Feedback Systems for Synchrotron Light Sources

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Mastering Beam Instabilities in Synchrotron Light Sources

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Talk Outline

I Instabilities, and Feedback principles

Feedback requirements

II. Technical Challenges

Pickups, Kickers

Signal processing options

Gain Limits, Noise effects

III. Example Implementations

ALS, PEP-II/ et al, CESR, KEK-B

IV. Evaluating System performance and Margins

Examples from PEP-II, DAFNE, ALS and BESSY

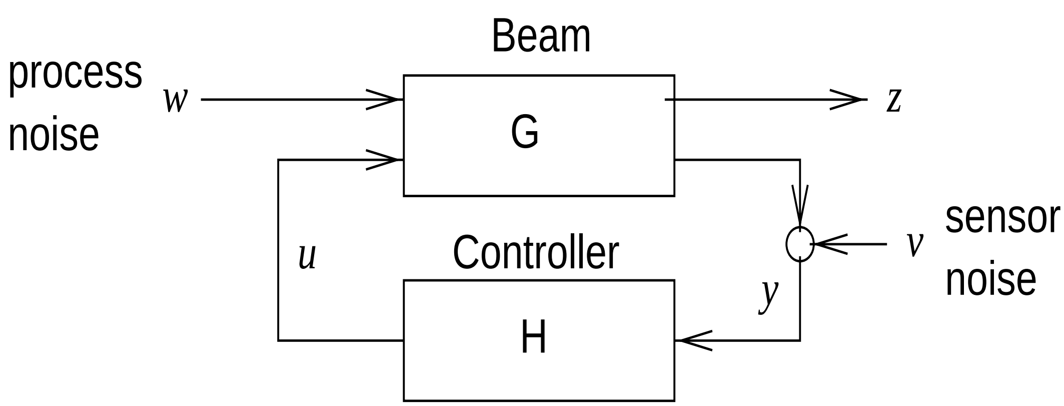
III. Summary

Feedback Principles - General Overview

Principle of Operation

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

Transverse - measure (δX , δY) - kick in X' , Y'



Technical issues

Loop Stability? Bandwidth?

Pickup, Kicker technologies? Required output power?

Processing filter? DC removal? Saturation effects?

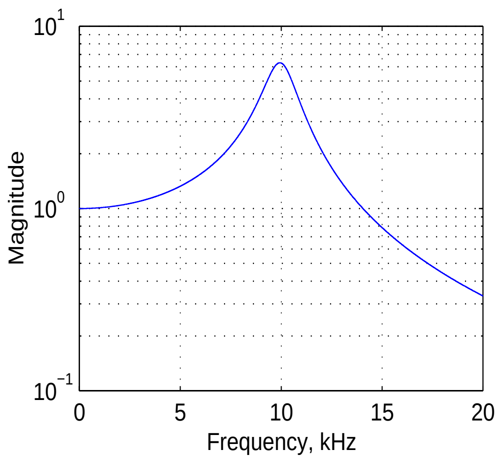
Noise? Diagnostics (system and beam)?

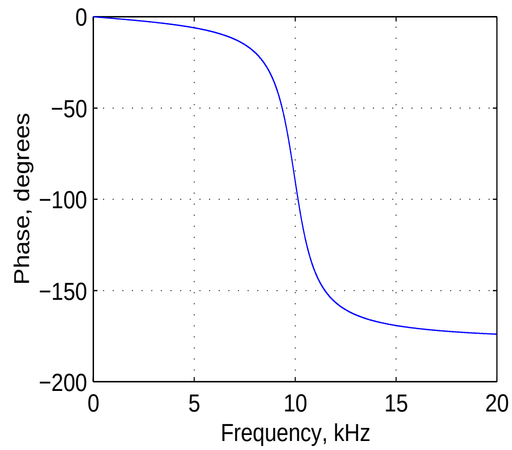
Harmonic Oscillators, Revisited

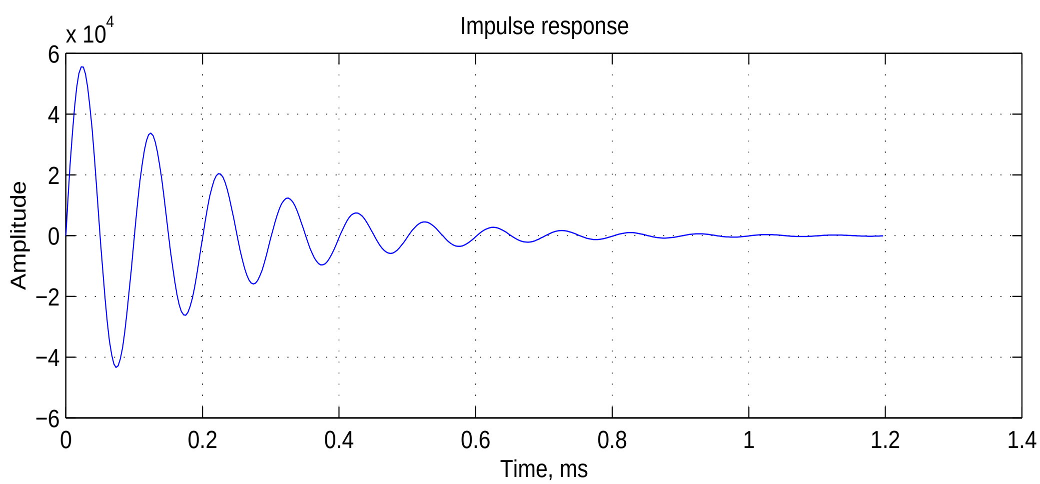
Equation of motion $\ddot{x} + \gamma\dot{x} + \omega_0^2 = f(t)$

where $\omega_0 = \sqrt{\frac{k}{m}}$

Damping term γ proportional to $\dot{x}$







Normal Modes, Revisited

N coupled Oscillators, N Normal Modes

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

Technical Challenges

Short interbunch Interval

- KEK-B, ALS, BESSY, PLS- 2 ns, DAFNE 2.7 ns, PEP-II 4.2 ns
- requires wideband pickups, kickers
- sets required processing bandwidths
- Resolution - oscillation rms 0.6 picosecond

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 - implementation choices

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)

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

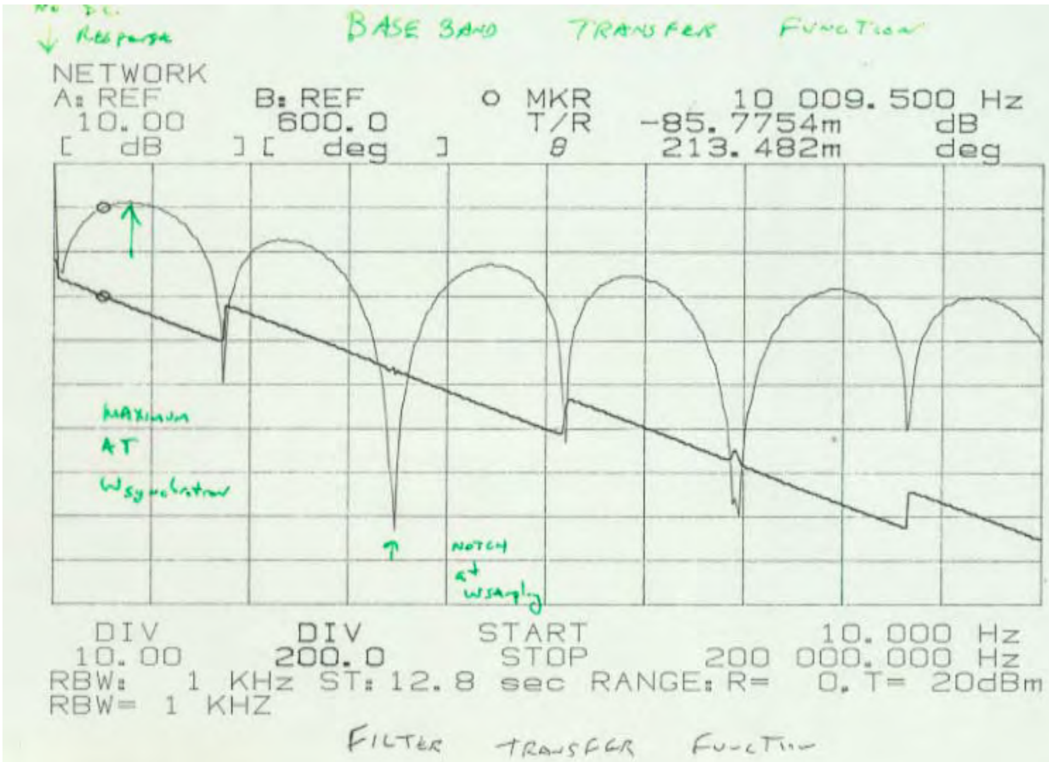
Analog Approach -

- N parallel mode by mode filters - or -
- FIR/IIR from analog delay (electrical, optical acoustic)
- Taps (multiplication of coefficients), Summation

Digital approach

A/D at F_{bunch}, DSP FIR/IIR filter, D/A at F_{bunch}

Baseband transfer function



Baseband Filter transfer function

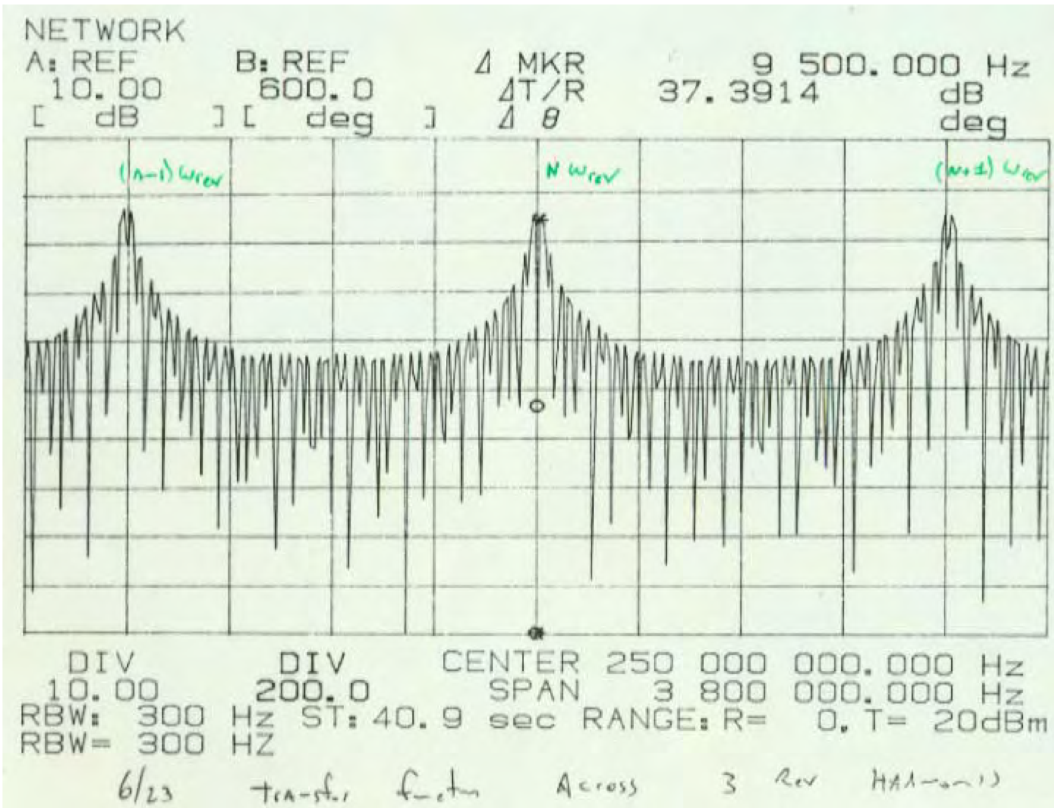
(each bunch sees this control filter)

Maximum gain at Synchrotron frequency

zero DC gain

Phase tailored for proper feedback phase and loop stability

RF transfer function



Total RF transfer function

(superposition of all individual bunch filters)

Zero gain at revolution harmonics

maximum gains at n*Frev +/- synchrotron frequency

Existing/Example Feedback Systems

DESY - Kohaupt et al. (transverse and longitudinal)

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

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

- 16 bunches - 16 analog filters with multiplexing

NSLS - Galayda, et al (transverse)

- 2 tap analog FIR ("correlator filter")

CESR - Billing, et al (transverse and longitudinal)

- 16 ns bunch spacing, digital FIR filter

ALS - Barry, et al (transverse)

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

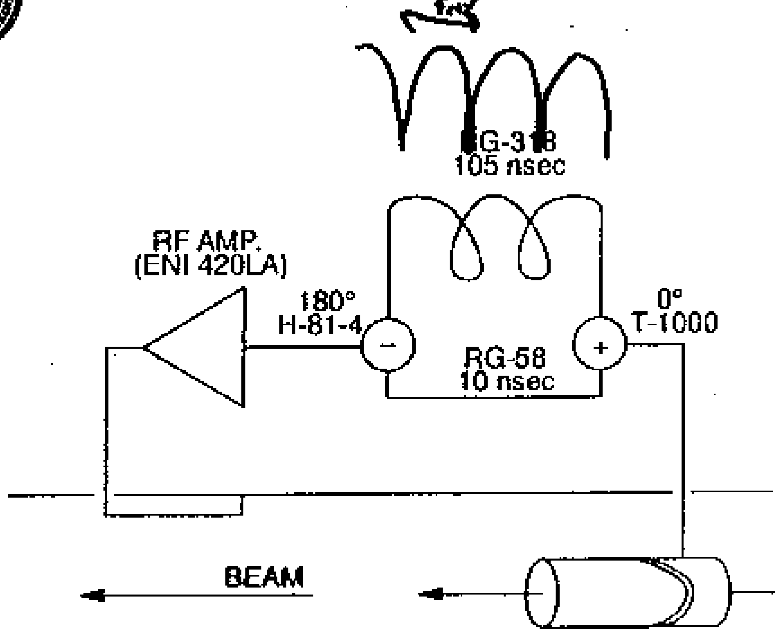
PEP-II/ALS/DAFNE - Fox, et al (longitudinal)

- 2 - 4 ns bunch spacing, 120 - 1746 bunches
- general purpose DSP processing

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

- 2 ns spacing, 5120 bunches, 2 tap digital FIR

NSLS Transverse Feedback



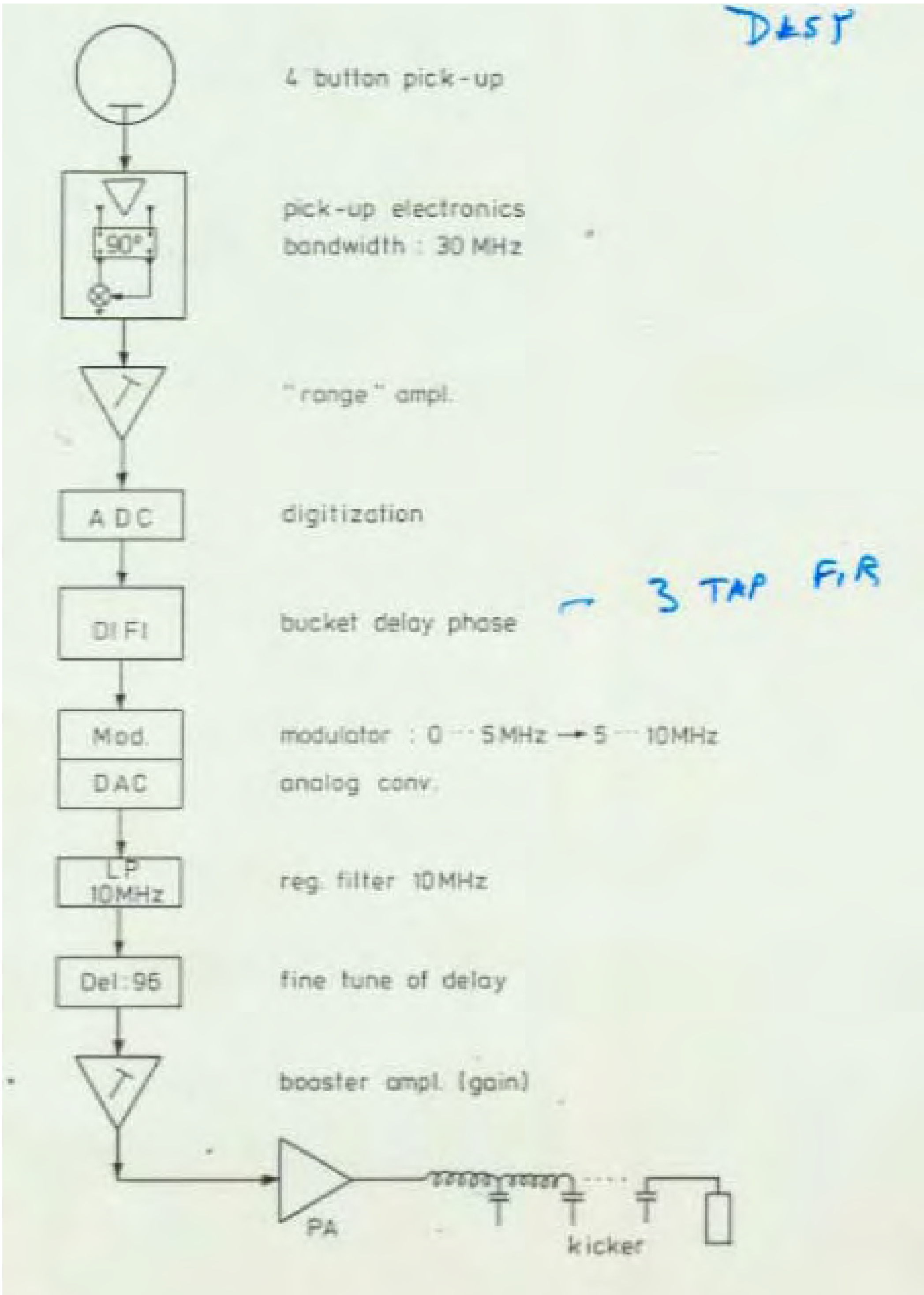
From J. Galayda

2-tap analog FIR

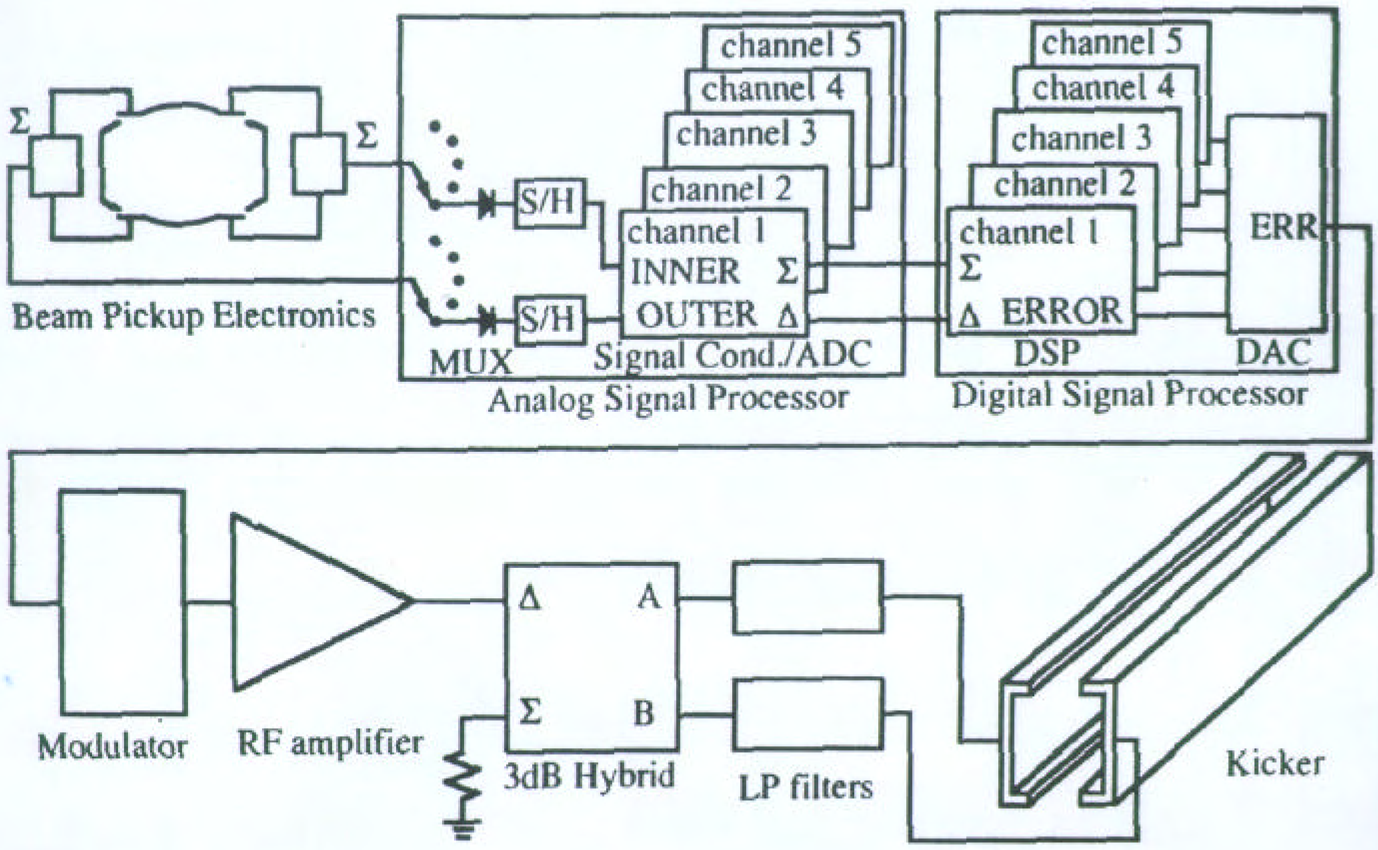
PHASE ADJUSTED VIA pickup, kicker Locations

Amp β function.

DESY


DESY
4 button pick-up
90°
pick-up electronics
bandwidth : 30 MHz
"range" ampl.
ADC
digitization
DI FI
bucket delay phase
→ 3 TAP FIR
Mod.
DAC
modulator : 0 ··· 5MHz → 5 ··· 10MHz
analog conv.
LP
10MHz
reg. filter 10MHz
Del:96
fine tune of delay
booster ampl. (gain)
PA
kicker

CESR Transverse Feedback



from J. Rodgers, et al

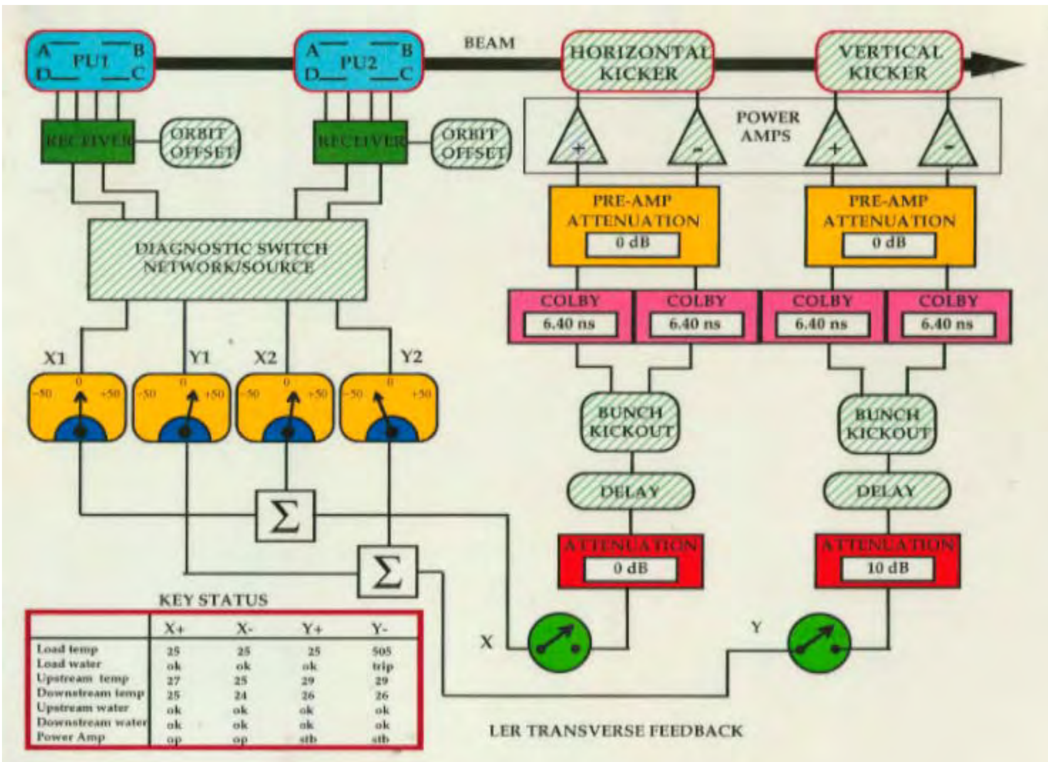
14 ns bunch spacing

hardware FIR filter (70 ns cycle) 5-WAY PARALLEL STRUCTURE

current normalisation via look-up table

output duty-cycle modulator explored

ALS Transverse Feedback Implementation



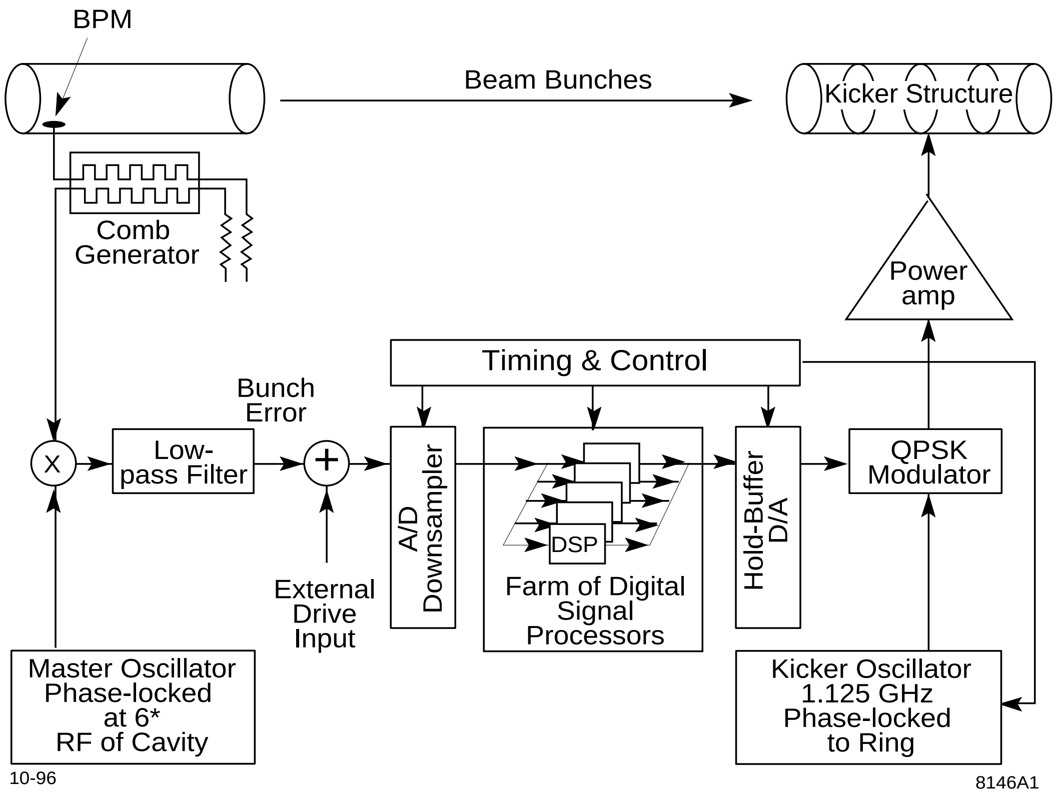
	X+	X-	Y+	Y-
Load temp	25	25	25	505
Load water	ok	ok	ok	trip
Upstream temp	27	25	29	29
Downstream temp	25	24	26	26
Upstream water	ok	ok	ok	ok
Downstream water	ok	ok	ok	ok
Power Amp	op	op	stb	stb

From W. Barry

Analog 2-tap FIR filter for DC orbit suppression

Quadrature processing via 2 pick-ups

PEP-II/DAFNE/ALS



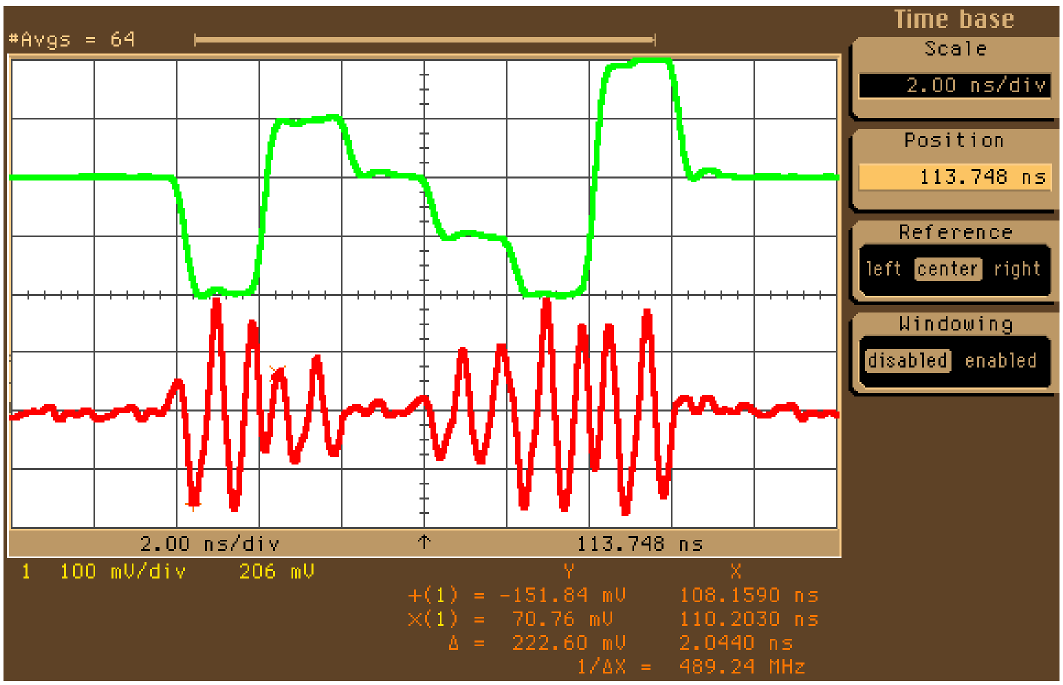
Phase Detection at 3*RF

General-Purpose DSP farm (40 - 80 processors)

QPSK-AM output modulator (9/4, 11/4 or 13/4 * RF)

Six Bunches and associated longitudinal kicks

2 ns bunch spacing

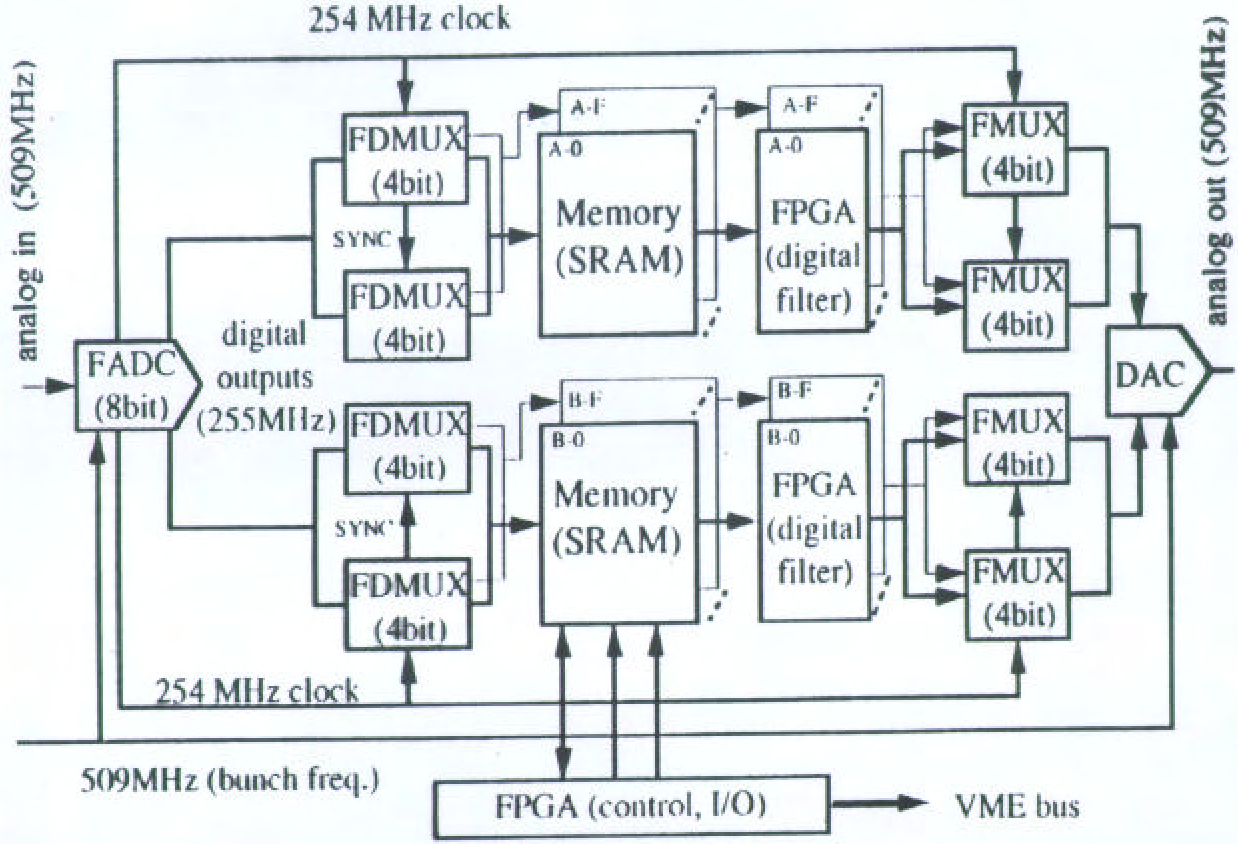


Baseband risetime 320 ps

(2ns/div)

QPSK-AM modulation

KEK-B Transverse and Longitudinal signal processing



from M. Tobiyama, et al

2 ns bunch spacing

2-tap FIR structure (fixed 1, -1 coefficients)

16 parallel channels

DIAGNOSTIC MEMORY IN 2nd PARALLEL SYSTEM WITH MEMORY INSTEAD OF OUTPUT CHANNEL

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 apposed 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

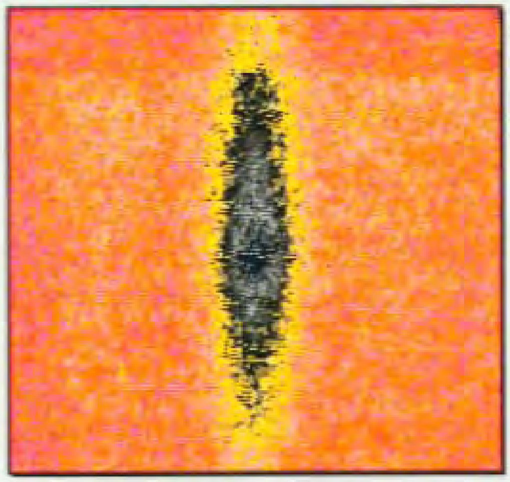
Drift-tube structures - designed by LBL Beam Electrodynamics Group, used by ALS, PLS, PEP-II. Useful in-band directivity. Cooling issues for ampere currents

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

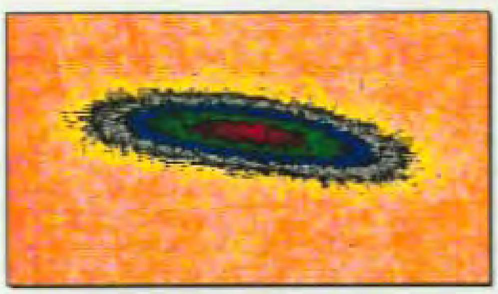
Beam Quality (ALS)

Effect of Coupled Bunch Feedback on Beam Quality

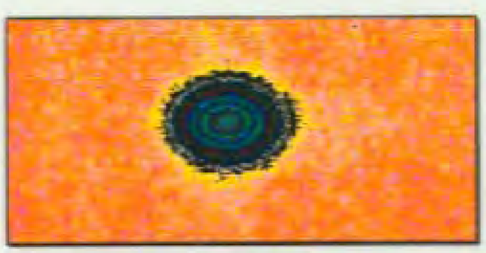
W. Barry, J. Byrd, J. Corlett (LBNL)
J. Fox, H. Hindi, I. Linscott, D. Teytelman (SLAC)



Vertical feedback OFF
Horizontal feedback ON
Longitudinal feedback ON



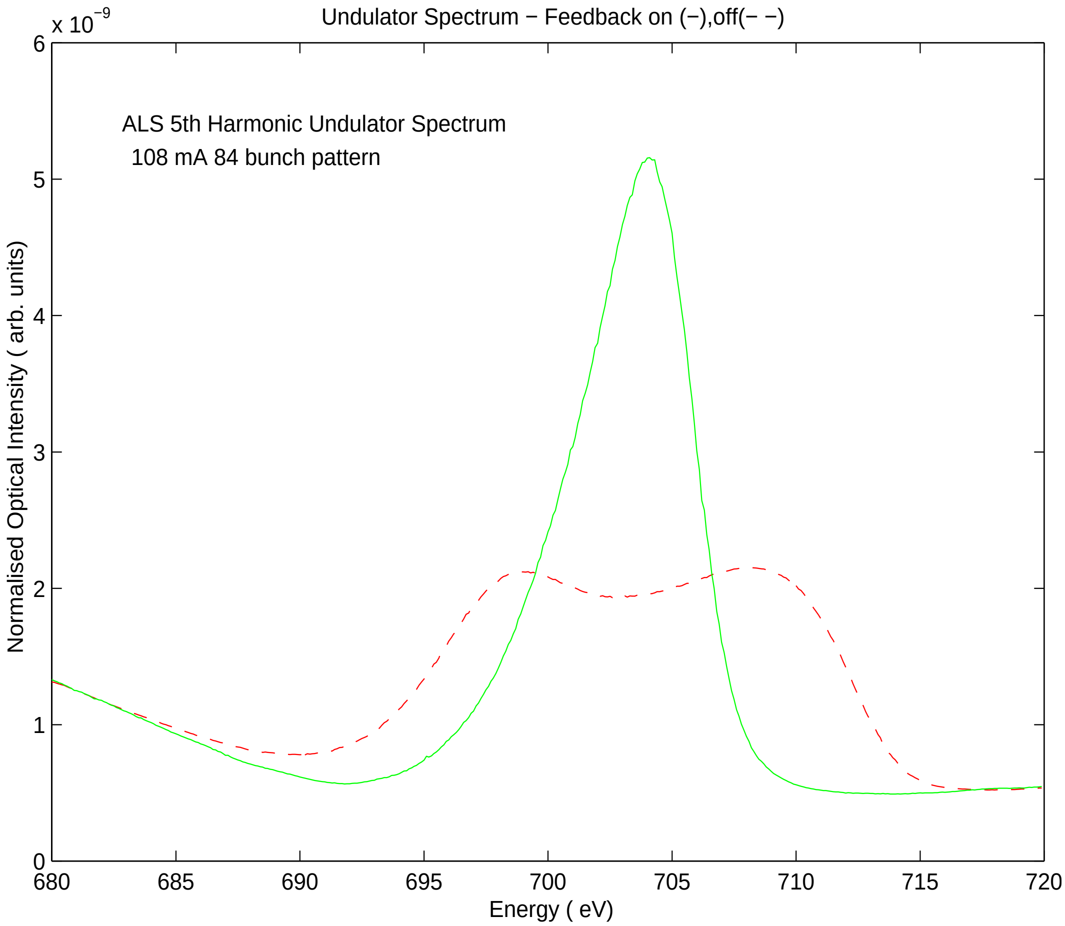
Vertical feedback ON
Horizontal feedback ON
Longitudinal feedback OFF
The increase in transverse beamsize results from large amplitude energy oscillations at a point of x and y dispersion in the lattice.



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

Undulator Spectrum



Thanks to Tony Warwick (ALS) for Undulator Spectrum

Evolution of DSP-based Diagnostics

Original motivation - stabilize coupled-bunch instabilities

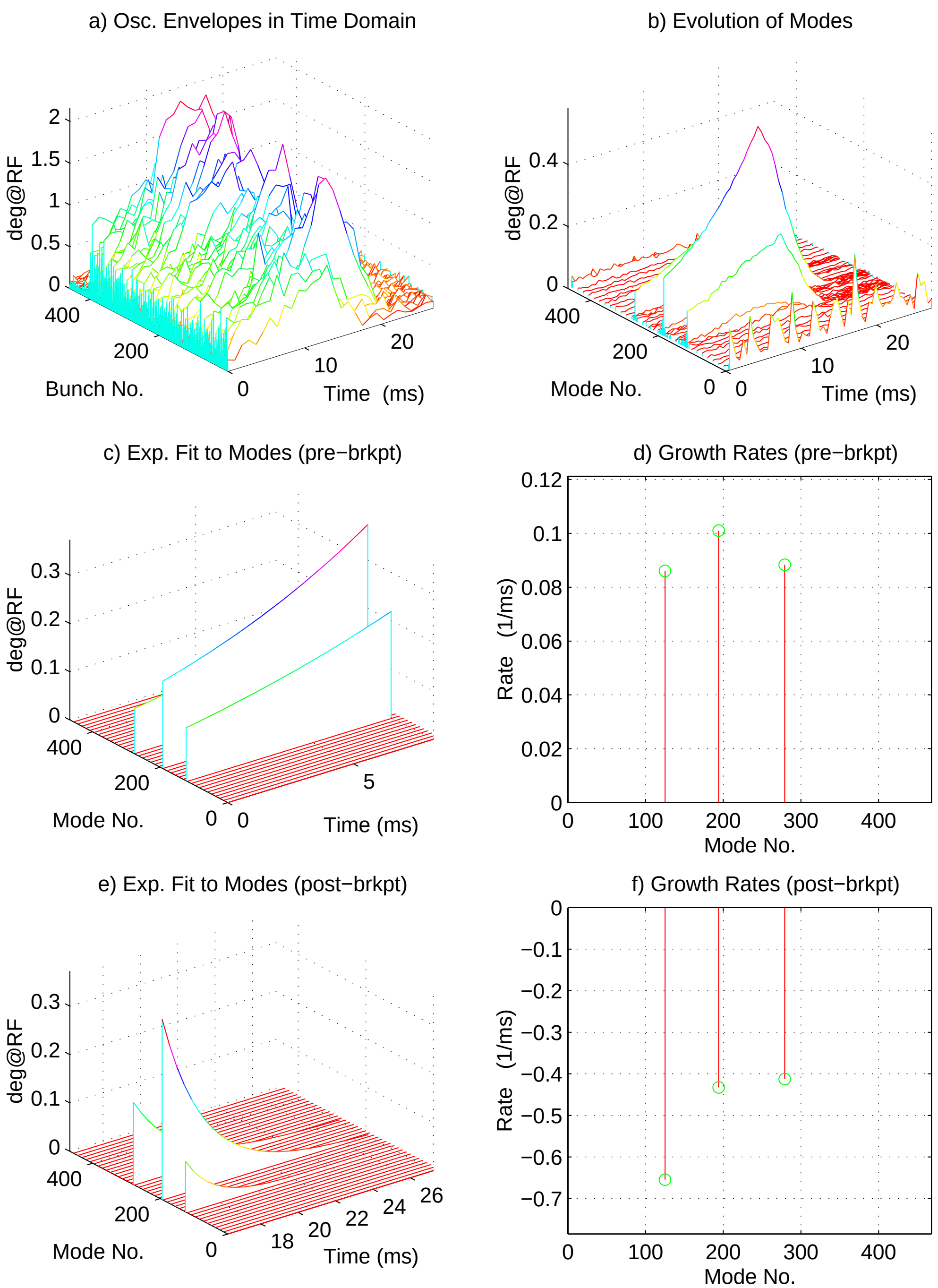
- Engineering-level system checks
- Identification of unstable eigenmodes, growth/damping rates at full design currents
- Beam Pseudospectra, Grow/Damp Modal Transients

Second-tier diagnostics

- Predictions of high-current unstable behavior from low-current stable machine measurements (growth/damping rates at design current estimated from low-current commissioning data)
- beam instrumentation - bunch by bunch current monitor, tune monitor, bunch power spectrum (noise) monitor
- Synchrotron tune vs. bunch number - gap transients, tune spread, Landau damping - instability thresholds for various configurations
- Longitudinal impedance vs. frequency from bunch synchronous phases
- Eigenstructures of uneven fills, phase space tracking
- Transverse Motion via DSP Data Recorder/Control

Techniques used at ALS, SPEAR, DAFNE, PEP-II, PLS and BESSY

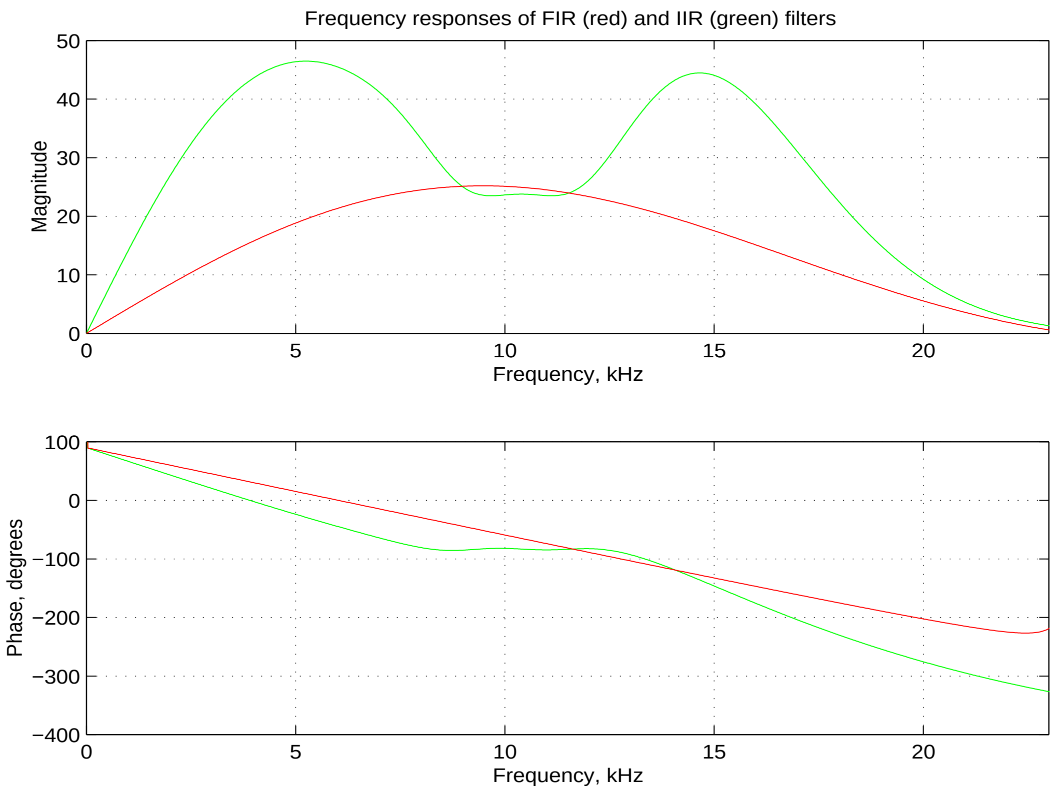
PLS Grow/Damp



PLS:dec1599/1237: Io= 150mA, Dsamp= 15, ShifGain= 5, Nbun= 460,
Gain1= −1, Gain2= 0, Phase1= 30, Phase2= 30, Brkpt= 1150, Calib= 11.02.

Harmonic Cavities at the ALS and Longitudinal Control

The addition of 5 3*RF passive cavities has added new HOM instabilities to the ALS, increasing growth rates for the passively-tuned state. Additionally, the coherent tune shifts from reactive impedances and current now require a much wider control filter than the FIR band-pass filter in use for five years.



Flexibility of the programmable DSP system allowed this new control technique to be implemented as a software change. Transient-domain diagnostics used to understand new operating requirements

Movie Synopsis

SPEAR -

- 70 bunch even fill, 30 mA
- FB stabilized mode (-3) grows when FB turned off
- 24 ms total sequence

DAFNE-

- 30 bunch even fill, 100 mA
- Mode zero unstable, beam lost in machine
- 650 microsecond total sequence

ALS-

- 320 bunch fill (h=328), 95 mA
- FB stabilized mode (233) grows when FB turned off
- 7 ms total sequence

LER PEP-II Phase Space tracking

- inner circle “modes “785 - 795, outer 805-815

HER Bunch train (vertical motion) 22 ms

- 150 buckets, 4.2 ns spacing
- FB stabilized train grows when FB turned off

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

Recent developments -

Longitudinal control of machines with harmonic cavities

- ALS experience - new IIR control techniques

Strategy of common hardware systems, software configured systems. Development of transient-domain machine diagnostics

Rapidly developing DSP technology suggests potential future applications (Elettra/SLS work in progress)

Acknowledgments

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