampling of the most unstable modes)

Scale of the numeric complexity in the DSP processing filter

- measured in Multiply/Accumulate operations (MACs)/sec.

SPS -5 GigaMacs/sec. (6*72*16*16*43kHz)

- 16 samples/bunch per turn, 72 bunches/stack, 6 stacks/turn, 43 kHz revolution frequency
- 16 tap filter (each slice)

KEKB (existing iGp system) - 8 GigaMacs/sec.

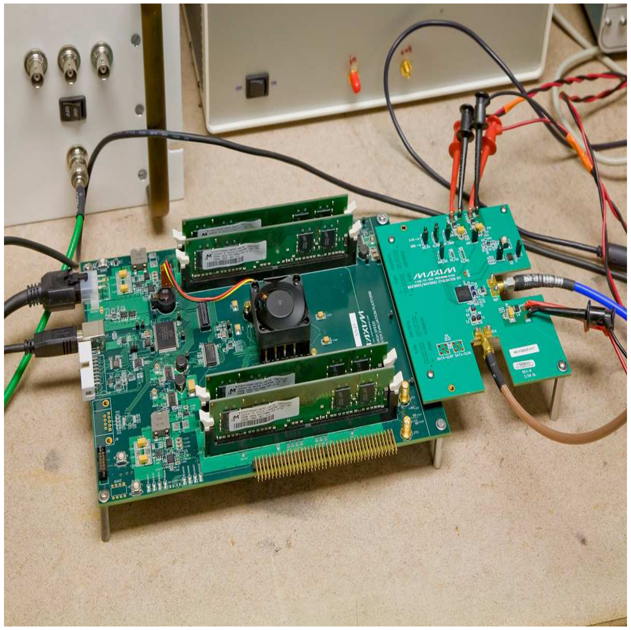
- 1 sample/bunch per turn, 5120 bunches, 16 tap filters, 99 kHz revolution frequency.

The scale of an FIR based control filter using the single-slice diagonal controller model is not very different than that achieved to date with the coupled-bunch systems.

What is different is the required sampling rate and bandwidths of the pickup, kicker structures, plus the need to have very high instantaneous data rates, though the average data rates may be comparable

Important dynamics difference - Ecloud tune shifts, even for stabilized beam. Controller complexity

Driven Beam Experiments



Develop excitation technique using existing exponential striplines

Can be frequency domain or time domain study

Estimate dynamics below instability threshold (pre-chaotic motion, see tune shifts below threshold)

Idea - use 4 GS/sec. DAC hardware to drive noise sequences onto selected bunch(es)

Time domain sequences - transform, average (transfer function estimator)

Frequency response of internal structure and modes

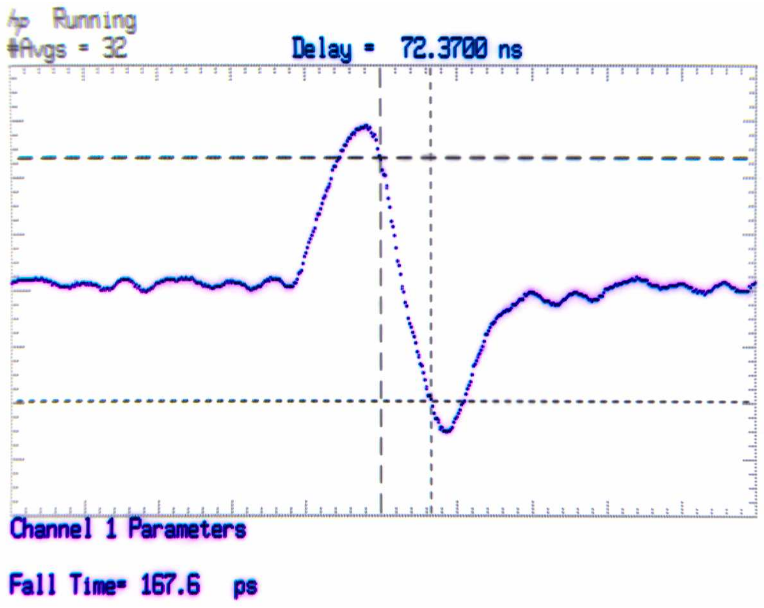
Can be done as excitation in simulation, too.

Valuable step in development of any possible feedback controller (Back End)

Progress - Synchronized excitation code

400W (4 100W) 20 - 1000 MHZ amplifiers ordered

Tunnel “cart” in progress for 2011 SPS MD



Doublet Response 4 GS/sec. D/A

The State of the Art

DAFNE, KEK-B, CESR, PEP-II, ALS, BESSY-II, PLS, Elettra, ESRF, Diamond et al. all have significant experience running multi-bunch instability control systems. All routinely operate well above instability thresholds. Other facilities developing mix of commercial and custom hardware.

The instabilities themselves are proportional to current, and proportional to the driving impedances. Running these facilities at higher currents requires some analysis to understand the practical limits of these instability control systems. PEP-II pushed the fundamental phase margin limit for control of low modes, and a special low group delay channel (the “woofer”) was commissioned.

The technology of these systems may evolve, but the fundamental limits to the performance of these systems, e.g. the saturation effects from noise limiting the gain, and the limits on gain and phase from loop stability of the feedback loop, are the central limits we must never ignore. Recent commercial activity in high speed FPGA platforms make 1-4 GS wideband feedback systems more feasible. Significant challenges exist in the transducers which sense and control beams.

The diagnostics possible with the programmable DSP based systems are very useful in validating dynamics and understanding the performance of the instability control. They also provide many very unique accelerator diagnostics (such as measurement of complex HOM impedances). The flexibility of these systems has been an opportunity to address several control needs as the accelerators were modified (such as the addition of harmonic cavities to the ALS, requiring novel IIR control filters, or the quadrupole mode control at DAFNE)

The new directions in Ecloud control for the SPS and LHC may require new ideas in control

Summary

Multi-bunch instability control -

Problem can be addressed with impedance control, careful cavity tuning, deliberate modulation of filling patterns, and/or active feedback

- Design choices - all-mode vs. selected modes
- difference between damped HOM structures (e.g. bands of unstable modes) and narrowband HOM structures
- Technology choices - processing approaches
- Issues of injected noise, required output power
- Sensitivity to variations in operating configurations

Likely Areas for future work

General-purpose reconfigurable building blocks - based on 1 GS/sec. to 8 Gs/sec. sampling rates. Software configured for multiple longitudinal/transverse applications, Ecloud control.

Wideband kicker and pickup technologies (GHz bandwith systems)

Very low group delay (e.g. 10s of nanosecond scale) FIR/IIR filter blocks, using electronic or electro-optic technologies

SPS Instrumentation - setup

Pickups - wideband (exponential taper) striplines (T. Linnecar)

(history of directivity, past use in P-Pbar program)

Cable plant from SPS Tunnel to Faraday cage (instrument room)

Hybrid receiver (Anzac H9 Hybrids)

- Cable delays trimmed, matched, hybrids selected for matching
- Issues with 1700 MHz propagating modes - use of 800 MHz (1 GHz etc.) Bessel Filters

Data Acquisition (vertical plane) in Tektronix fast scope (2.5 GHz bandwidth, 10 or 40 PS/sample)

Offline data analysis in Matlab (and Python)

Equalisation of stripline signal (thanks WH and RDM), removal of longitudinal motion

RMS techniques (with subtraction of DC transient)

- on SUM and Delta (estimation of motion of the beam, head-tail time evolution, charge loss)

FFT based sliding window techniques

- slice by slice (tune shifts within a bunch)
- within bunch (bandwidth or internal modes)

A possible controller design approach

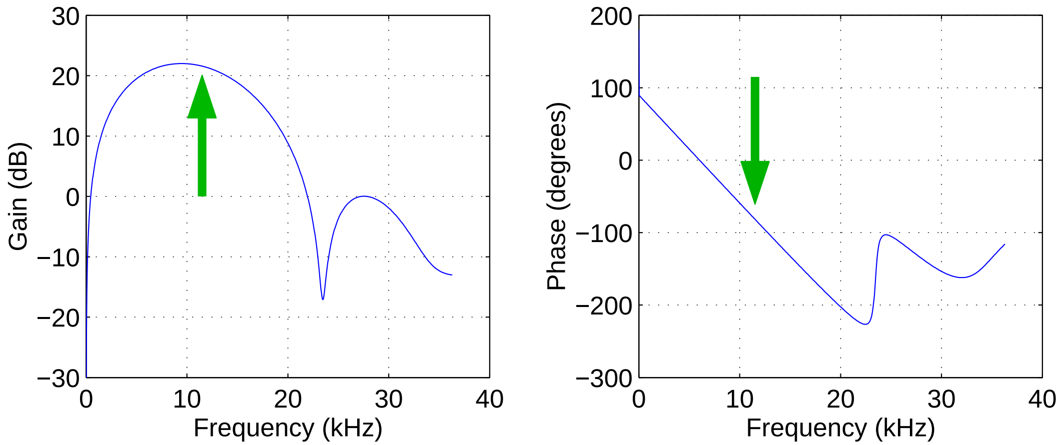
Constraints

- Control of phase & gain at the oscillation frequency F_s (90 degree phase shift)
- DC rejection
- Frequency selectivity

FIR Filter implementation: $y_n = \sum_{k=0}^{M} b_k x_{n-k}$

Design approach

- Let filter impulse response sample a sine wave at the oscillation frequency.
- Phase and gain adjustments are simple
- Set sum of the impulse response to 0 (DC rejection)
- Resulting filter has bandpass characteristic around the F_s



What if the oscillation frequency changes with current?(ALS, Harmonic Cavities).

What if quadrupole as well as dipole oscillations are present? (DAFNE)