Beam Feedback - Examples from Instability Control, and Ideas for the Future

J. Fox

H. Dong, T. Mastorides, C. Rivetta, D. Teytelman, D. Van Winkle, A. Young

SLAC

A. Drago, M. Serio

LNF-INFN

J. Flanagan, M. Tobiyama

KEK

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Talk Outline

Background - Accelerator Instabilities, Feedback control

- Feedback basics

Possible Solutions and Technical Challenges - State of the Art Review

- Example systems from around the world
- parallel processing DSP structures, iGp and Gproto 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

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.

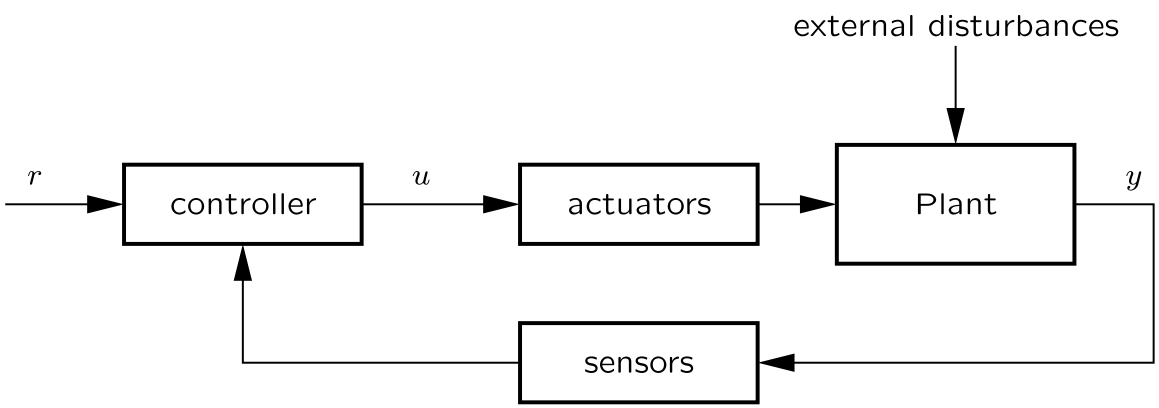
In the past circular machines were designed to operate below the instability threshold.

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 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.

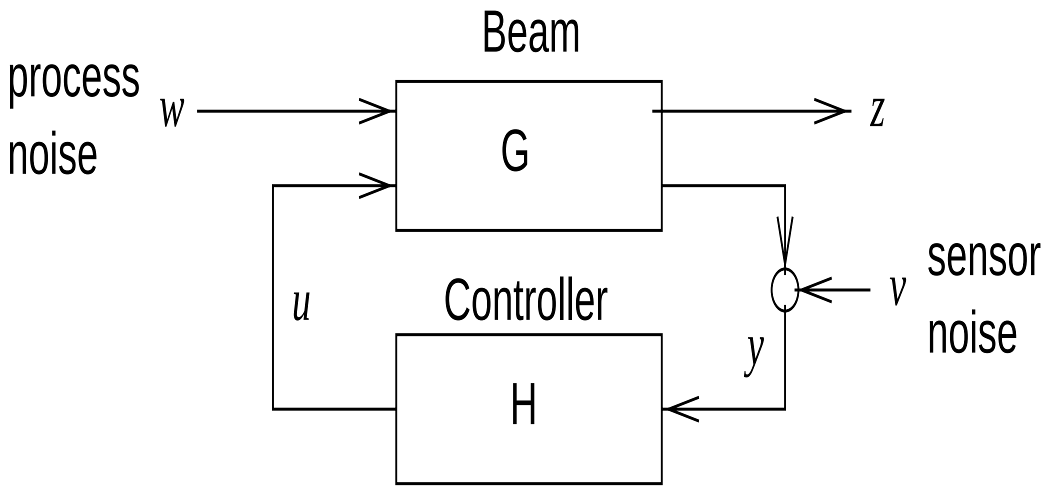
Feedback system robustness - how does the performance change if the plant parameters or dynamics change? How do the changes in sensors and actuators affect the system?

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

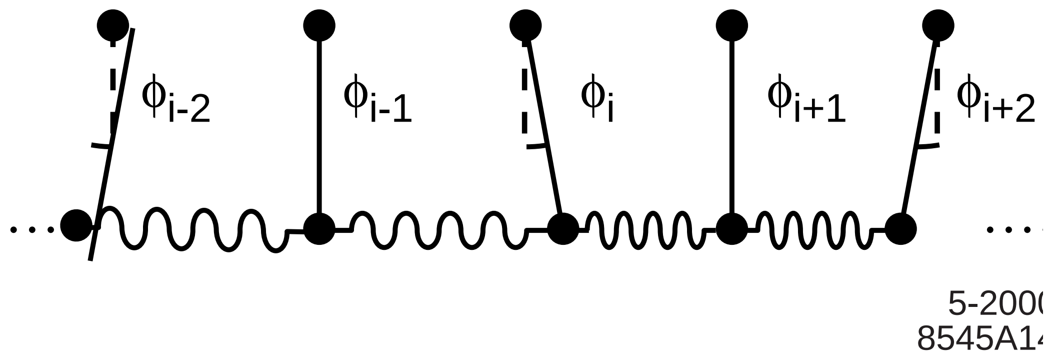
Loop Stability? Bandwidth?

Pickup, Kicker technologies? Required output power?

Processing filter? DC removal? Saturation effects?

Noise? Diagnostics (system and beam)?

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.

Modal eigenvalues are given by

Accelerator parameters — Beam current — Aliased impedance

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

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

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

Block diagram of a longitudinal feedback system

First Generation DSP, programmable system installed in:

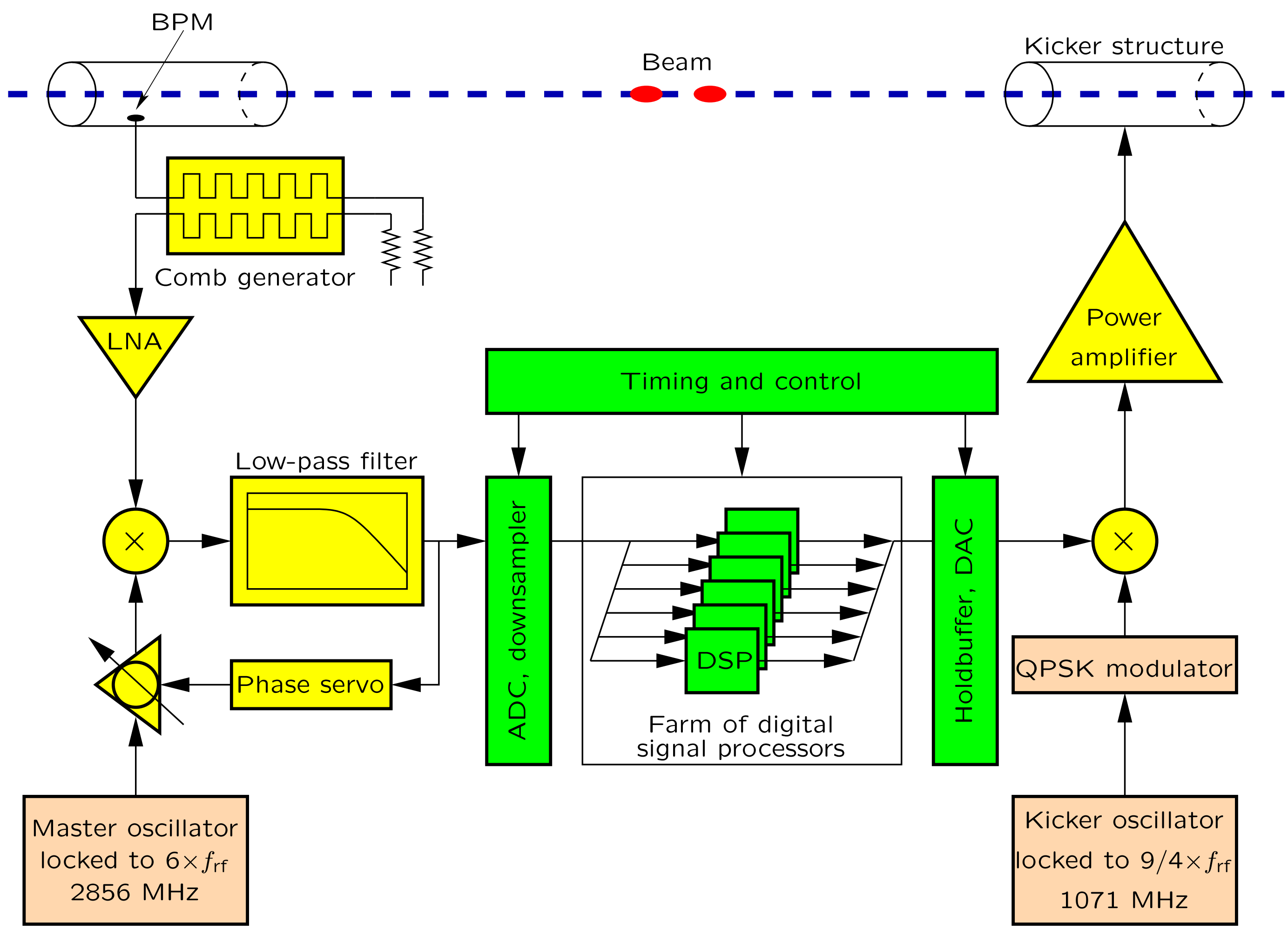
PEP-II, ALS, BESSY-II, PLS, DAΦNE and demonstrated at SPEAR

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

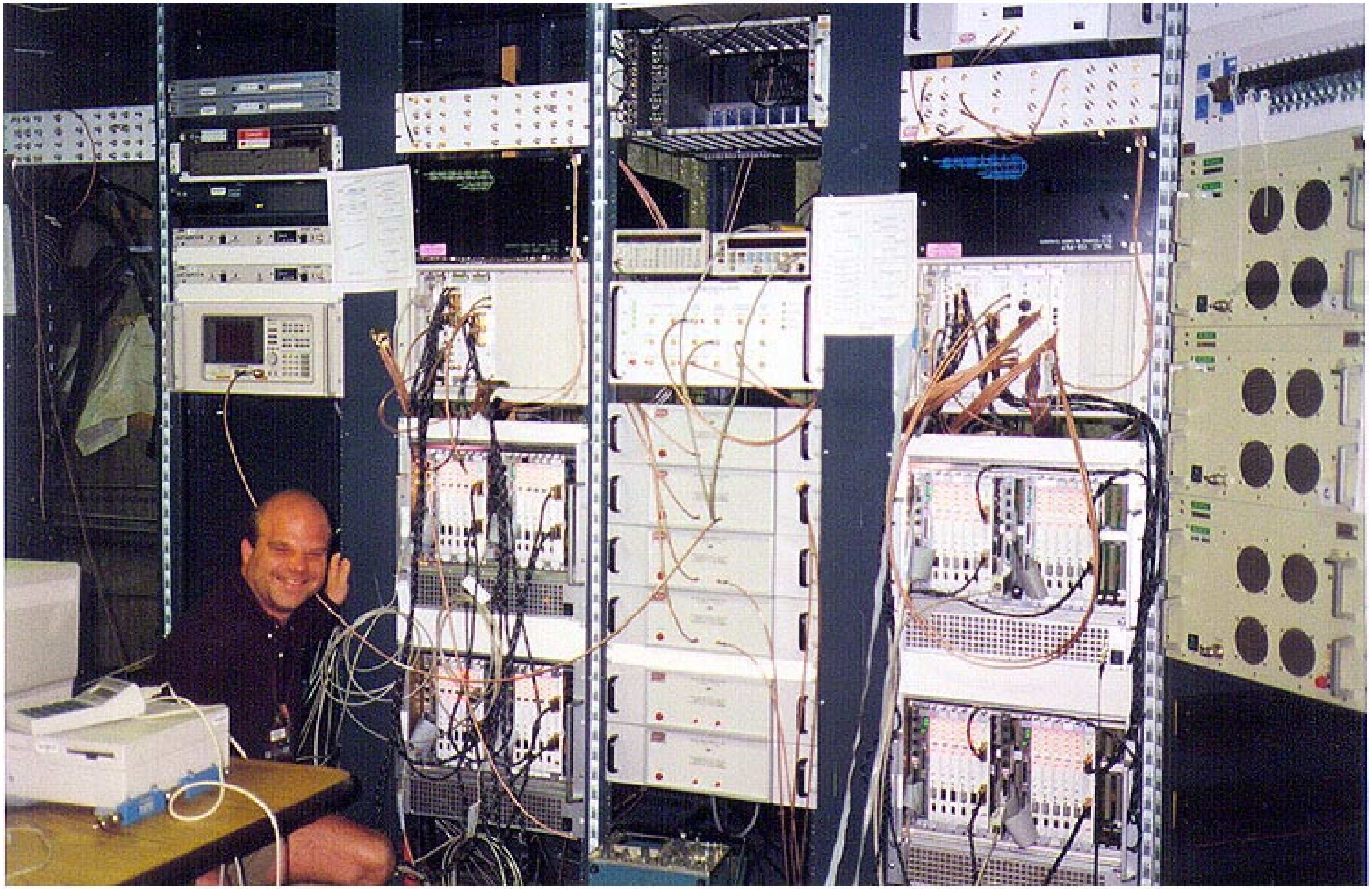
Scalable processing array, up to $3.2 \cdot 10^9$ MAC/sec.

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

Existing/Example Coupled-Bunch 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

Elettra, SLS- Bulfone, et al (transverse)

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

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
- 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/Gproto - Tetytelman, et al (general purpose, transverse, longitudinal)

- 2nd Generation technology - reconfigurable gate arrays
- parallel processor - uneven stepping applicable to various harmonic numbers
- 2 ns spacing, 5120 bunches, 12 tap FIR,
- Demonstrated transverse processor channel at PEP-II, DAFNE
- Demonstrated longitudinal channel at ATF (downsampled)

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)

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

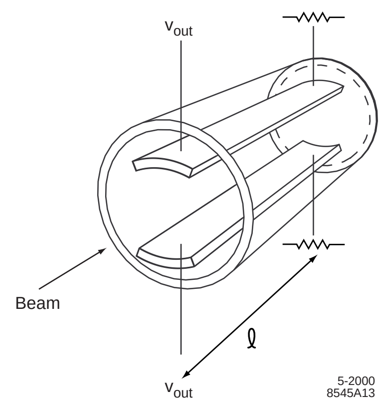
wide bandwidth filter - insensitive to variations in machine tune

narrow bandwidth filter - helps reject detector noise

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

“Kicker” Technology Issues

Basic ideas - Transverse Control via Stripline Electrodes



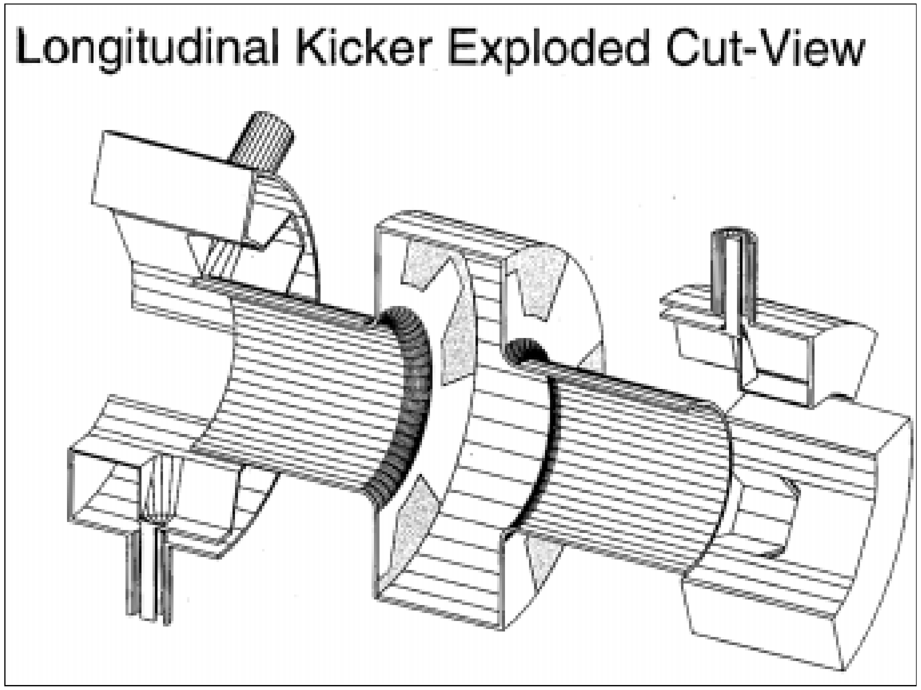
Longitudinal kick via periodic drift-tube

(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.



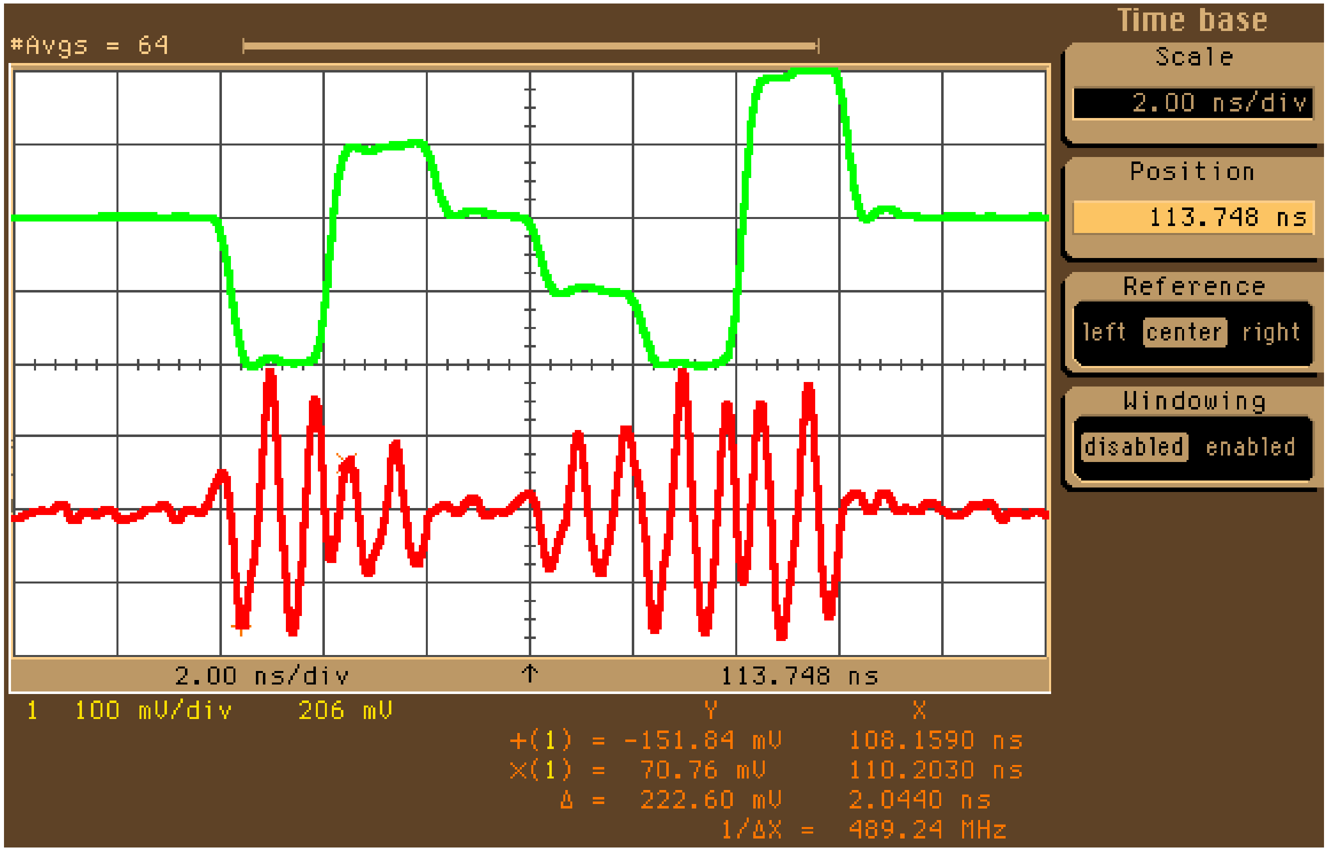
Six Bunches and associated longitudinal kicks

2 ns bunch spacing

Baseband risetime

320 ps (2ns/div)

QPSK-AM modulation



Measuring beam & system dynamics

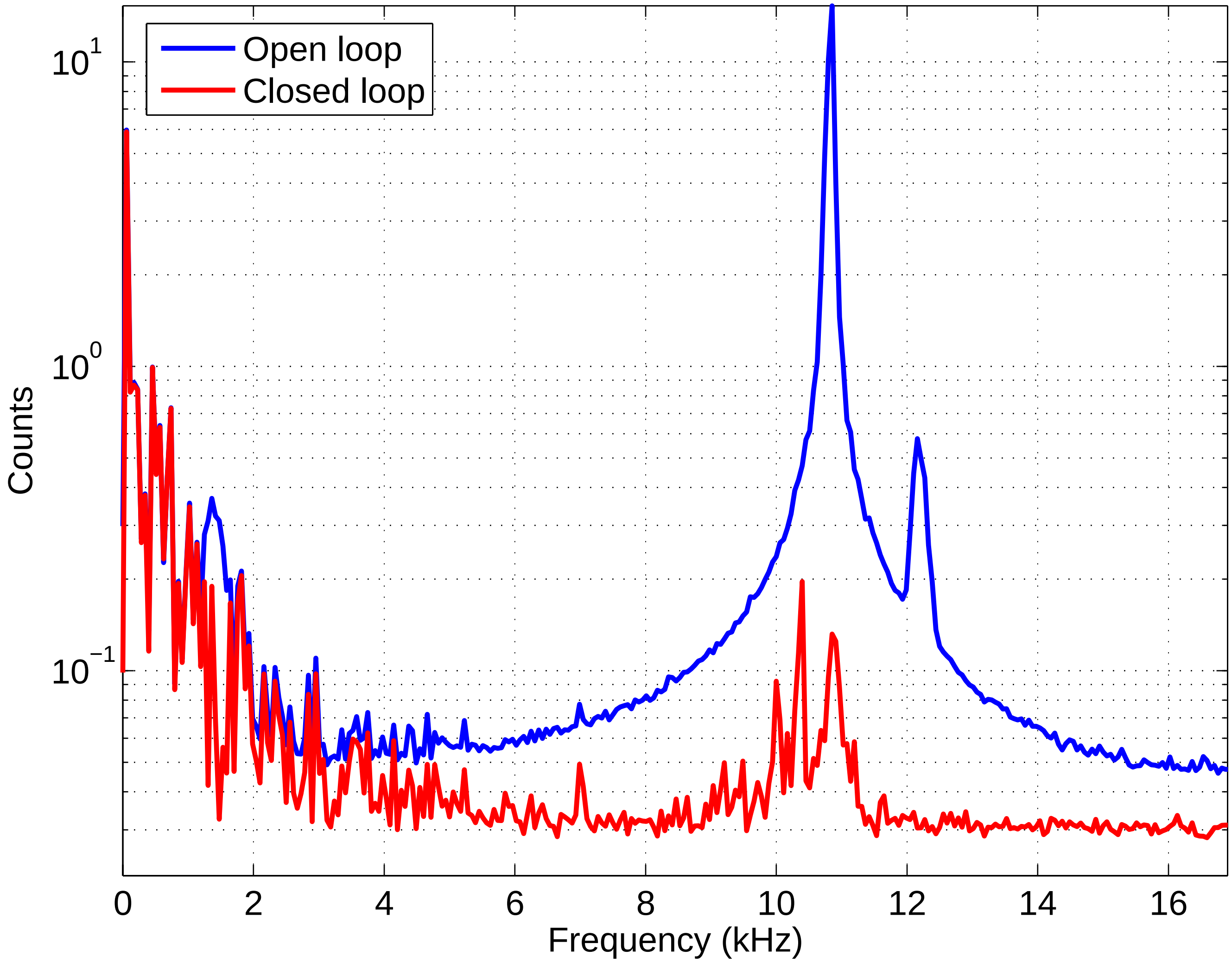
Many uses

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

How to characterize an unstable system? Possible approaches

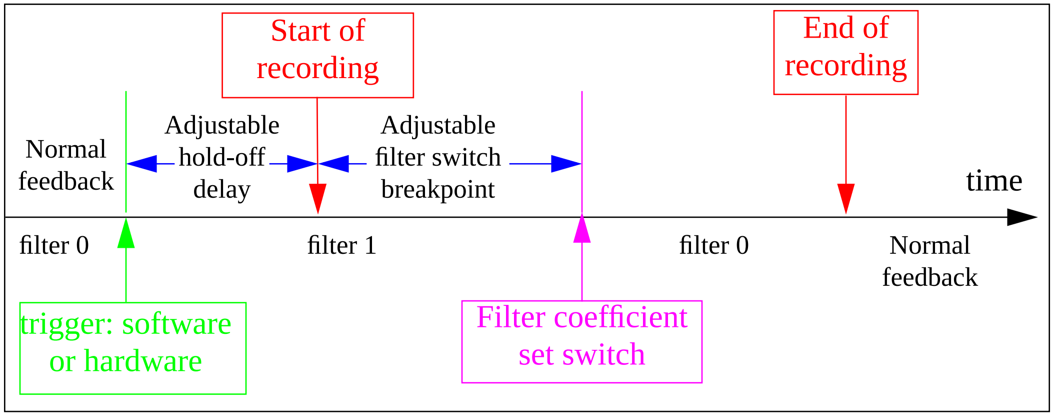
- Power Spectrum measurement - no phase information but shows frequency information
- Open-loop transfer function - measurement is only possible below instability threshold. Each mode to be quantified requires a separate network analyzer sweep.
- Closed-loop transfer function - extracting beam dynamics 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

Grow/damp transient measurement

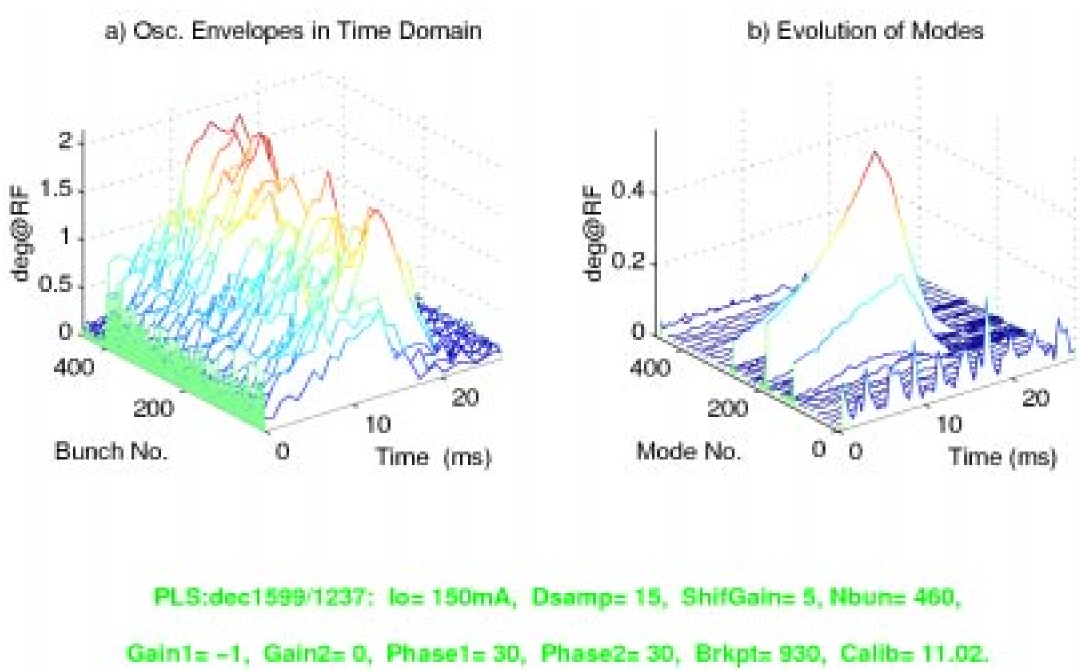


A transient diagnostic technique that generates

- 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.



Grow/damp measurement example from PLS

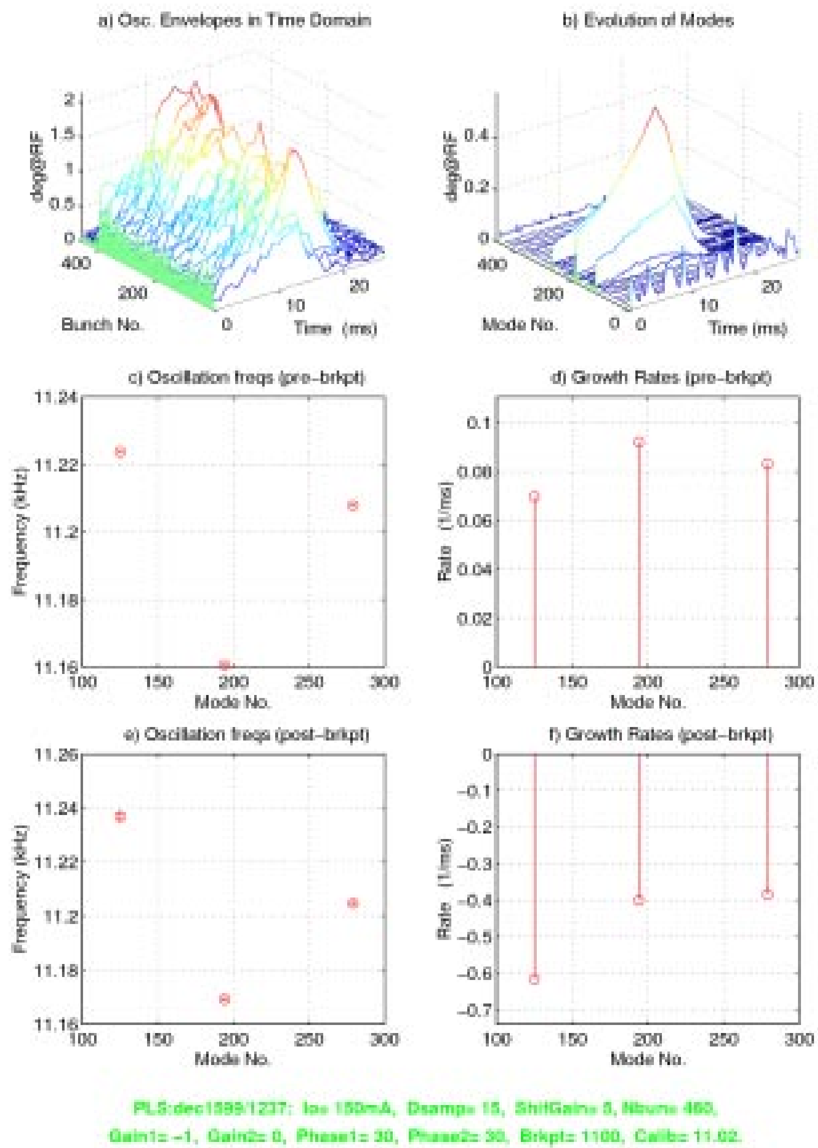
A 30 ms long data set with 15 ms open-loop section.

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.

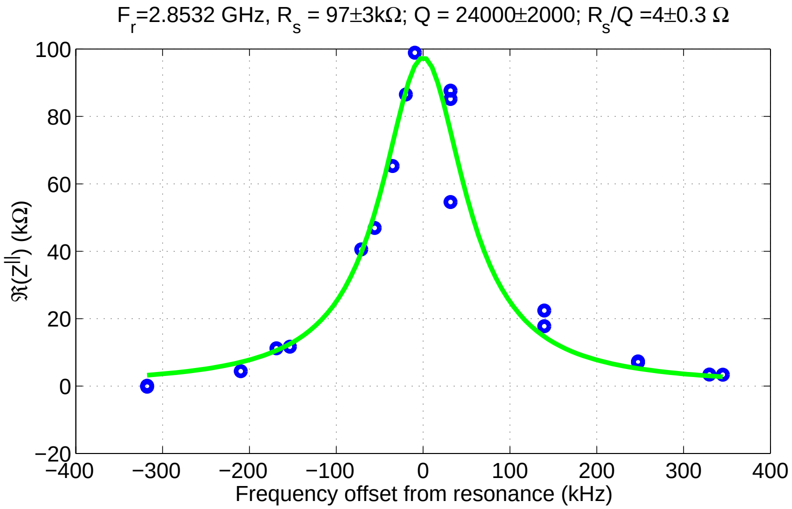
A single measurement like this only characterizes the instabilities and the feedback at a single accelerator operating point.

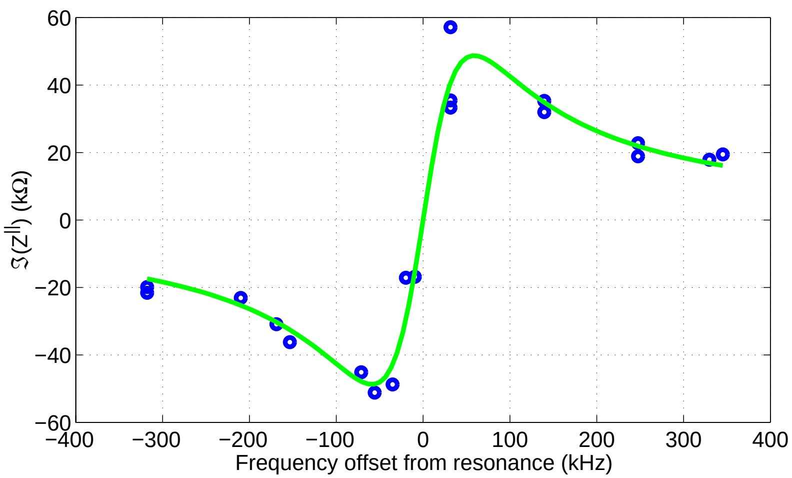
A very powerful technique - measure modal eigenvalues as a function of beam current, RF system configuration, etc. Reveals the impedances directly driving the beam

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.



ALS HOM Complex Impedance Measurement

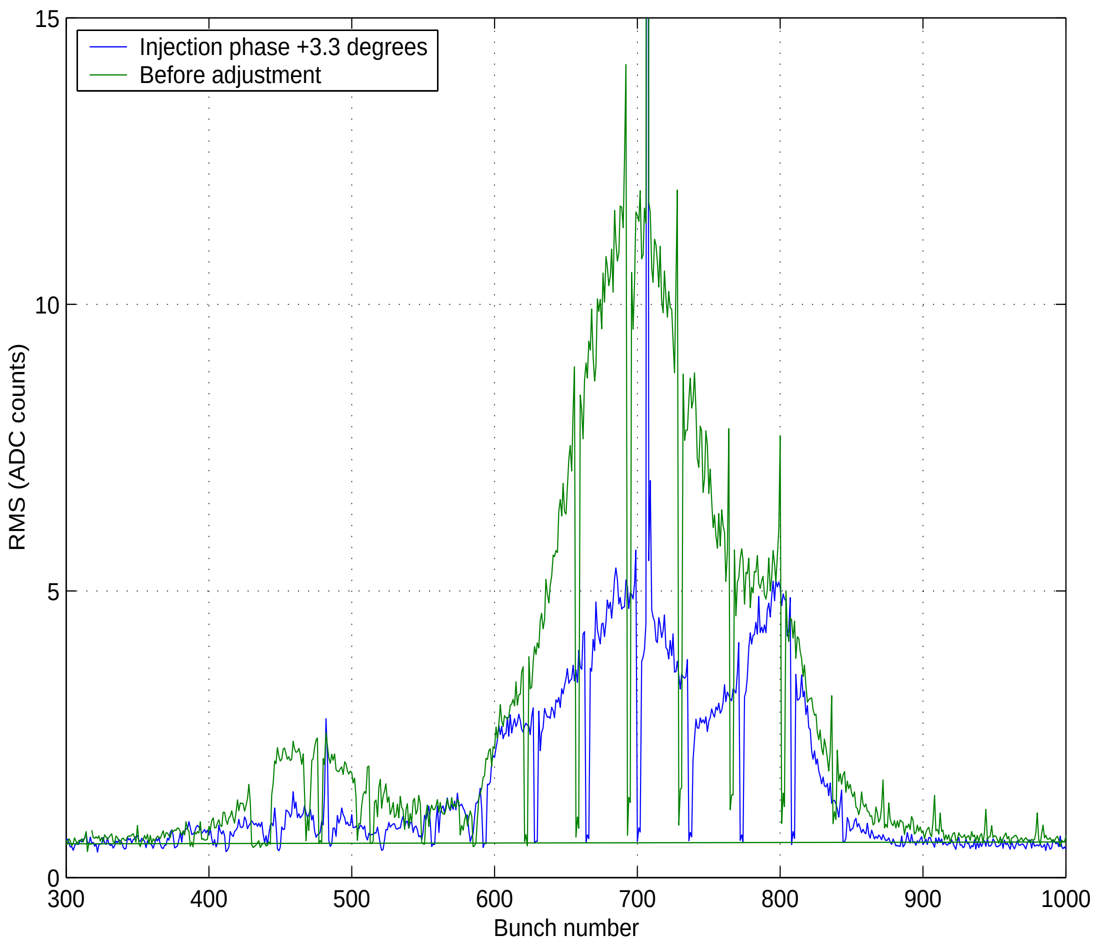




These techniques allow beam-based measurement of in-situ HOM impedances

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)

Beam Diagnostics, Accelerator Diagnostics via the processing channel



iGp processing channel

Transverse processor, LER

Transient recording, synched to injection

measures rms motion after injection

real-time (2 hz update)

Allows injection line tuning for best injection efficiency

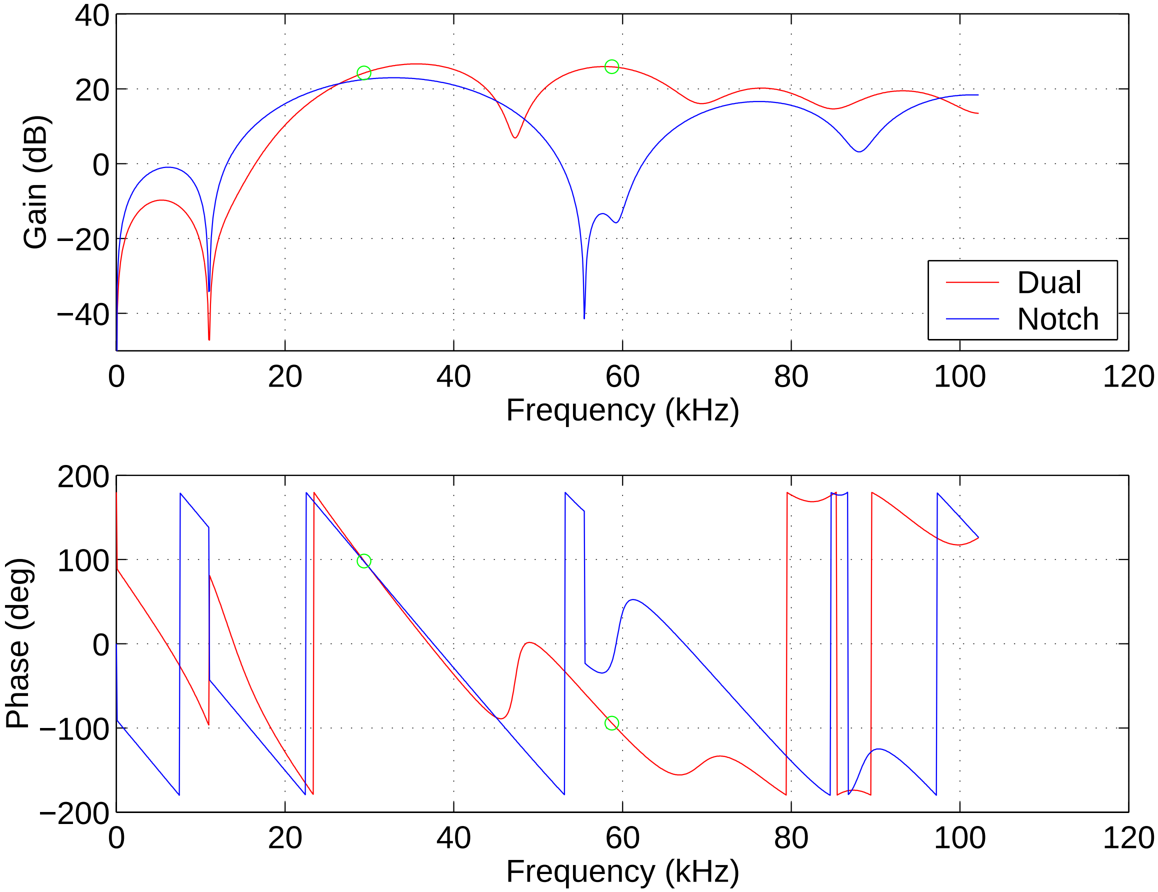
Quadrupole instability control

DAFNE e+/e-collider at LNF

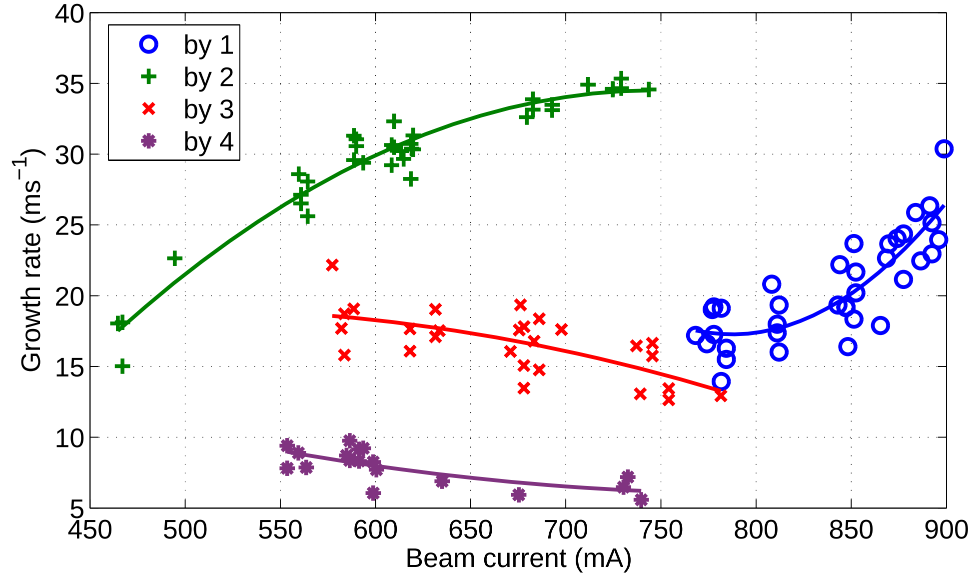
- increased operating currents
- quadrupole mode longitudinal instabilities have appeared (the installed system suppresses the dipole modes).

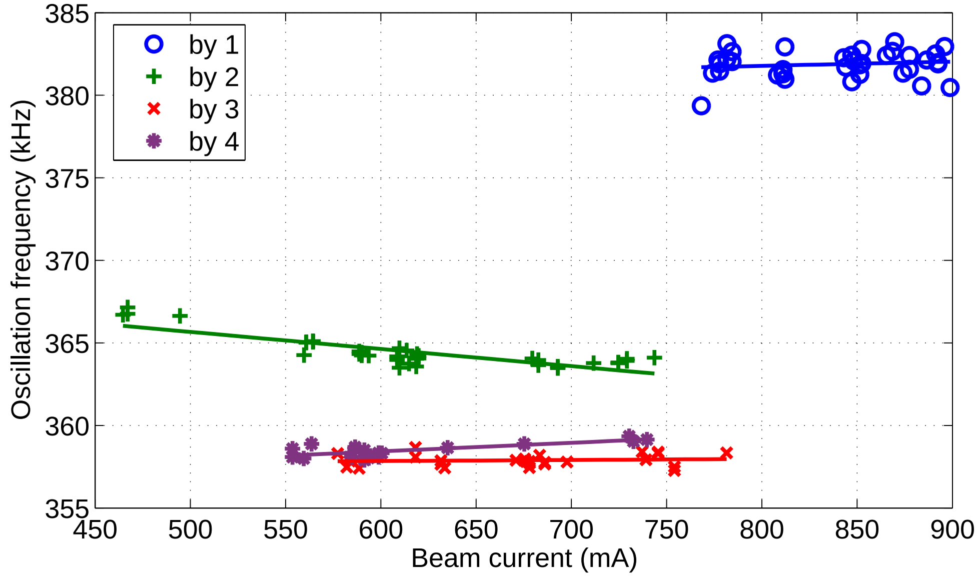
Flexible DSP code implemented a novel quadrupole control filter

- 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.



Study of X plane growth rates, tune shifts vs. current (DAFNE)





Multiple grow/damp measurements characterize the dependence of growth rates and oscillation frequencies on the beam current and bunch spacing.

Significant changes in the growth rates and tune shifts as a function of bunch spacing are inconsistent with the simple resistive wall model and, most likely, indicate the effects of the electron cloud.

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

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
- Complex Longitudinal impedance vs. frequency from bunch synchronous phases, tune shifts
- Eigenstructures of uneven fills, phase space tracking
- Injection Monitor, injection tuning
- Study of tune vs. bunch position, tunes vs. current - Ion and electron cloud studies

In some ways the development of the beam diagnostics has been the most useful and significant benefit of the use of the programmable technology in the DSP feedback systems.

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)

Processing Block - gain limited by noise in filter bandwidth. Quantizing noise (broadband) is one system limit - noise from RF system or front-end circuitry may also contribute. 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) may set limit on achievable gain

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 - 1.5 GS/sec. processing channels

General-purpose reconfigurable building blocks - based on reconfigurable FPGA architectures. Software configured for multiple longitudinal/transverse applications. SLAC/KEK/LNF 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

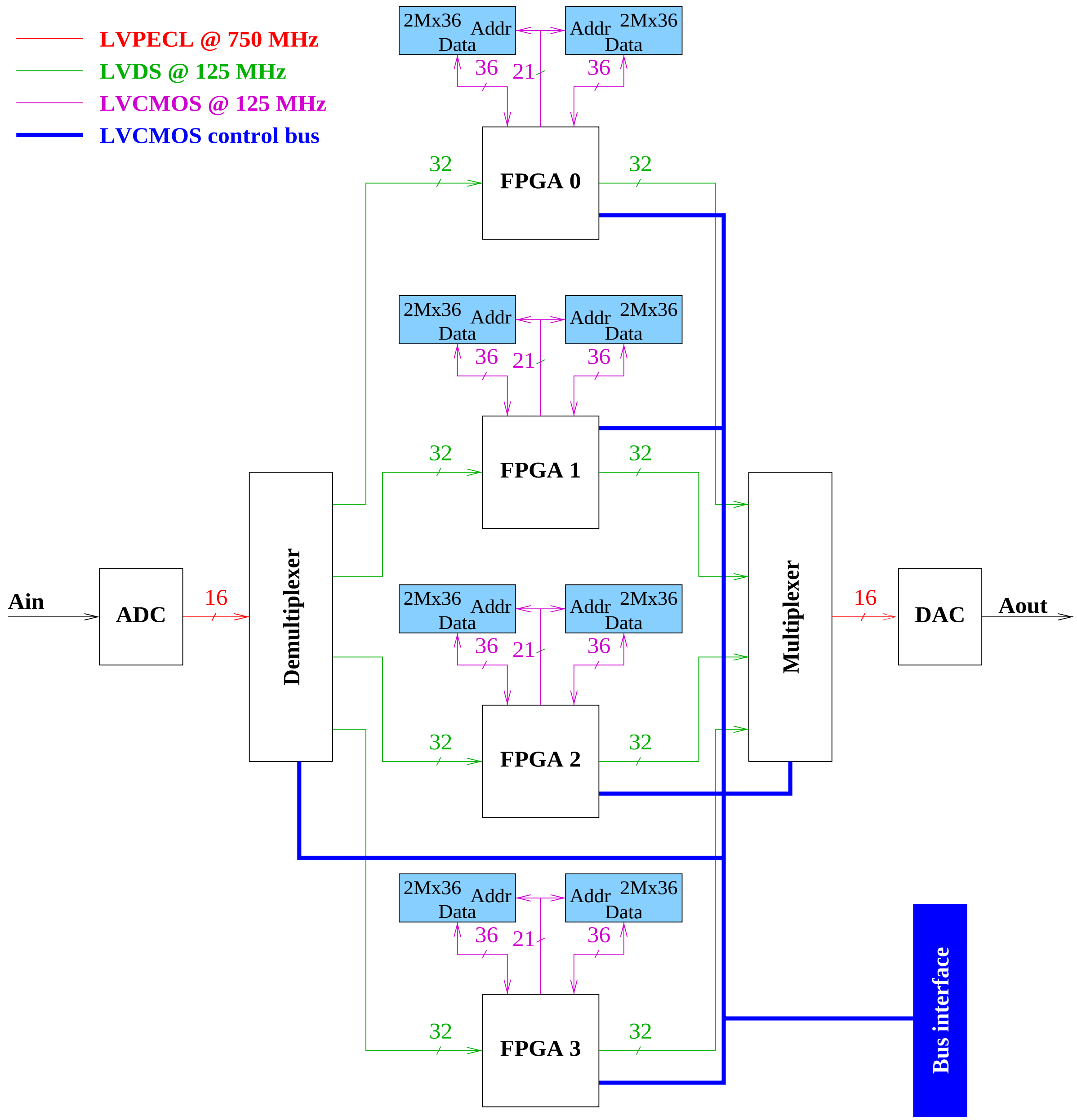
Kicker structures

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

GBoard 1.5 GS/sec. processing channel Model

- Next-generation instability control technology
- SLAC, KEK, LNF-INFN collaboration - useful at PEP-II, KEKB, DAFNE and several light sources.
- Transverse instability control
- Longitudinal instability control
- High-speed beam diagnostics (1.5 GS/sec. sampling/ throughput rate)
- Builds on existing program in instability control and beam diagnostics.
- Significant advance in the processing speed and density previously achieved.



Gproto/IGP Technology Development

The Gproto and iGp systems implement roughly 1/4 of the aggregate signal processing resources of the Gboard concept. A proof of principle technology program, with

- PEP-II - 476 MHz transverse configurable processor, beam diagnostic processor
- DAFNE - 368 MHz transverse configurable processor
- KEKB - 500 MHz 5120 bunch transverse processor
- ATF - 714 MHz longitudinal processor (run in RF/2 mode, downsampled)

Summary

DAFNE, KEK-B,CESR, PEP-II, ALS, BESSY-II, PLS, Elettra all have significant experience running multi-bunch instability control systems. All routinely operate well above instability thresholds.

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”) has been 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 these wideband feedback systems 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 technology in development (e.g. the iGP/Gboard effort) offers faster, more complex options and a path for higher current operation, new diagnostics in KEKB/DAFNE/PEP-II.

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, 714 MHz, etc.)
- DC offset removal from the processing channel (e.g. from DC synchronous phase position, or static orbit offset)
- Saturation on large input errors (injection errors, etc.)
- 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)

A possible controller design approach

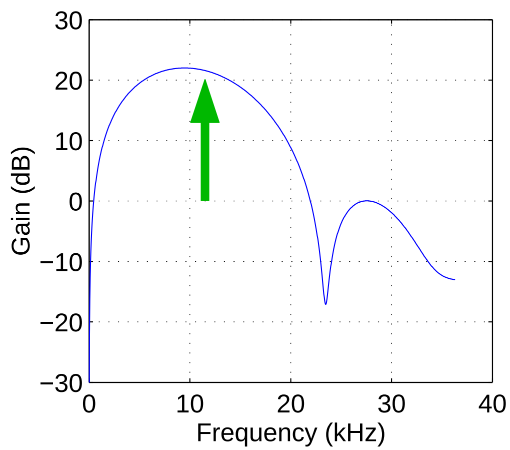
Constraints

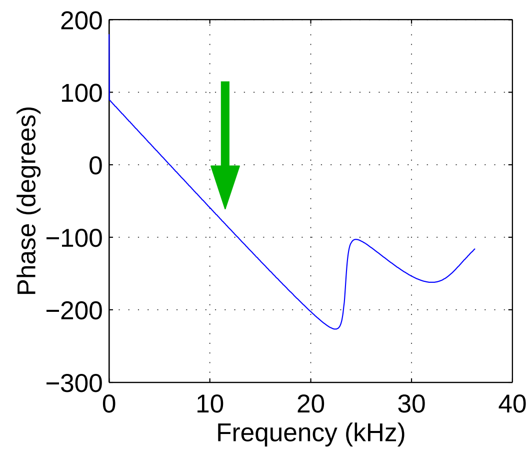
- Control of phase & gain at the synchrotron frequency F_s (90 degree phase shift)
- DC rejection
- Frequency selectivity

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 synchrotron 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

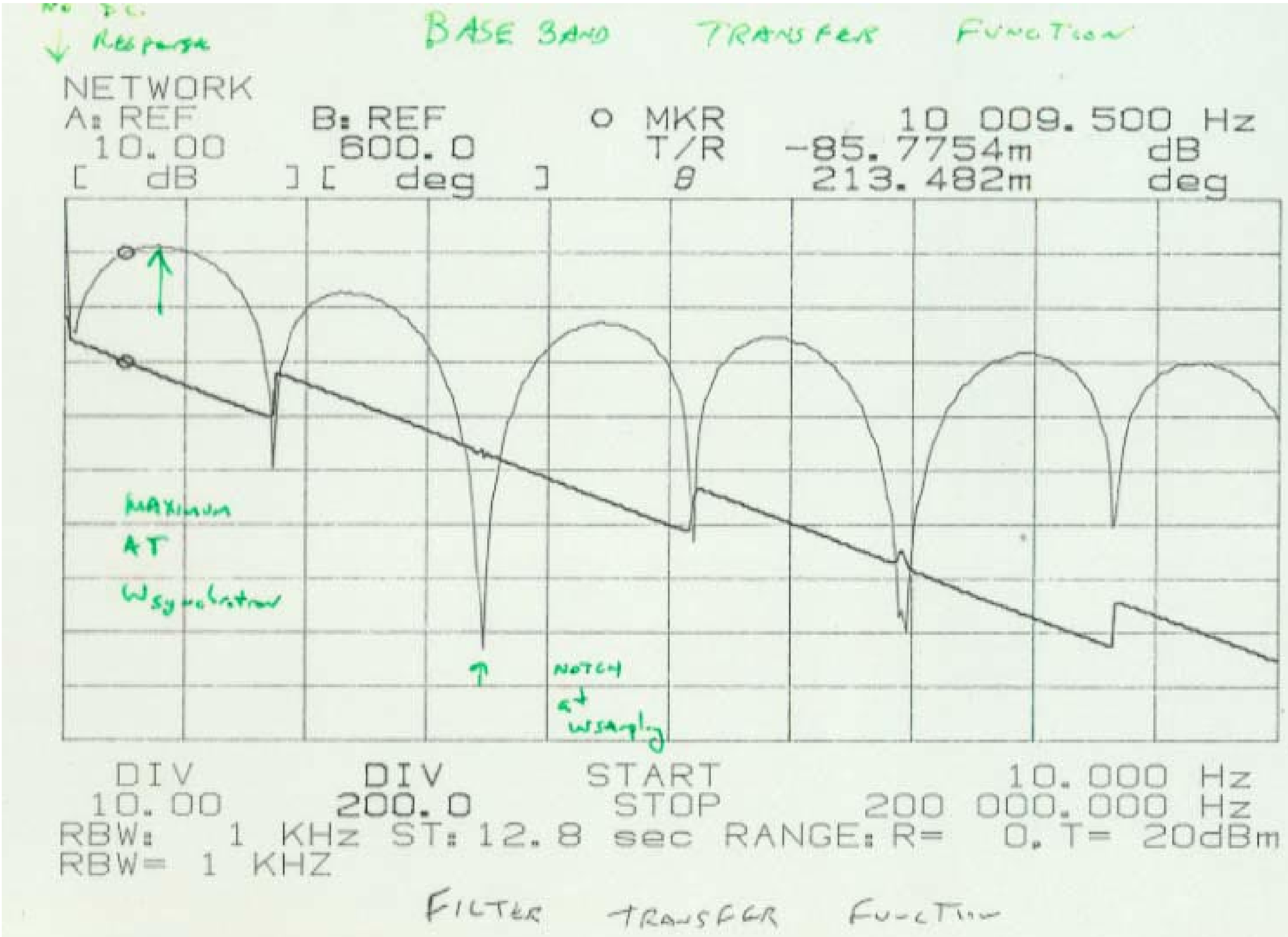




What if the oscillation frequency changes with current? (ALS, Harmonic Cavities).

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

Baseband transfer Function



RF Transfer Function