IBIC 2012 - Learning From Beams

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Stanford Linear Accelerator Center
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Outline

Common Control Room Measurements

- Particle Currents
  - Total
  - Current distribution (bunch by bunch currents)
- Orbits
- Tunes
  - Betatron
  - Synchrotron
- Bunch Profile
  - Transverse
  - Longitudinal
- Bunch Motion, Signatures of Instabilities

Time and Frequency Domains

Fourier transforms

A function f(x) may be Fourier transformed into a function F(s),

$$F(s) = \int_{-\infty}^{\infty} f(x) e^{-i2\pi xs} dx \tag{1}$$

and likewise a function F(s) can be transformed into a function f(x)

$$f(x) = \int_{-\infty}^{\infty} F(s) e^{i2\pi xs} ds \tag{2}$$

The Laplace transform is related to the Fourier Transform but involves an integral from 0 to infinity

Time and Frequency Domains

Discrete Fourier Transform

For systems involving discrete samples of data, such as from sampling circuits or from samples taken from circulating bunches, the discrete-time Fourier transform is similar

$$F(\nu) = \frac{1}{N} \sum_{\tau=0}^{N-1} f(\tau) e^{-i2\pi(\nu/N)\tau} \tag{3}$$

$$f(\tau) = \sum_{\nu=0}^{N-1} F(\nu) e^{i2\pi(\nu/N)\tau} \tag{4}$$

There is a related transform, the Z transform, which is the discrete-time equivalent of the Laplace transform

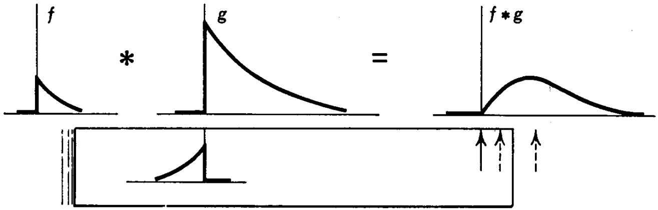
Time and Frequency Domains

Convolution of two functions

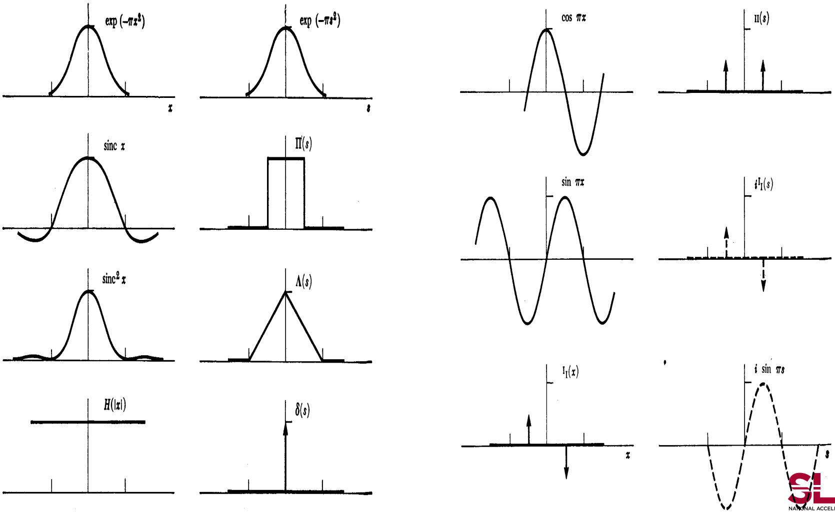
The convolution of two functions f(x) and g(x) is defined as $f(x) \star g(x)$

$$f(x) \star g(x) = \int_{-\infty}^{\infty} f(u) g(x-u) du \tag{5}$$

In pictorial form



Common Transform Pairs (from Bracewell)



Linear Time Invariant Systems

If a system converts an input $u(t)$ into an output $y(t)$

$$y(t) = L\left[u(t)\right] \tag{6}$$

the system is linear if for two constants a1 and a2

$$L\left[a_1 u_1 + a_2 u_2\right] = a_1 L\left[u_1(t)\right] + a_2 L\left[u_2(t)\right]. \tag{7}$$

The response of two inputs is the superposition of the individual outputs. If an input is only a single frequency ω, the output can only contain that single frequency ω.

Linear Time Invariant Systems

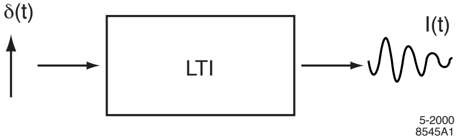
A system is time invariant if for a time delay δ the output has shift invariance, or that

$$L\left[u(t)\right] = y(t) \tag{8}$$

$$L\left[u(t-\delta)\right] = y(t-\delta) \tag{9}$$

Impulse response of LTI system

The impulse response $I(t)$ of a system is found by exciting the system with a δ-function in the time domain.

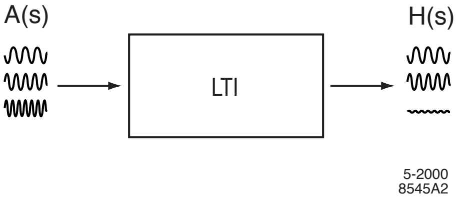


for a general input $u(t)$ the output is a convolution

$$y(t) = u(t) \star I(t) \tag{10}$$

Frequency Response of LTI system

Frequency response $H(s)$ is the transfer function in the frequency domain. Measured by network analyzer via magnitude and phase vs. frequency.



For a general input in the frequency domain $I(s)$ the output $O(s)$ is the product

$$O(s) = H(s)I(s) \tag{11}$$

Frequency Response and Time Response relationship

The time response is also the inverse transform of the product of the Fourier transform of the input $u(t)$ and the frequency response $H(s)$

$$y(t) = u(t) * I(t) \tag{12}$$

$$y(t) = IFT\left[FT(u(t))H(s)\right] \tag{13}$$

For an LTI system, we can measure in either domain, and compute the response via appropriate convolutions, transforms or inverse transforms

The sampling function Ш

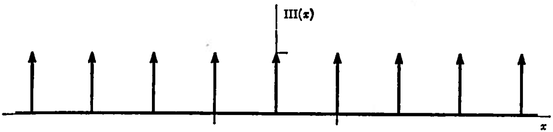


Fig. 5.4 The shah symbol Ш(*x*).

$$Ш(x) = \sum_{n=-\infty}^{n=\infty} \delta\left(x-n\right)$$

The Ш is its own Fourier Transform

$$Ш(S) = \sum_{n=-\infty}^{n=\infty} \delta\left(S-n\right)$$

For a sampling rate τ

$$Ш(S) = 1/\tau \sum_{n=-\infty}^{n=\infty} \delta\left(S-n/\tau\right)$$

The sampling function Ш multiplied by a waveform

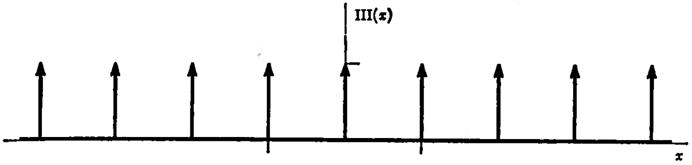


Fig. 5.4 The shah symbol III(*x*).

$$Ш(x) = \sum_{n=-\infty}^{n=\infty} \delta(x-n)$$

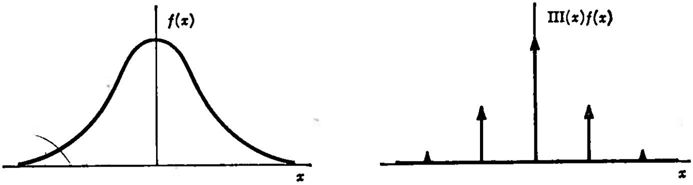


Fig. 5.5 The sampling property of III(*x*).

The sampling function Ш convolved with a spectrum (replicating property)

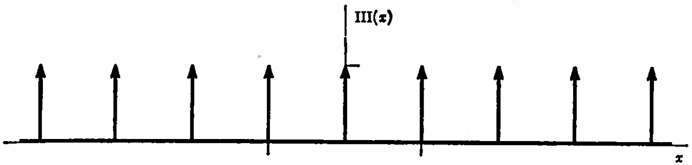


Fig. 5.4 *The shah symbol* III(x).

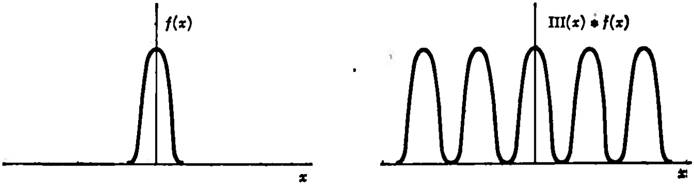
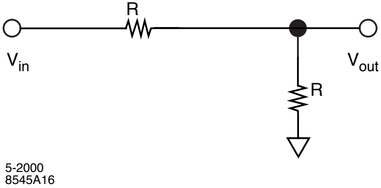


Fig. 5.6 *The replicating property of* III(x).

A Quiz on LTI Systems

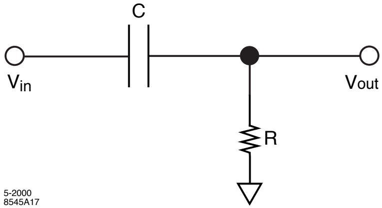
Consider this simple circuit - a voltage divider



Is this an LTI system? Is it ALWAYS an LTI system?

A Quiz on LTI Systems

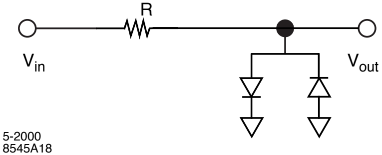
Consider this simple circuit - a high-pass filter



Here the output is frequency dependent. Is this an LTI system?

A Quiz on LTI Systems

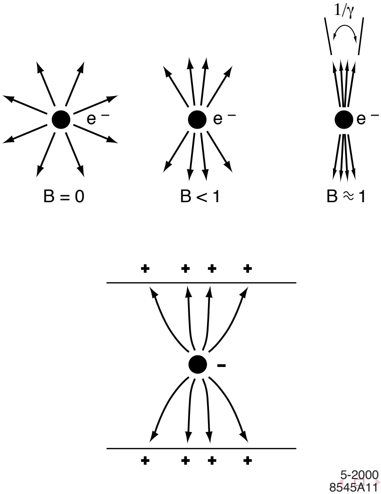
Consider this simple circuit - a diode clipper (a limiter)



Is this an LTI system? When? What output frequencies are present for an input at ω?. Two signals ω_1 and ω_2? Does it have an Impulse Response $I(t)$?

Signals from Beams

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



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.

$$f(t) = \sum_{k=-\infty}^{\infty} \delta(t - kT_0), \quad (14)$$

T_0 is the revolution period of the ring.

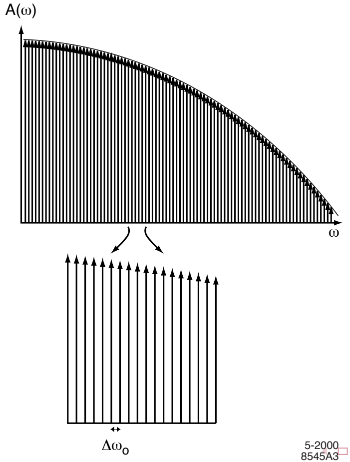
- frequency domain -line spectrum, with spacing $\Delta\omega_0 = 1/2\pi T_0$

$$F(\omega) = \int_{-\infty}^{\infty} f(t) \exp(-i\omega t) dt \quad (15)$$

$$F(\omega) = \omega_0 \sum_{m=-\infty}^{\infty} \delta(\omega - m\omega_0) \quad (16)$$

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

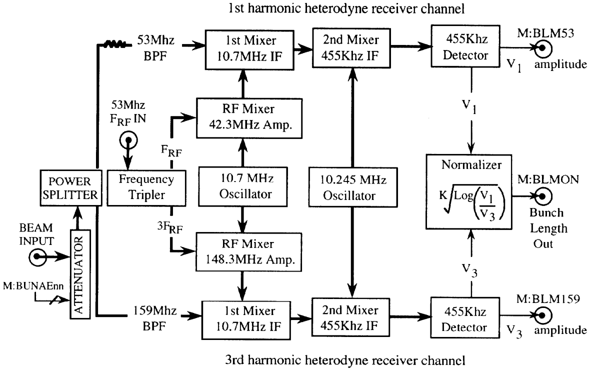


Figure 1: Bunch Length Monitor Block Diagram

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

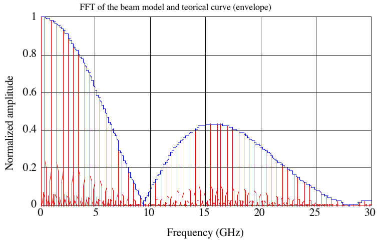


Figure : 2 Comparison between theoretical pulse and MB periodic structure pulses spectra.

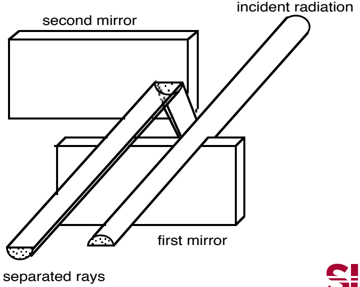


Figure : 3 Schematic of the double mirrors assembly.

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 $g(t)$

$$f(t) = g(t) \sum_{k=-\infty}^{\infty} \sum_{n=0}^{M-1} \delta(t - kT_0 - nT_0/M) \quad (17)$$

$$H(\omega) = G(\omega) \star F(\omega) \quad (18)$$

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

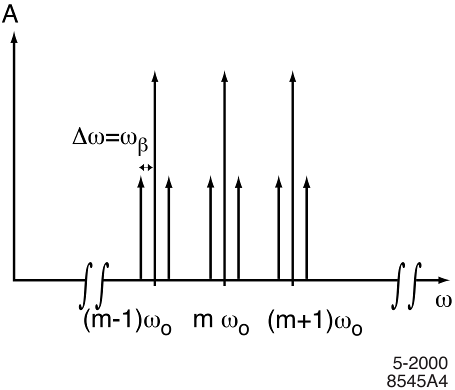
- Betatron Motion - amplitude modulation
- Position sensitive pickup

$$f(t) = A_\beta \cos(\omega_\beta t) \sum_{k=-\infty}^{\infty} \delta(t - kT_0), \tag{19}$$

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

$$f(\omega) = \frac{A_\beta \omega_0}{2} \sum_{m=-\infty}^{\infty} (\delta(\omega - m\omega_0 + \omega_\beta) + \delta(\omega - m\omega_0 \omega_\beta)). \tag{20}$$

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

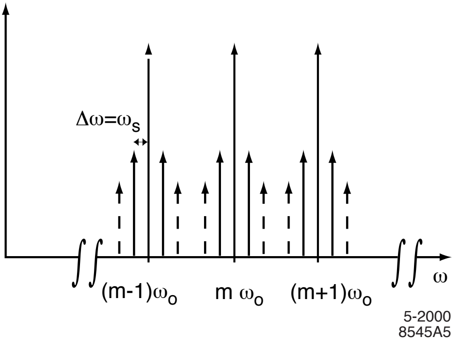
$$f(t) = \sum_{k=-\infty}^{\infty} \delta(t + \tau sin(\omega_s t + \phi) - kT_0) \tag{21}$$

phase modulation of magnitude τ at the synchrotron frequency ω_s.

$$F(\omega) = \omega_0 \sum_{l=-\infty}^{\infty} e^{il\varphi} J_l(\omega_\tau) \sum_{m=-\infty}^{\infty} \delta(\omega - l\omega_s - m\omega_0) \tag{22}$$

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

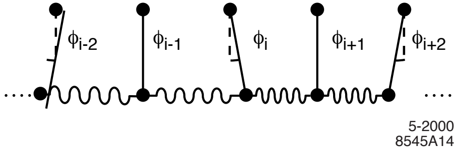


Single bunch synchrotron motion is revealed in synchrotron sidebands, each spaced $l \Delta\omega_s$ away from the revolution harmonics. $l = -1, 0, 1$ sidebands shown, for small amplitudes the higher terms fall off in amplitude. Amplitudes of l=0 and l=+1/-1 sidebands show the magnitude of the phase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

Signals from a multiple bunches- signatures of motion

Consider M coupled oscillators (bunches coupled via impedances)

- M Oscillators - M normal modes



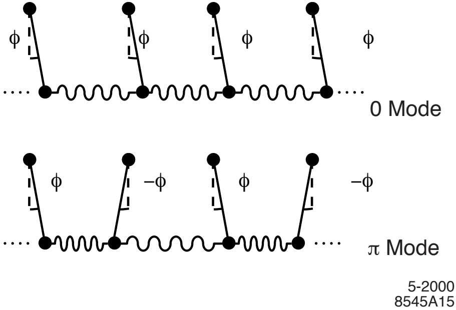
The phase between bunches is specified for each eigenmode m as

$$\Phi_i = \Phi_0 - 2\pi \frac{im}{M} \quad (23)$$

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

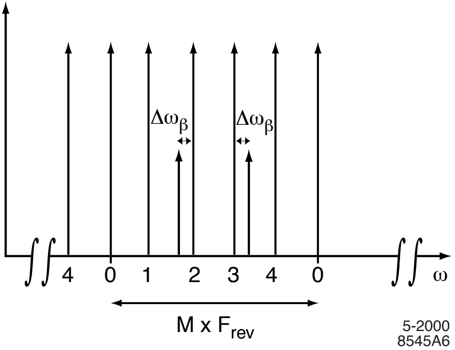
Multi-bunch betatron motion, uniform fill M identical bunches, betatron amplitude modulation

$$f(t) = \sum_{k=-\infty}^{\infty} \sum_{n=0}^{M-1} \cos(\omega_\beta t + \varphi_n)\delta(t - (kT_0 + nT_0/M)) \qquad (24)$$

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

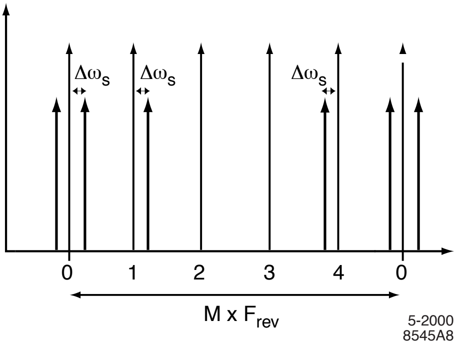
Multi-bunch betatron motion, uniform fill M identical bunches, betatron amplitude modulation



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

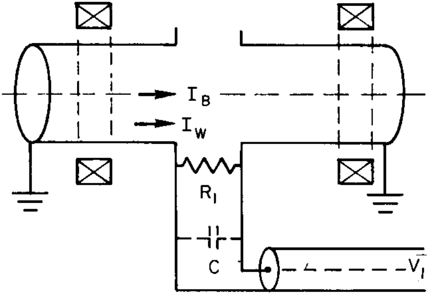


Simplified spectrum for multi-bunch synchrotron motion, showing only the first-order lines. The case M=5 is shown, with motion at mode 0 and mode 1

Signals From Beams - 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

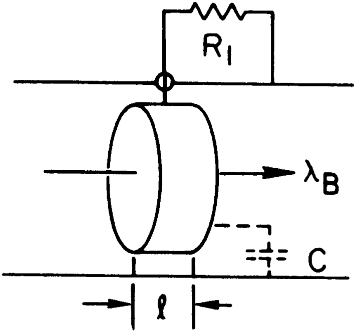


Physical implementation - spread lots of R's around circumference

Signals From Beams - Ring Electrode

Another sensor for beam image charge

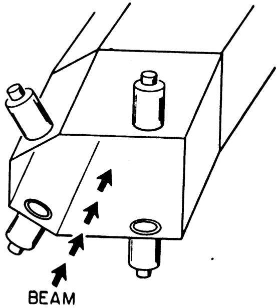
- High-pass filter response
- measures charge in beam, longitudinal structure
- insensitive to position
- RC sets time constant, bandwidths of GHz achievable

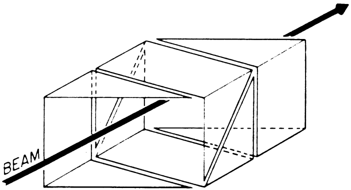


Signals From Beams - Position Monitors

Sensors for position in duct - capacitive coupling

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

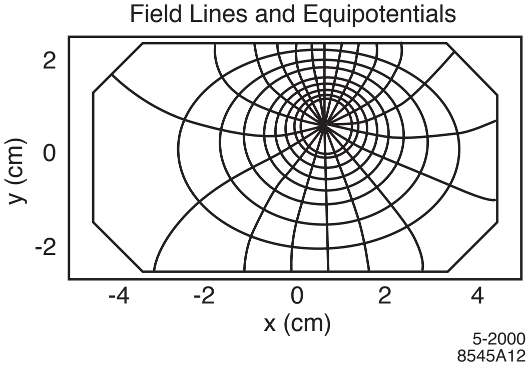




Signals From Beams - Position Monitors

Sensors for position encoded in relative amplitudes of electrode signals

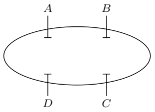
- Fields found via conformal mapping

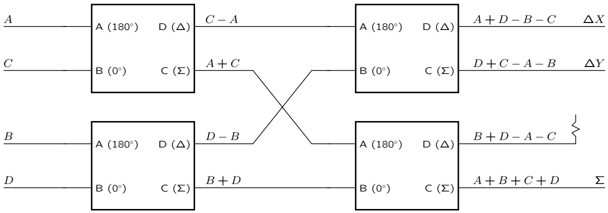


Signals From Beams - Position Monitors

Computing position - normalizing for charge

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

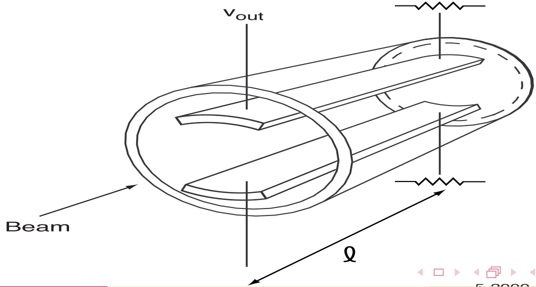




Signals From Beams - Stripline Monitors

Similar to a directional coupler

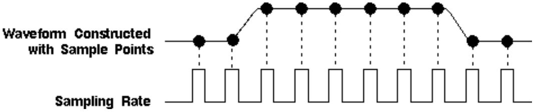
- Can be terminated, open or short circuited strips
- Signals taken on upstream port
- Signal is two impulses separated by $2L/c$
- Frequency domain - response maxima at $l = (2n+1)\frac{\lambda}{4}$
- Frequency domain - response minima at $n\lambda/2$
- Can be used as a kicker to drive the beam - feed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



Common Control Room Instrumentation

Most control rooms contain a mix of commercial, general purpose instruments and lab-designed, specialized instruments

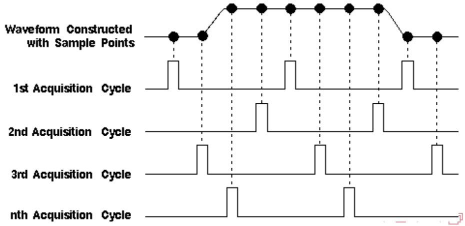
- Real-Time Oscilloscopes
  - Digital or analog
  - Data taken in single continuous triggered sweep
  - Bandwidth to 2 - 8 GHz Common (gets expensive)
  - Resolution (dynamic range) 40 - 50 DB



Common Control Room Instrumentation

Higher bandwidths can be achieved by taking several passes through the data

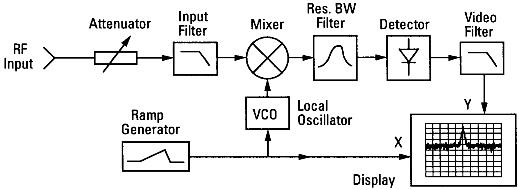
- Equivalent-Time (sampling) Oscilloscopes
  - Digital or analog
  - Data taken over multiple triggered sweeps
  - Bandwidth to 50 + GHz Common (gets expensive)
  - Requires repetitive waveform
  - STABLE trigger (what is risetime on logic signal?)
  - Resolution of sampler, averaging improves SNR
  - Related to boxcar integrator



Common Control Room Instrumentation

Spectrum Analyzer and Frequency domain

- Tuned radio Receiver
  - analog heterodyned receiver with multiple IF stages
  - Dynamic Range up to 120dB or more
  - Bandwidth to 50 + GHz Common (gets expensive)
  - Requires periodic waveform
  - Can be set zero span, triggered sweep
  - Intrinsic relationship between resolution bandwidth, sweep time



Common Control Room Instrumentation

Spectrum Analyzer and Frequency domain

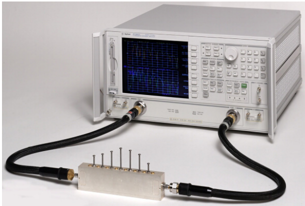
- FFT (Fast Fourier Transform) spectrum analyzers
  - Time domain sampling data acquisition
  - Bandwidth to 10's MHz Common (gets expensive)
  - FFT Band can be heterodyned from higher band
  - Numeric computation of DFT
  - Intrinsic relationship between resolution, sampling rate, length of sequence bandwidth
  - Make pretty waterfall displays

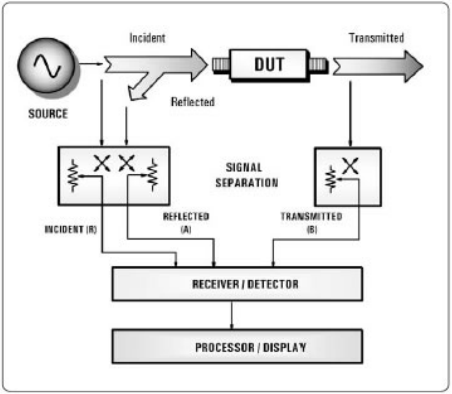
SLAC NATIONAL ACCELERATOR LABORATORY

Common Control Room Instrumentation

Network Analyzer - tool of frequency domain measurement

- Swept excitation, swept complex receiver
- Measures ratio of incident and reflected, incident and transmitted
- S parameter (Scattering Matrix) representation

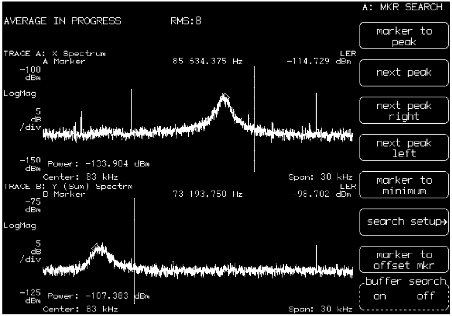




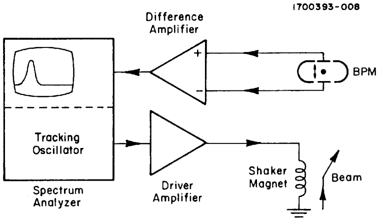
Signals From Beams - Tune measurement

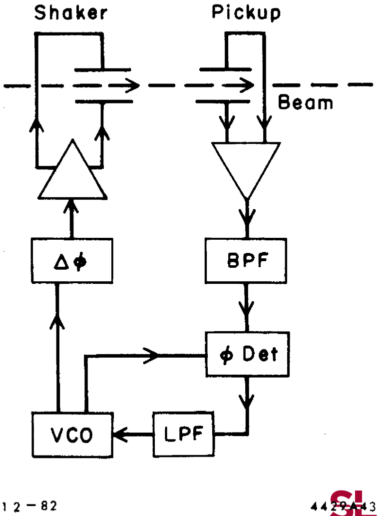
Tunes can be seen in position monitor signals

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



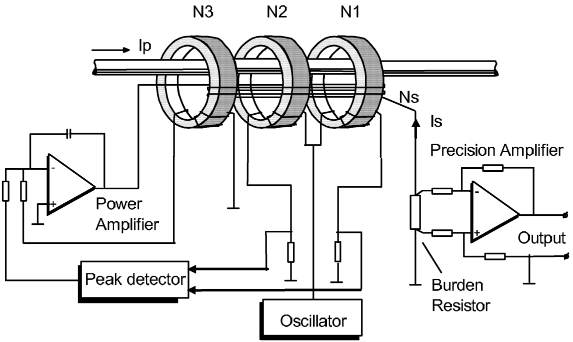
Signals From Beams - Excited Tune measurement





the PLL technique is useful in a tune feedback system

Signals From Beams - the DC current transformer

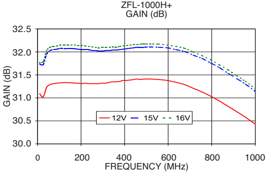


The DCCT is a feedback technique that drives a reference current to null out the beam current in a non-linear magnetic transformer

Amplifiers - are they LTI systems?

ZFL-1000HX(+)

ZFL-1000H(+)

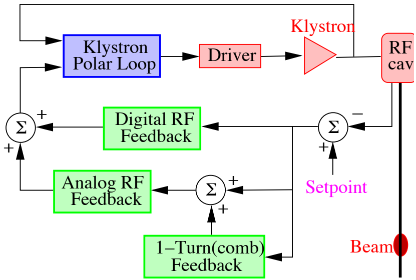


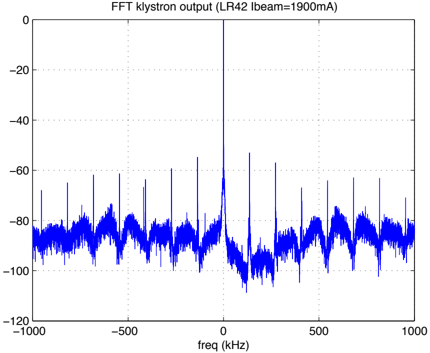
RE Model Shown

	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

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

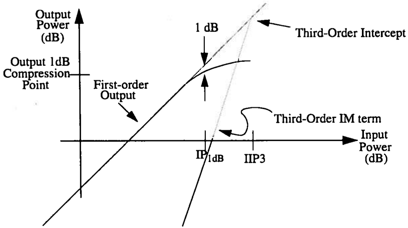
Impedance-Controlled LLRF architecture (LHC Example)

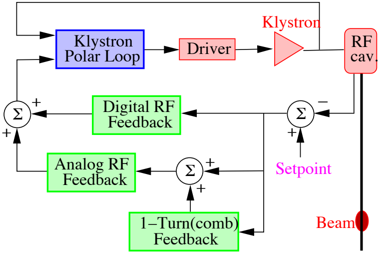




A feedback technique where the beam-induced signals are cancelled through the direct and comb loops, so that the effective impedance seen by the beam in reduced. Dynamic range of signals within the loop is 90 dB or more.

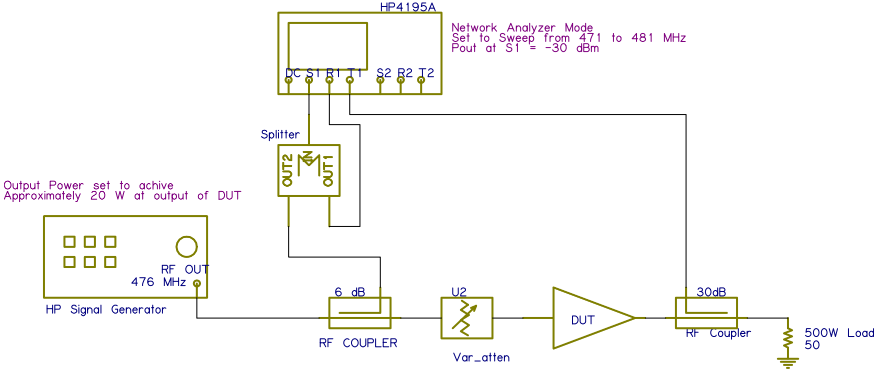
What does Linearity have to do with this?





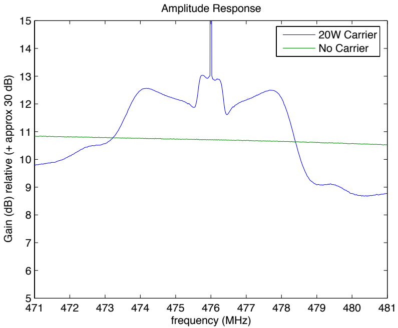
The third-order intercept (IP3) is a common amplifier specification for communications purposes. Two equal amplitude signals at frequencies ω_1 and ω_2 are applied, the nonlinear product terms $2\omega_1 \pm \omega_2$ and $\omega_1 \pm 2\omega_2$ are measured vs input power. Data is available - is this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

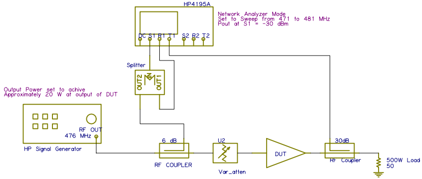
A little knowledge is a dangerous thing

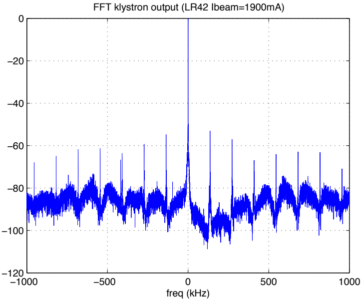


Measuring small-signal transfer function in the presence of a large-signal carrier

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

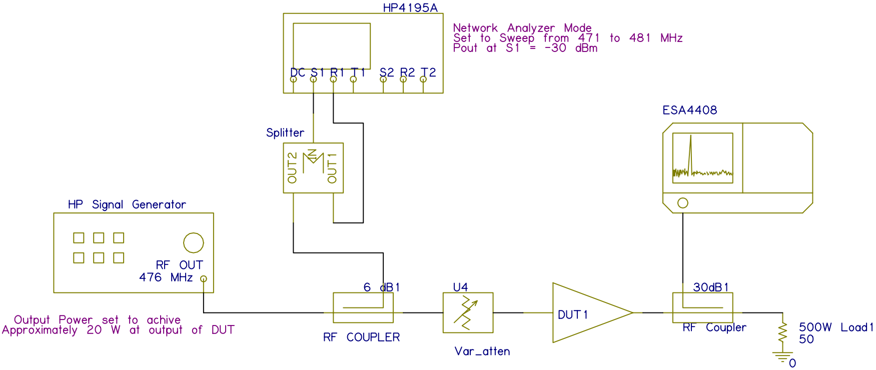






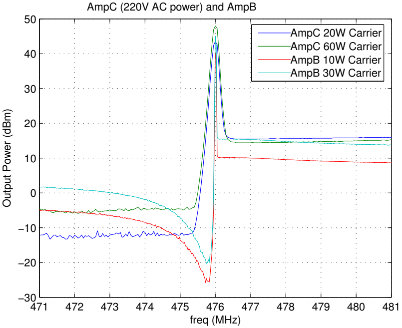
Is this a useful amplifier for a LLRF amp within the feedback loop? What impact does this behavior have?

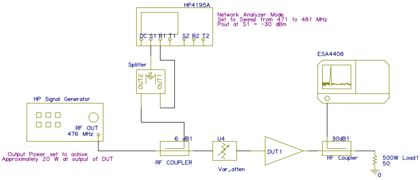
A little knowledge is a dangerous thing



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

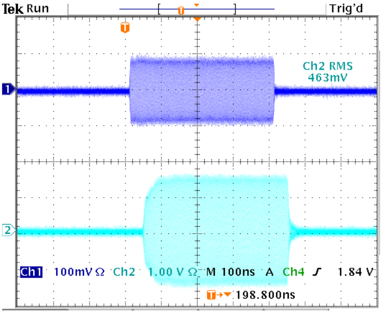
Does the carrier impact the image frequencies? Test a 50W amplifier

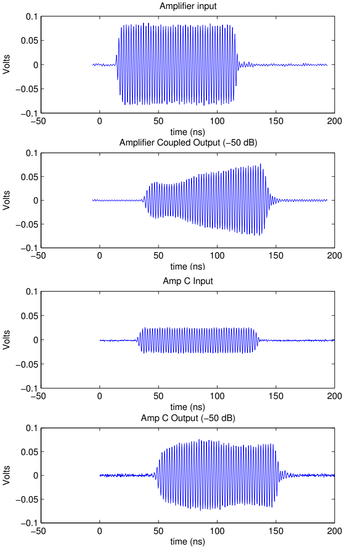




Is this a useful amplifier for a LLRF amp within the feedback loop? What impact does this behavior have?

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

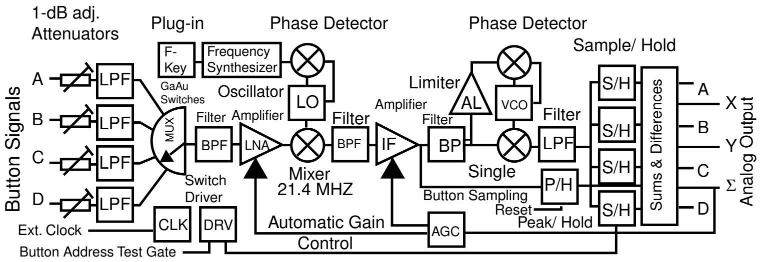
- Time and frequency domains, transforms
- LTI formalism - but are accelerator systems LTI?
- Oscilloscopes, Spectrum analyzers (Network Analyzers, too)
- Signals from Bunched Beams
- Ideas on pickups and kickers
- Common Control Room needs - tune measurements
- Current Measurement - the DDCT

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

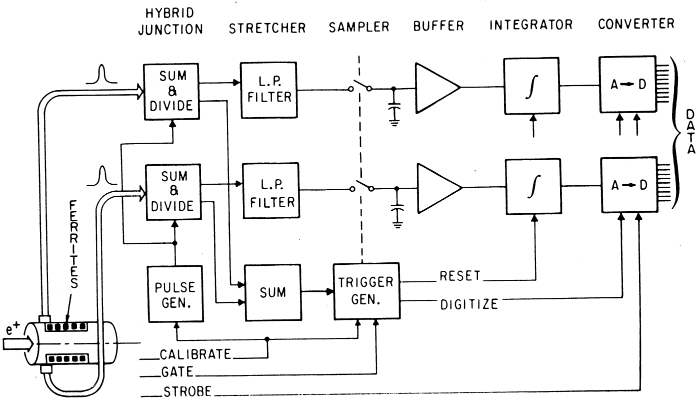
It has been a pleasure to think about these issues of Signals from Beams with colleagues from many labs, who have all contributed to this talk in their expertise. I particularly want to thank J-L Pellegrin, F. Pedersen, M. Serio, D. Teytelman, and M. Tobiyama for their contributions to the field and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

Signals From Beams - Frequncy Domain BPM processing



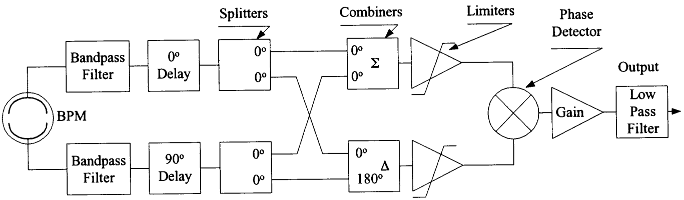
A multiplexed system, uses single receiver to measure sequentially 4 signals. Can Measure at high harmonic of RF for pickup sensitivity. Requires multiple turns, measures average orbit (Bergoz)

Signals From Beams - Time Domain BPM processing



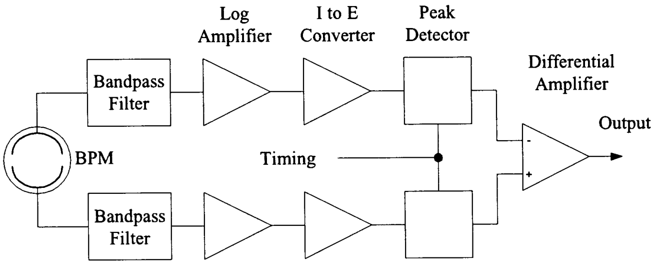
A self-timed system, uses pulse stretching gaussian filters to replicate amplitudes, sample/hold . Applicable to single pulses (Pellegrin)

Signals From Beams - 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)