Understanding Signals from Beams - part II

Contributed to the ACAS 2016 School

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Outline

Signals from a single bunch

- pick-up signal, time domain a series of impulses
- shape related to the bunch structure and the pick-up response.

$$f(t) = \sum_{k=-\infty}^{\infty} \delta(t - kT_0), \tag{1}$$

T_0 is the revolution period of the ring.

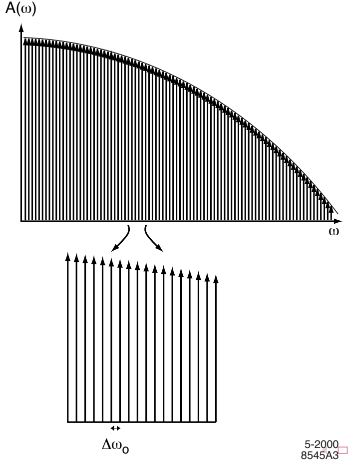
- frequency domain -line spectrum, with spacing $\Delta\omega_0 = 1/2\pi T_0$

$$F(\omega) = \int_{-\infty}^{\infty} f(t) \exp(-i\omega t) dt \tag{2}$$

$$F(\omega) = \omega_0 \sum_{m=-\infty}^{\infty} \delta(\omega - m\omega_0) \tag{3}$$

Signals from a single bunch - Frequency Domain

- Envelope related to F.T. of bunch distribution (and the pick-up response).
- typical electron storage ring, the spectrum extends to 20 GHz and beyond



Bunch Length Measurement

- Measure the spectrum of the bunch signal at two harmonics
- Requires bandwidth consistent with harmonics

Main Ring Bunch Length Monitor

K. Meisner and G. Jackson
Fermi National Accelerator Laboratory[1], Box 500, Batavia, IL 60510

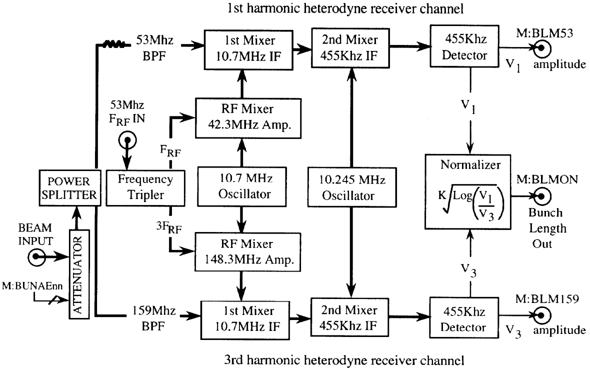


Figure 1: Bunch Length Monitor Block Diagram

Bunch Length Measurement via spectrum of superposition of two short pulses

- delay beam optical signal by τ combine with itself
- Combined spectral envelope shows bunch length (function of τ)

A NEW FREQUENCY-DOMAIN METHOD FOR BUNCH LENGTH MEASUREMENT

M. Ferianis, M. Pros, Sincrotrone Trieste, Italy and A. Boscolo, Università di Trieste-DEEI, Italy

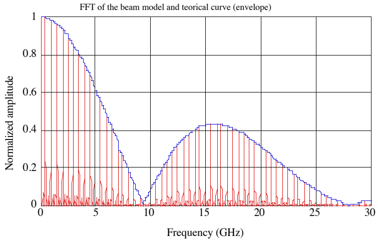


Figure : 2 Comparison between theoretical pulse and MB periodic structure pulses spectra.

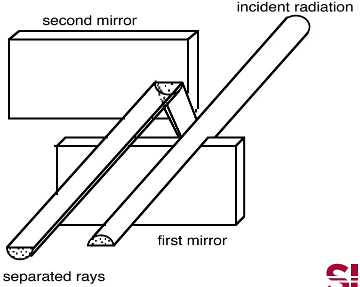


Figure : 3 Schematic of the double mirrors assembly.

Signals from a multiple bunches - Uneven fills

Identical, uniformly spaced bunches - ring looks as if it is $1/M$ smaller. Non-uniform spacing, or current variations, the time domain signal is multiplied by a modulating function $g(t)$

$$f(t) = g(t) \sum_{k=-\infty}^{\infty} \sum_{n=0}^{M-1} \delta(t - kT_0 - nT_0/M) \tag{4}$$

$$H(\omega) = G(\omega) \star F(\omega) \tag{5}$$

rectangular gap (or current variation) is multiplication with a modulating function, transform of the rectangular modulating function will be of $sin(x)/x$ form. A $sin(x)/x$ envelope will be convolved with the uniform line spectra, replicates information across many revolution harmonics

Signals from an Oscillating bunch - betatron motion

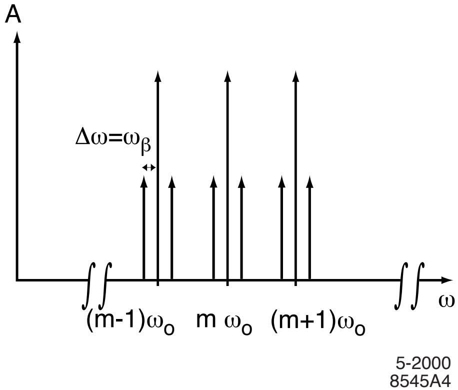
- Betatron Motion - amplitude modulation
- Position sensitive pickup

$$f(t) = A_\beta \cos(\omega_\beta t) \sum_{k=-\infty}^{\infty} \delta(t - kT_0), \tag{6}$$

frequency domain - a convolution of the cosine modulating function with bunch spectrum

$$f(\omega) = \frac{A_\beta \omega_0}{2} \sum_{m=-\infty}^{\infty} (\delta(\omega - m\omega_0 + \omega_\beta) + \delta(\omega - m\omega_0 \omega_\beta)). \tag{7}$$

Signals from an Oscillating bunch - Betatron motion



Every revolution harmonic has betatron sidebands at $\Delta\omega_\beta$ away from the revolution harmonics

Signals from an Oscillating bunch - Synchrotron motion

- Bunch oscillates about synchronous phase

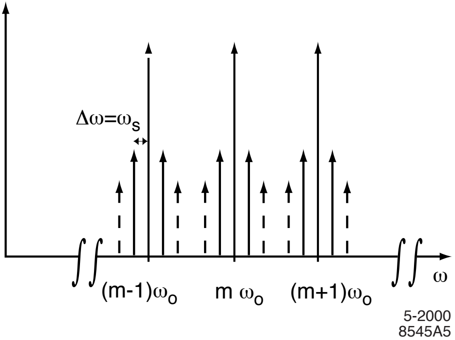
$$f(t) = \sum_{k=-\infty}^{\infty} \delta(t + \tau sin(\omega_s t + \phi) - kT_0) \tag{8}$$

phase modulation of magnitude τ at the synchrotron frequency ω_s.

$$F(\omega) = \omega_0 \sum_{l=-\infty}^{\infty} e^{il\varphi} J_l(\omega_\tau) \sum_{m=-\infty}^{\infty} \delta(\omega - l\omega_s - m\omega_0) \tag{9}$$

For small oscillation amplitudes we can just consider the lowest order terms of the Bessel functions (the l=-1,0,1 terms)

Signals from an Oscillating bunch - Synchrotron motion

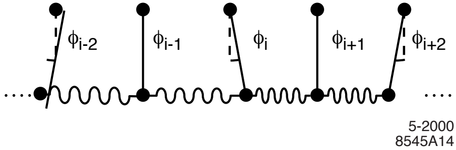


Single bunch synchrotron motion is revealed in synchrotron sidebands, each spaced $l\Delta\omega_s$ away from the revolution harmonics. $l = -1, 0, 1$ sidebands shown, for small amplitudes the higher terms fall off in amplitude. Amplitudes of l=0 and l=+1/-1 sidebands show the magnitude of the phase oscillation.

Signals from a multiple bunches- signatures of motion

Consider M coupled oscillators (bunches coupled via impedances)

- M Oscillators - M normal modes



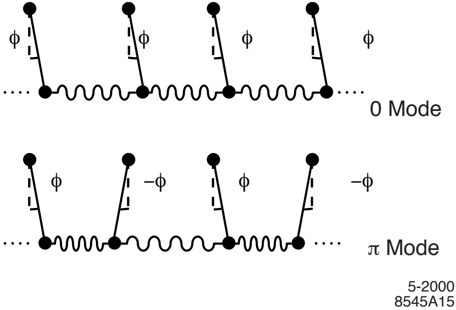
The phase between bunches is specified for each eigenmode m as

$$\Phi_i = \Phi_0 - 2\pi \frac{im}{M} \tag{10}$$

where the index i runs $i = 0, 1 ... M - 1$

Signals from a multiple bunches- signatures of motion

The lowest and highest frequency modes are 0, π between oscillators



Multiple bunch Betatron Motion Signature

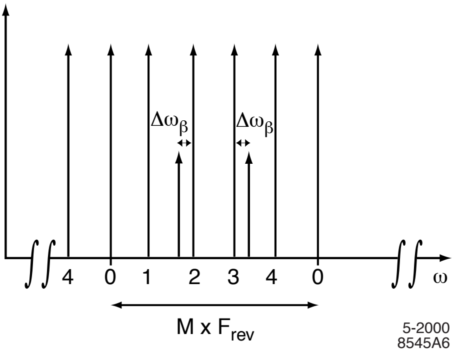
Multi-bunch betatron motion, uniform fill M identical bunches, betatron amplitude modulation

$$f(t) = \sum_{k=-\infty}^{\infty} \sum_{n=0}^{M-1} \cos(\omega_\beta t + \varphi_n)\delta(t - (kT_0 + nT_0/M)) \tag{11}$$

Frequency domain sideband information for each mode exist as an upper sideband, and a lower sideband. Across M revolution harmonics are found the spectral information for the M normal modes. The spectrum repeats this information every M revolution harmonics.

Multiple bunch Betatron Motion Signature

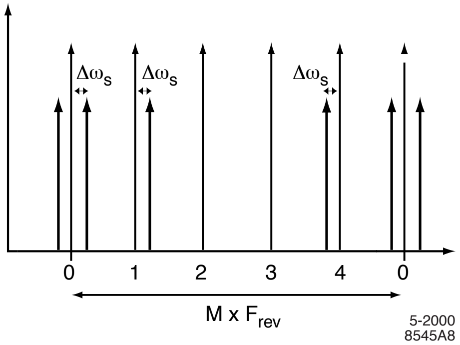
Multi-bunch betatron motion, uniform fill M identical bunches, betatron amplitude modulation



Multi-bunch betatron spectrum, for the M=5 case. Motion of mode 2 is seen as a lower sideband around the second revolution harmonic, and an upper sideband of the M-2 revolution harmonic.

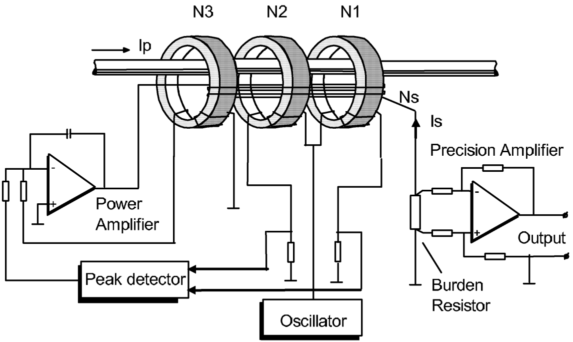
Multiple Bunch Synchrotron Motion Signature

Multi-bunch Synchrotron motion, uniform fill M identical bunches, phase modulation



Simplified spectrum for multi-bunch synchrotron motion, showing only the first-order lines. The case M=5 is shown, with motion at mode 0 and mode 1

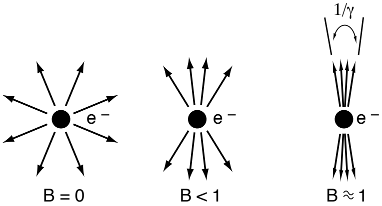
Signals From Beams - the DC current transformer

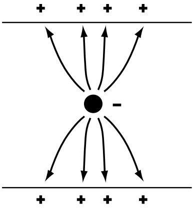


The DCCT is a feedback technique that drives a reference current to null out the beam current in a non-linear magnetic transformer

Signals from Beams

Charged particles in a conducting vacuum chamber - Lorentz contracted longitudinal E-field





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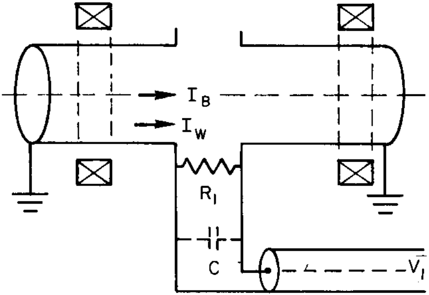
Signals From Beams - Gap Monitor

The most direct sensor for beam image charge

- measures charge in beam, longitudinal structure
- insensitive to position
- RC sets time constant, bandwidths of 5 GHz achievable

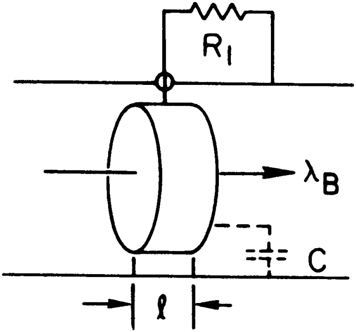


Physical implementation - spread lots of R's around circumference

Signals From Beams - Ring Electrode

Another sensor for beam image charge

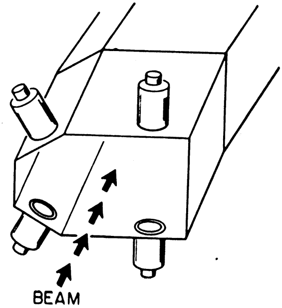
- High-pass filter response
- measures charge in beam, longitudinal structure
- insensitive to position
- RC sets time constant, bandwidths of GHz achievable

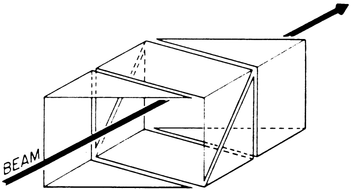


Signals From Beams - Position Monitors

Sensors for position in duct - capacitive coupling

- High-pass filter response
- RC sets time constant, bandwidths of GHz achievable

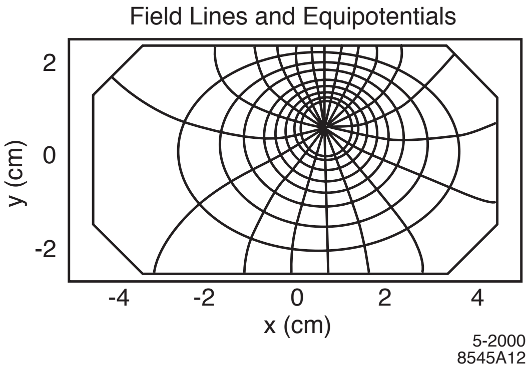




Signals From Beams - Position Monitors

Sensors for position encoded in relative amplitudes of electrode signals

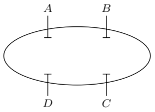
- Fields found via conformal mapping

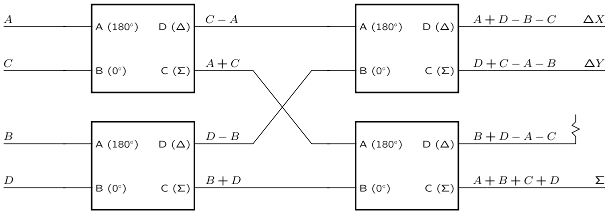


Signals From Beams - Position Monitors

Computing position - normalizing for charge

- can be processed via Delta-Sigma circuits
- Sum signal encodes current
- can use independent channels, calculate difference/sum numerically

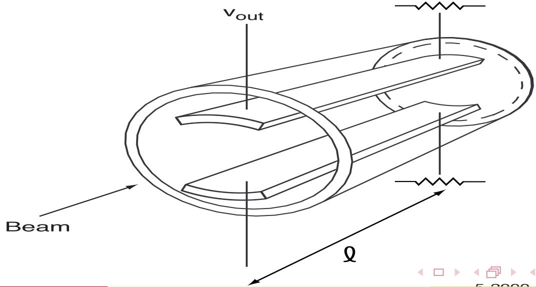




Signals From Beams - Stripline Monitors

Similar to a directional coupler

- Can be terminated, open or short circuited strips
- Signals taken on upstream port
- Signal is two impulses separated by $2L/c$
- Frequency domain - response maxima at $l = (2n+1)\frac{\lambda}{4}$
- Frequency domain - response minima at $n\lambda/2$
- Can be used as a kicker to drive the beam - feed power downstream



Cavity BPM Techniques

- Idea - excite transverse mode in cavity
- Amplitude depends on moment (charge * displacement)
- Normalize to charge via monopole mode
- Useful for nanometer sensitivity
- Examples from CLIC and LCLS (IBIC2013)

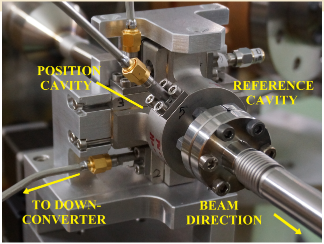


Figure 1: Prototype cavity BPM installed in TBTS.

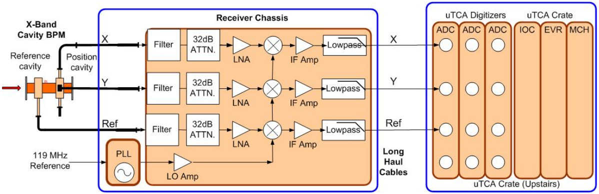


Figure 4: System block diagram. The receiver is mounted on the undulator stand while the digitizers are upstairs.

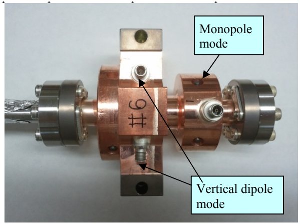
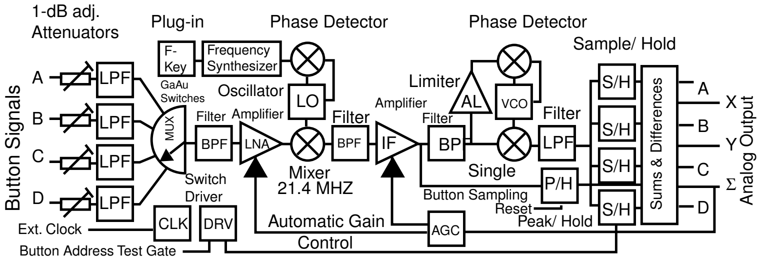


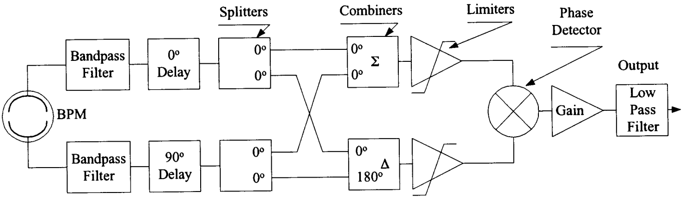
Figure 1: BPM Cavity with electric fields of position (dipole) and reference (monopole) cavities.

Signals From Beams - Frequency Domain BPM processing



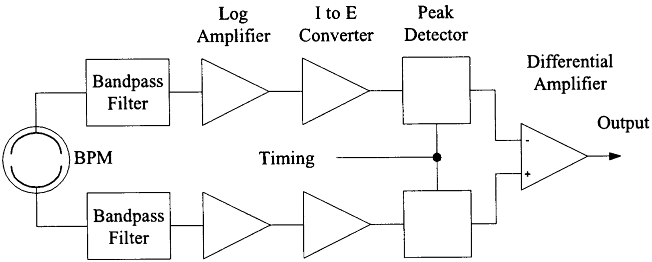
- A multiplexed system, uses single receiver to measure sequentially 4 signals.
- Measure at high harmonic of RF for pickup sensitivity
- Requires multiple turns, measures average orbit (Bergoz)
- Advantage of 1 channel (multiplexed) vs. 4 channels?

Signals From Beams - AM/PM BPM processing



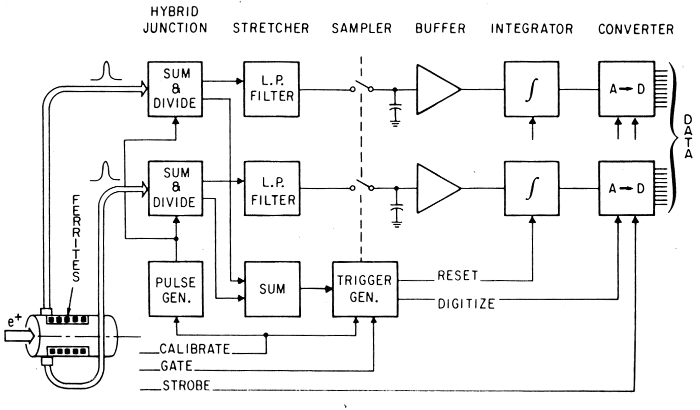
A frequency domain system, rings filter to make long quasi-cw pulse.
Measures relative amplitudes in AM-PM conversion, phase detector.
can be applied to single pulses (Tobiyama)

Signals From Beams - Log ratio BPM processing



Processing uses log technique, difference amp to compute ratio of amplitudes. Frequency domain system, can be applied to single pulses (Shafer)

Signals From Beams - Time Domain BPM processing

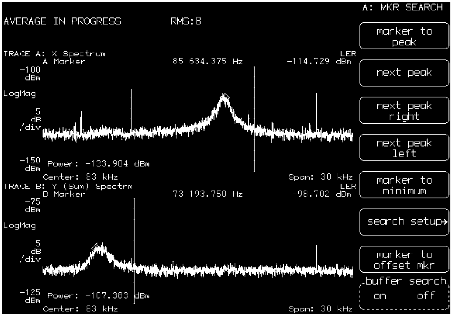


A self-timed system, uses pulse stretching gaussian filters to replicate amplitudes, sample/hold . Applicable to single pulses (Pellegrin)

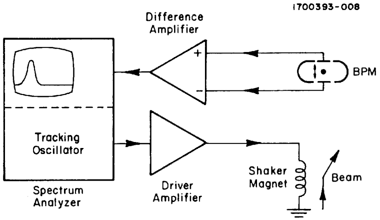
Signals From Beams - Tune measurement

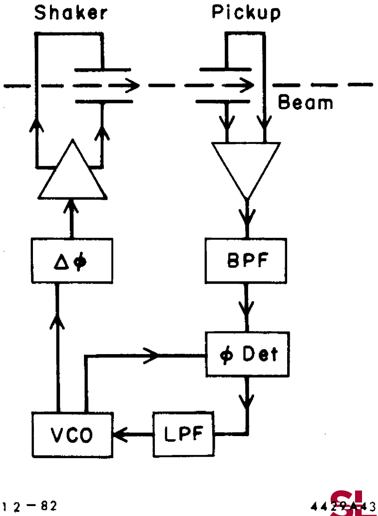
Tunes can be seen in position monitor signals

- self-excited (often in colliders)
- excited by kicker
- measure BPM response, look at betatron sideband



Signals From Beams - Excited Tune measurement

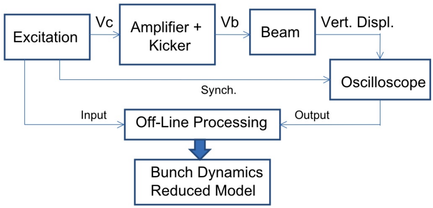




the PLL technique is useful in a tune feedback system

Modes within a single Bunch - Hadron example from SPS

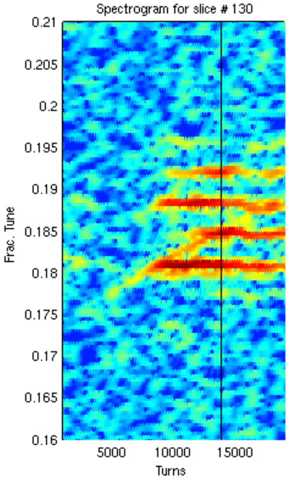
- A single bunch in the SPS, 1×10^{11}protons, 2 ns length
- Excite vertical betatron motion through GHz bandwidth excitation system
- Explore internal motion, part of feedback development program

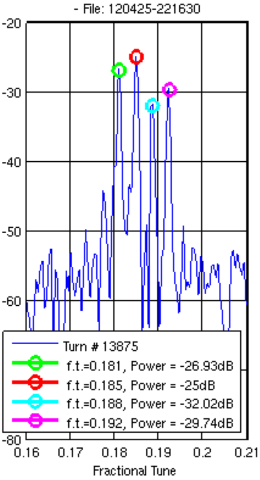


- Drive individually different areas of the bunch (Excitation - Amplifier - Kicker)
- Measure with scope the receiver signals $\Delta - \Sigma$. Estimate vertical displacement for different sections of the bunch.
- Based on Input-Output signals, estimate bunch reduced model.

Excitation of intra-bunch vertical betatron motion

- Excitation methods (chirps, random, selected modes)
- Chromaticity 0, on the verge of instability



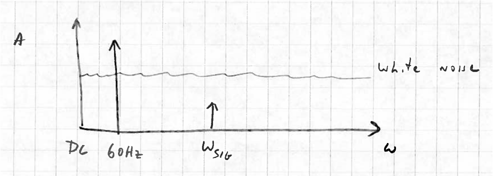


- Spectrogram of beam motion for a slice in the tail of the beam
- In looking at particular turns, we can see the relative amplitudes of the excited modes
- In this example, we see the excitation of 4 modes, from ν_{β_y} to $\nu_{\beta_y} + 3\nu_s$

Excitation of multiple internal beam modes - time domain

Additive noise and interfering Signals

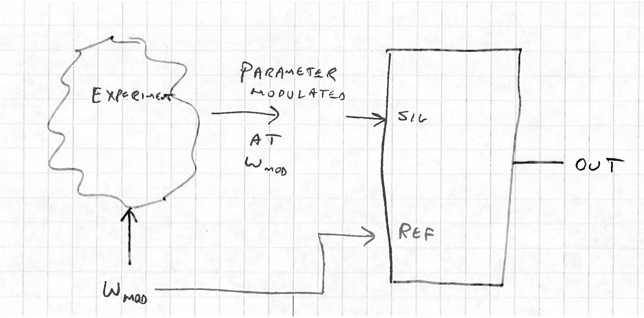
- Noise - random uncorrelated additive power
- Typically flat with frequency
  - Johnson Noise - thermal noise in resistance $V_n = \sqrt{4kTRB}$
  - Shot Noise- fluctuations in discrete charge carriers $I_n = \sqrt{2qI_{dc}B}$
  - 1/f noise (not flat with frequency)
- Every Measurement has Broadband Additive Noise
- DC Drifts, 1/f noise
- Interfering signals



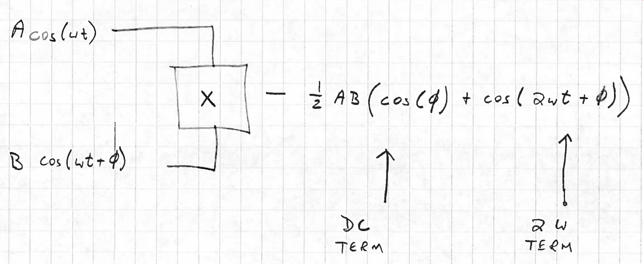
- We want to selectively amplify ω_{sig}
- Ignore other components

Synchronous Modulation

- Modulate your desired signal at a known frequency ω_{mod}
    - could be - chopping optical signals
    - directly modulating electronic signals
    - mechanically modulating signals (rocking antenna)
    - modulation - is multiplication by known modulating signal
    - Purpose - move signal of interest to a known frequency with specific phase relationship

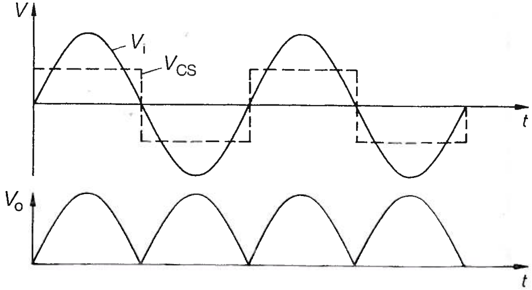


Multiplier as a Phase Detector



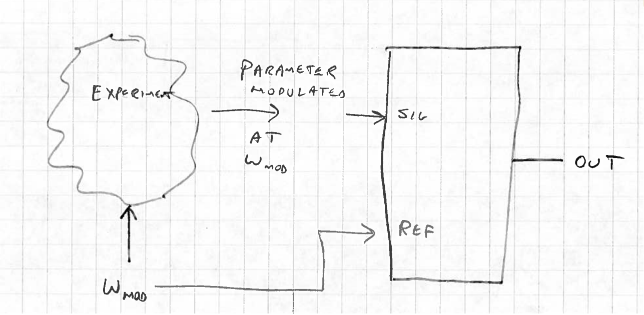
- Output contains sum and difference terms
  - filter output with low pass filter
  - only difference term (DC term) remains
  - $V_{output} = (AB)/2 \cos \phi$
  - if amplitude AB constant, output is phase detected
  - if phase constant, output is amplitude detected
- Suppose B is a square wave ω_{mod}
  - Output contains harmonics at $(2n+1)\omega_{mod}$ frequencies
  - DC term as before (plus $2/\pi$ normalization)

Multiplier as a Phase Detector - or Synchronous Rectifier



- Action of demodulation produces synchronous rectifier
  - ANY signal not at ω_{mod} averages to zero
  - Noise, interference, DC signals - average to zero
  - $V_{output} = (AB)/2 \cos \phi$
  - If $\phi = 0$ output is DC maximum positive
  - if $\phi = \pi$ output is DC negative minimum
  - if $\phi = +\pi/2$ or $-\pi/2$ output averages to zero
-

Measurement - Synchonous Modulation/Demodulation Block Diagram

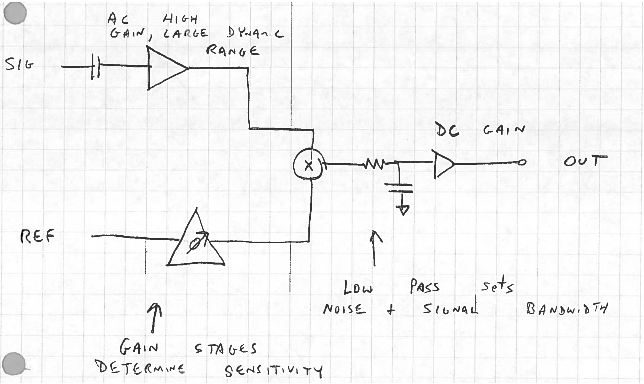


USPAS2012/

- System must be modulated by reference oscillator
- Receiver must have reference signal (frequency and phase)

Processing must amplify signal, reject noise/interference, improve Signal/Noise ratio

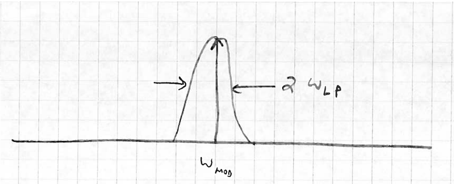
Lockin Block Diagram



- Gain stages (AC and DC) Determine sensitivity
- Low Pass sets noise and signal bandwidth
- Only noise in the limited detector bandwidth $2\omega_{lp}$ is present - this is the processing gain
- For amplitude detection, adjust phase shifter to maximize (peak up) output - can also use two channel complex receiver, no phase shifter

Lockin Essential Functions

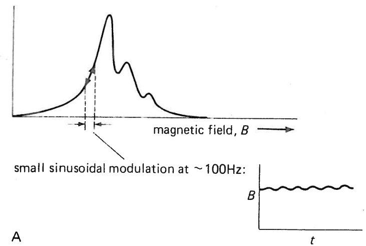
- Modulation of signal of interest with reference function
- Amplify all signals (noise, modulated signal, interference, etc.)
- Demodulate (detect) at ω_{mod} with phase sensitive detector
- Low Pass demodulated signal with low pass at ω_{lp}
- Final bandwidth - $2\omega_{lp}$ about ω_{mod}
- Noise bandwidth is reduced, only signals phase coherent with ω_{mod} remain



- Do you need a physical "box" ?
- If signals are inherently digital, no
- If signal of interest is a sequence of numbers
- Modulation must be synchronous with sampling of signal
- DSP processing- a computer program

Using Synchronous Demodulation for a feedback signal

- Modulation (dithering) of signal of interest with reference function
- Recover signal via amplification, demodulation, bandwidth reduction
- Use derivative of signal as feedback error discriminant



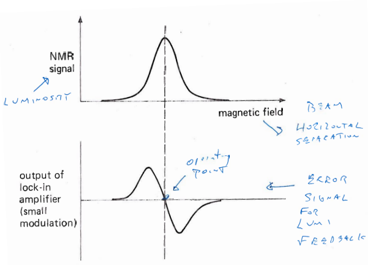
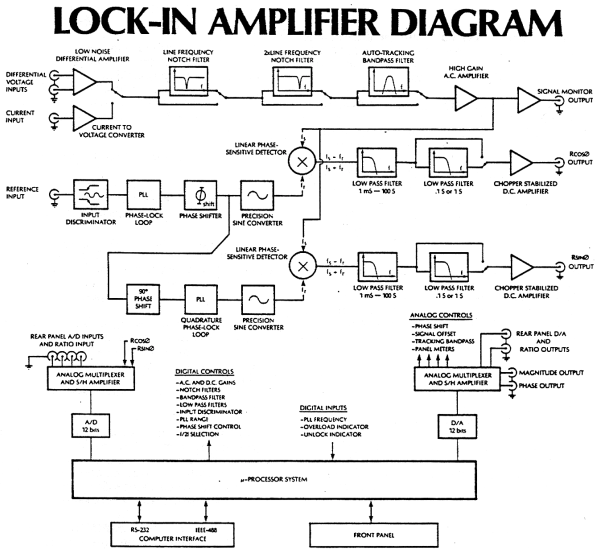


Figure 15.40. Line shape differentiation resulting from lock-in detection.

SRS 530 Analog Lockin Block Diagram

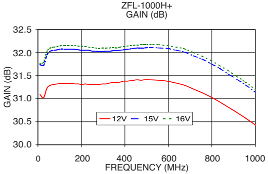


- Commercial analog general purpose
- Two Channel (complex) processing
- no phase shifter to peak up
- output magnitude is $\sqrt{real^2 + imag^2}$

Amplifiers - are they LTI systems?


ZFL-1000HX(+)


ZFL-1000H(+)

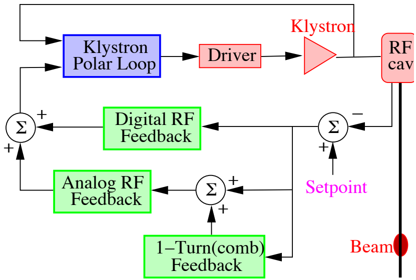


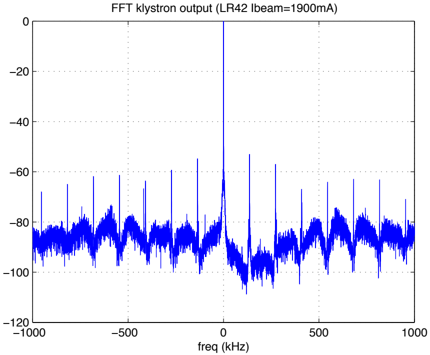

RE Model Shown

Can you determine the time domain behavior from network analyzer data?

	Parameter	Specification @ 25º C
Electrical		
1	Frequency Range	20 – 1000 MHz
2	Saturated Output Power	120 Watts rated
3	Power Output @ 1dB Comp.	70 Watts min
4	Small Signal Gain	+52 dB min
5	Small Signal Gain Flatness	± 2.0 dB max
6	IP_3	+55 dBm typical
7	Input VSWR	2:1 max
8	Harmonics	-20 dBc typical @ 70 Watts
9	Spurious Signals	< -60 dBc typical @ 70 Watts
10	Input/Output Impedance	50 Ohms nominal
11	AC Input Power	1500 Watts max
12	AC Input	100 – 240 VAC, single phase
13	RF Input	0 dBm max
14	RF Input Signal Format	CW/AM/FM/PM/Pulse
15	Class of Operation	AB

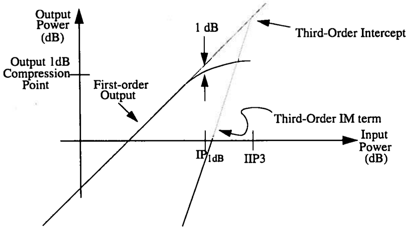
Impedance-Controlled LLRF architecture (LHC Example)

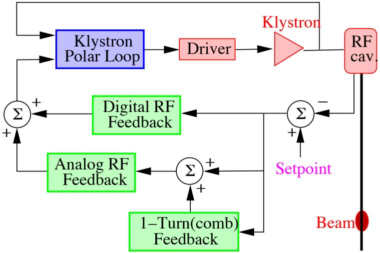




A feedback technique where the beam-induced signals are cancelled through the direct and comb loops, so that the effective impedance seen by the beam in reduced. Dynamic range of signals within the loop is 90 dB or more.

What does Linearity have to do with this?

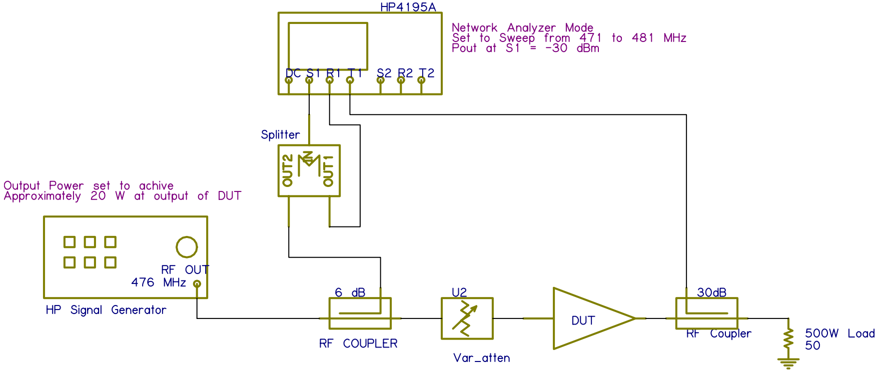




The third-order intercept (IP3) is a common amplifier specification for communications purposes. Two equal amplitude signals at frequencies ω_1 and ω_2 are applied, the nonlinear product terms $2\omega_1 \pm \omega_2$ and $\omega_1 \pm 2\omega_2$ are measured vs input power. Data is available - is this a useful test for a LLRF amp in the block diagram?

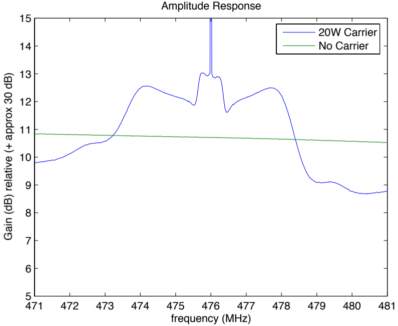
What is the IP3 for an LTI amplifier?

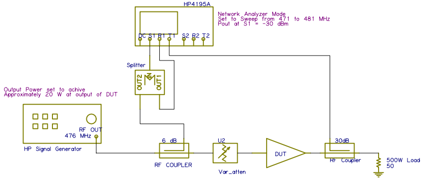
A little knowledge is a dangerous thing

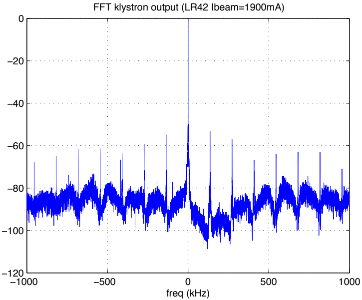


Measuring small-signal transfer function in the presence of a large-signal carrier

Does the carrier impact the small-signal frequency response? Test a 50W amplifier

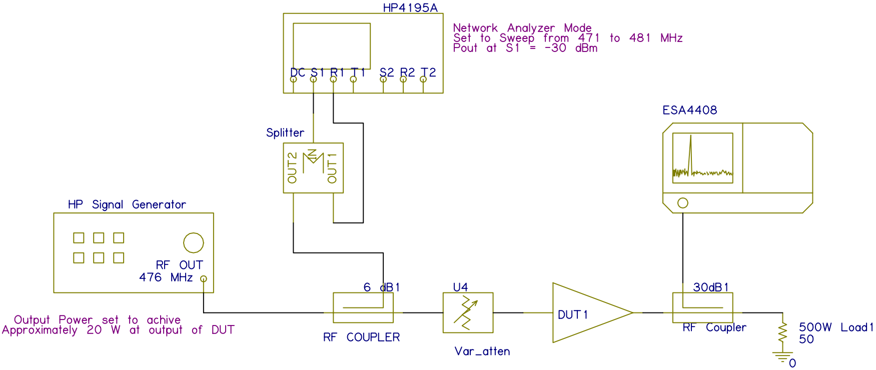






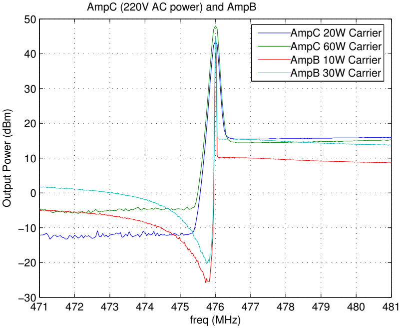
Is this a useful amplifier for a LLRF amp within the feedback loop? What impact does this behavior have?

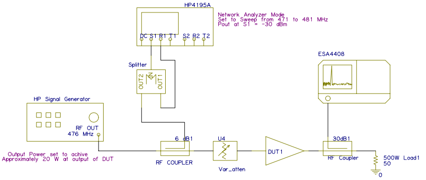
A little knowledge is a dangerous thing



Measuring image responses from a two tone test (large signal carrier, swept small signal)

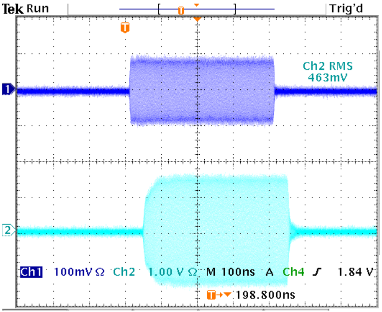
Does the carrier impact the image frequencies? Test a 50W amplifier

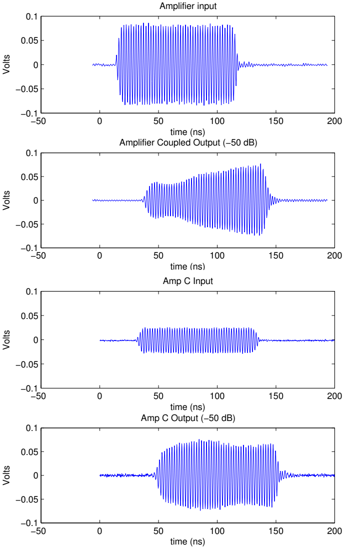




Is this a useful amplifier for a LLRF amp within the feedback loop? What impact does this behavior have?

LTI ideas, time and frequency domains





Does the small-signal frequency response tell you the large-signal pulse response? Is this an LTI system?

Summary

- Time and frequency domains, transforms
- LTI formalism - but are accelerator systems LTI?
- Oscilloscopes, Spectrum analyzers (Network Analyzers, too)
- Signals from Bunched Beams
- Ideas on pickups and kickers
- Common Control Room needs - tune measurements
- Current Measurement - the DDCT

To learn more, look at the various courses of the USPAS (US Particle Accelerator School) , the CERN Accelerator School, the course proceedings from the US-Japan-Russia-CERN accelerator schools, also in the Beam Instrumentation Workshop (BIW) and DIPAC proceedings. The JACOW website has all sorts of reference material from PAC, EPAC, APAC and IPAC meetings, as well topical meetings on Accelerator Science and Technology

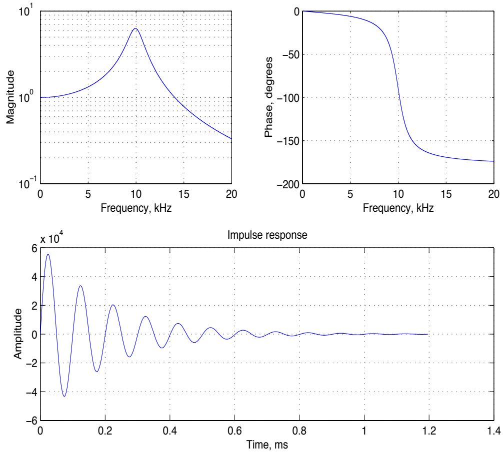
Acknowledgements

It has been a pleasure to think about these issues of Signals from Beams with colleagues from many labs, who have all contributed to this talk in their expertise. I particularly want to thank J-L Pellegrin, F. Pedersen, M. Serio, D. Teytelman, and M. Tobiyama for their contributions to the field and for so many fun hours in the control room doing interesting measurements and so freely sharing their expertise with young scientists.

Harmonic Oscillators, a review

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 $\dot{x}$



Parallel RLC Circuit

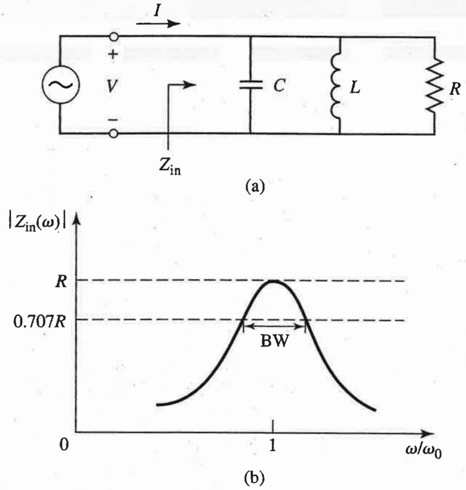
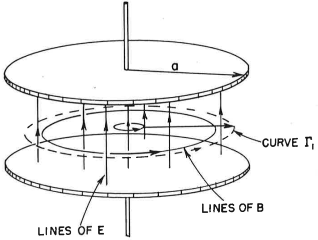
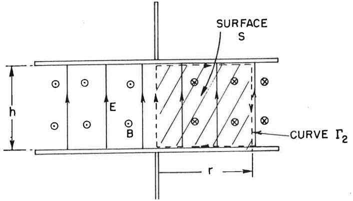


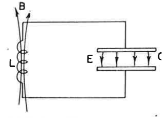
FIGURE 6.2 A parallel RLC resonator and its response. (a) The parallel RLC circuit. (b) The input impedance magnitude versus frequency.

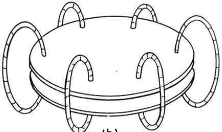
Fields in a capacitor



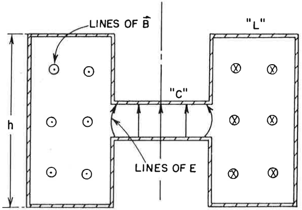


turn an RLC into a cavity

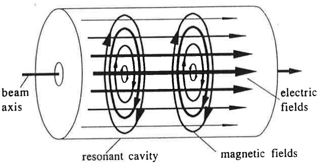




(b)



Use RF cavities in a LINAC



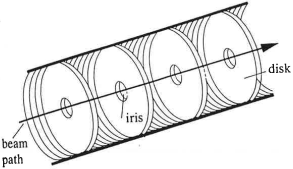


Fig. 2.8. Disk loaded accelerating structure for an electron linear accelerator (schematic)

- A time varying Electric (Magnetic) field
- Why? at resonance build up very large voltage
- Fields oscillate at resonance frequency
- To accelerate - particles must arrive at proper time
- How do you get the RF in?