Beam Diagnostics & Instrumentation

D. W. Posthuma de Boer
Diagnostics Development Section Leader,
ISIS Neutron and Muon Source

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E.g. for a drift

$$x_1 = x_0 + L p_{x0} + O(2)$$
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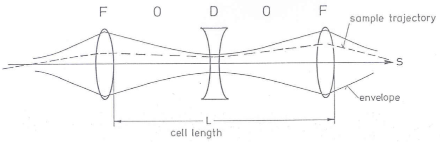

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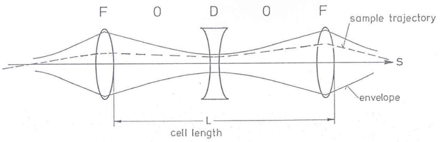

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What properties might we want to know?

Diagnostic Tools

Exactly how to measure a property depends on the details.

Generally start with an idea of what a property will be, and choose a suitable tool.

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- Secondary particle detectors (ion chambers, scintillators etc)
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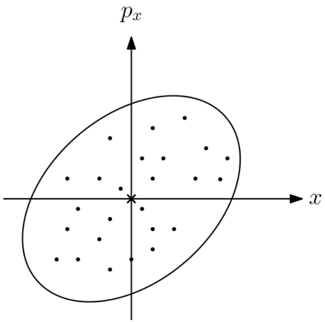
We process their signals with dedicated electronics to measure the property we're interested in. We often filter out the information we want at this stage.

Transverse Profile

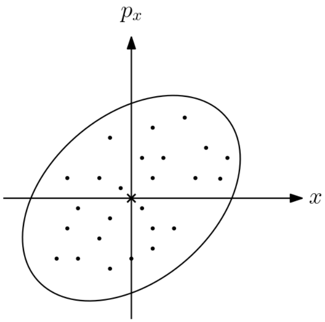
Key point: Diagnostics in the context of phase space.

Probing Transverse Phase Space



Probing Transverse Phase Space

Imagine it were possible to rapidly insert a scraper into a beam, how could we represent this?



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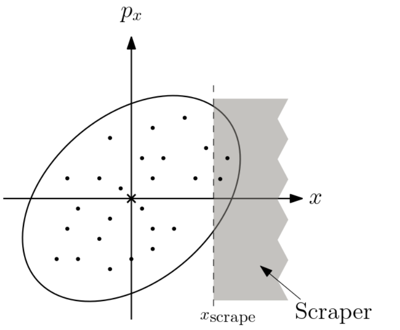

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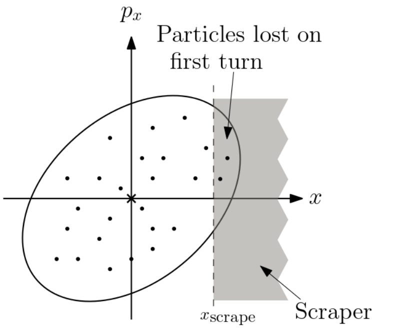

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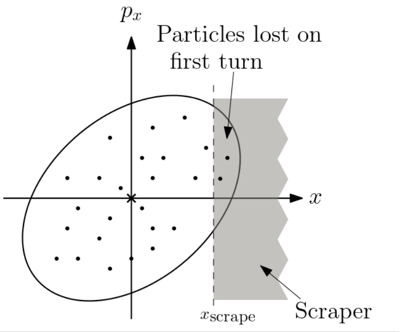

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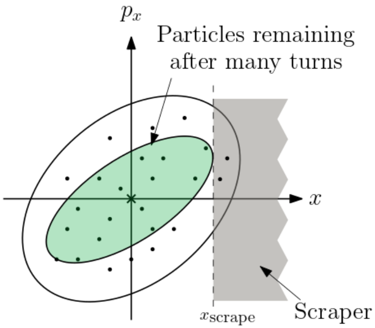

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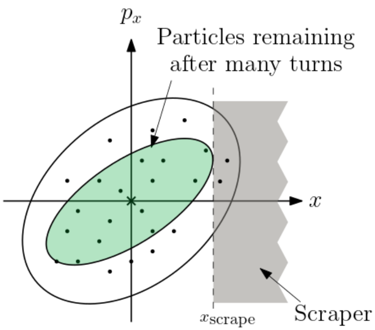
Distribution of particles with amplitude from:

- Current intercepting scraper
- Number of particles lost/ remaining



Interceptive Profile Monitors

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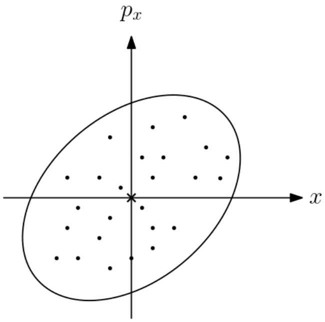

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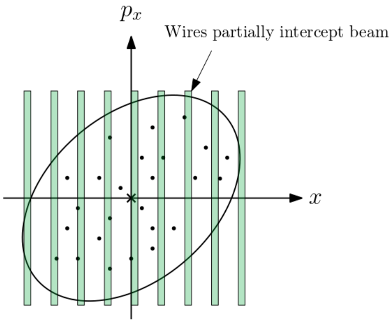

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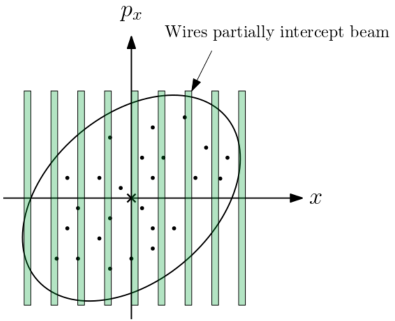

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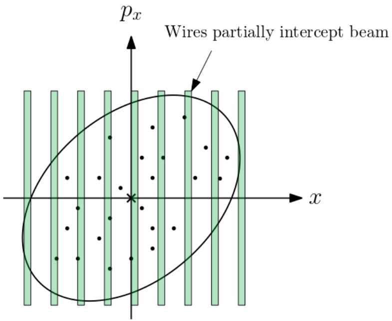

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This method is considered reliable, but what issues can you see?

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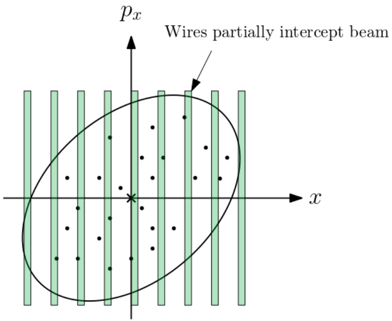

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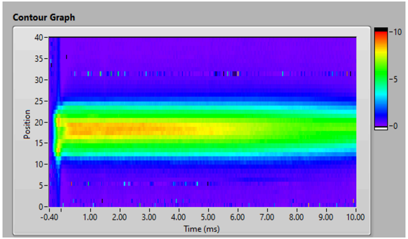

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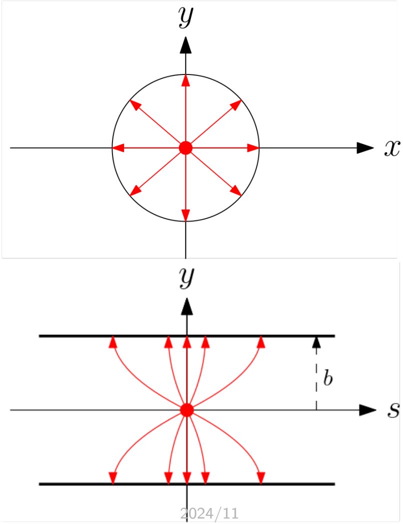
Questions?

Average Transverse Position

Key point: A beam's EM fields provide a wealth of information.

Average Transverse Position

Profile monitors can measure position, but it's more common to use the beam's EM fields [1].



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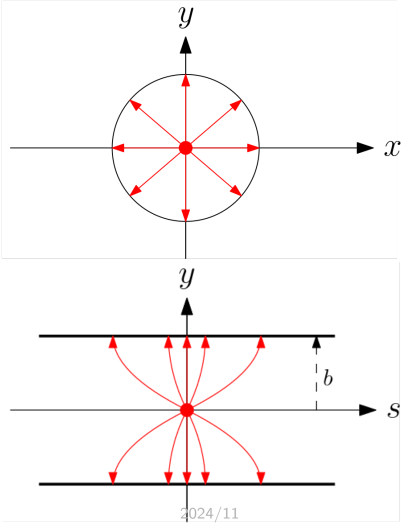

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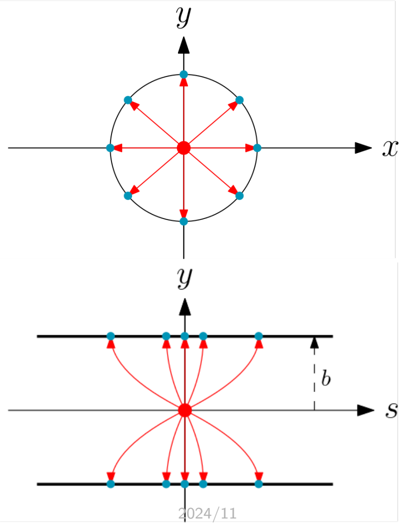

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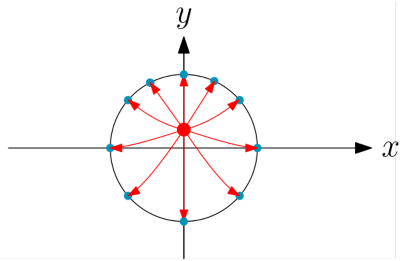

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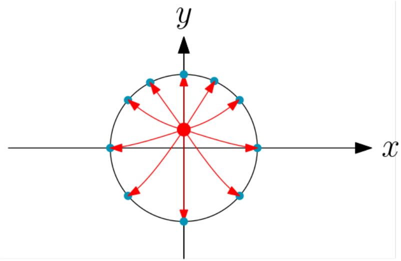
Understanding the distribution of the image charges or fields, allows us to measure beam position and more, without intercepting it.



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Longitudinal Charge Distribution

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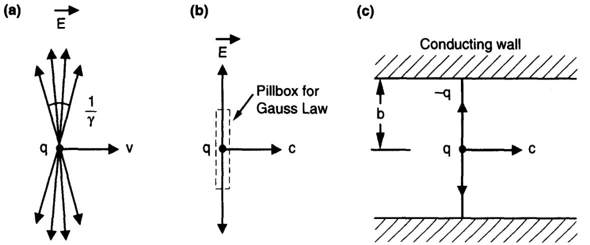

Figure 1.2. Electromagnetic field carried by an ultrarelativistic point charge: (a), (b) in free space; (c) in a perfectly conducting smooth pipe.

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Beam position monitors are useful for studying longitudinal, and transverse dynamics.

Average Transverse Position

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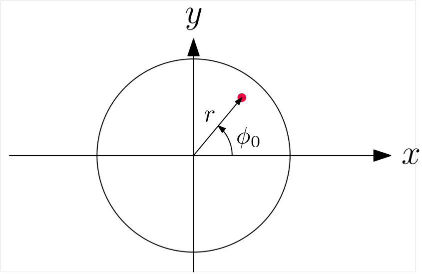

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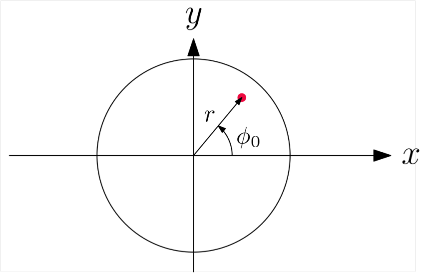
$$i_w(r, \phi, t) = \frac{-I_b(t)}{2\pi b}\left(1 + 2\sum_{n=1}^{\infty}\left(\frac{r}{b}\right)^n \cos(n(\phi - \phi_0))\right)$$



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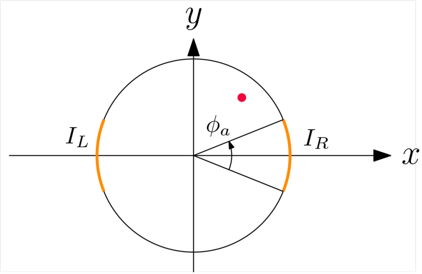
The total current flowing in an angular regions $\pm\frac{\phi_a}{2}$ and $\pi \pm \frac{a}{2}$ are I_R and I_L



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$$I_R = \int_{\phi=-\phi_a}^{\phi_a} i_w(r,\phi,t) b \,\mathrm{d}\phi = \frac{-I_b(t)}{2\pi}\left(\phi_a + 4\sum_{n=1}^{\infty}\frac{1}{n}\left(\frac{r}{b}\right)^n \sin\left(\frac{n\phi_a}{2}\right)\cos(n\phi_0)\right)$$

$$I_L = \frac{-I_b(t)}{2\pi}\left(\phi_a + 4\sum_{n=1}^{\infty}\frac{1}{n}\left(\frac{r}{b}\right)^n (-1)^n \sin\left(\frac{n\phi_a}{2}\right)\cos(n\phi_0)\right)$$

Average Transverse Position

Taking the difference between these currents,

$$I_R - I_L = \frac{-2I_b(t)}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \left(\frac{r}{b}\right)^n \cos(n\phi_0) \sin\left(\frac{n\phi_a}{2}\right) (1 - (-1)^n)$$

$$= \frac{-4I_b(t)}{\pi} \frac{r}{b} \cos(\phi_0) \sin\left(\frac{\phi_a}{2}\right) + A_3 \left(\frac{r}{b}\right)^3 + A_5 \left(\frac{r}{b}\right)^5 + \ldots$$

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With only a vertical offset, $\phi_0 = \frac{\pi}{2}$, so $I_R - I_L = 0$. This is a horizontal BPM. For vertical position, use two more electrodes centred on $\phi = \pm\frac{\pi}{2}$.

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For now assume $\phi_0 = 0$ so we are only discussing horizontal position.

Average Transverse Position

In theory, we could use this difference signal

$$I_R - I_L \approx \frac{-4I_b(t)}{\pi}\frac{r}{b}\sin\left(\frac{\phi_a}{2}\right),$$

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It would be preferable to remove this dependence. Consider the sum signal

$$I_R + I_L = \frac{-I_b(t)}{2\pi}\left(2\phi_a + 4\sum_{n=1}^{\infty}\frac{1}{n}\left(\frac{r}{b}\right)^n \sin\left(\frac{n\phi_a}{2}\right)(1+(-1)^n)\right) \approx -I_b(t)\frac{\phi_a}{\pi}$$

Average Transverse Position

In theory, we could use this difference signal

$$I_R - I_L \approx \frac{-4I_b(t)}{\pi}\frac{r}{b}\sin\left(\frac{\phi_a}{2}\right),$$

to determine the horizontal position. This would require us to know $I_b(t)$.

It would be preferable to remove this dependence. Consider the sum signal

$$I_R + I_L = \frac{-I_b(t)}{2\pi}\left(2\phi_a + 4\sum_{n=1}^{\infty}\frac{1}{n}\left(\frac{r}{b}\right)^n \sin\left(\frac{n\phi_a}{2}\right)(1+(-1)^n)\right) \approx -I_b(t)\frac{\phi_a}{\pi}$$

We often use the ratio, because this is independent of $I_b(t)$

$$\frac{I_R - I_L}{I_R + I_L} \approx \frac{4}{\phi_a}\frac{r}{b}\sin\left(\frac{\phi_a}{2}\right)$$

Transverse Position Sensors

Examples of beam position monitors include [4]:

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- capacitive pickups

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Transverse Position Sensors

Examples of beam position monitors include [4]:

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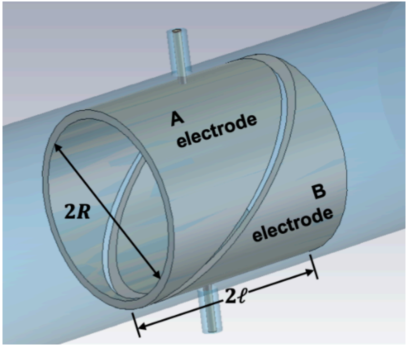
  - split-plate pickups



Transverse Position Sensors

Examples of beam position monitors include [4]:

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  - split-plate pickups
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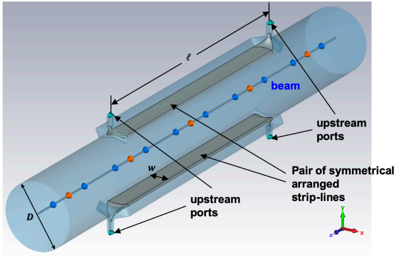

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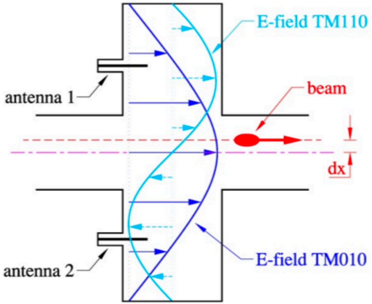

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- capacitive pickups
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- etc

Device suitability depends on bunch structure. Split-plate BPMs popular for large bunches, and buttons are common at light sources.

Questions?

Betatron Tune

Key point 1: A beam can be made to reveal its properties.

Key point 2: Fourier analysis is very useful.

Betatron Tune

Every particle performs betatron oscillations as it travels around the accelerator. The tune is the number of oscillations per revolution.

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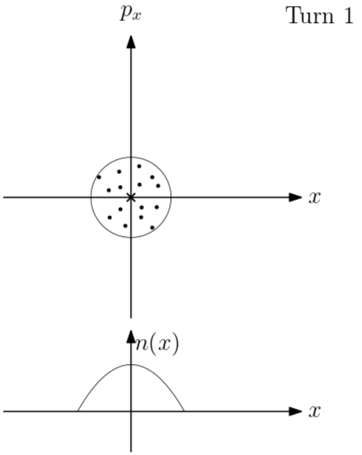
Even though the particles all have some transverse offset, usually we can't detect these offsets because they are incoherent; the beam's average, or coherent, position doesn't oscillate.



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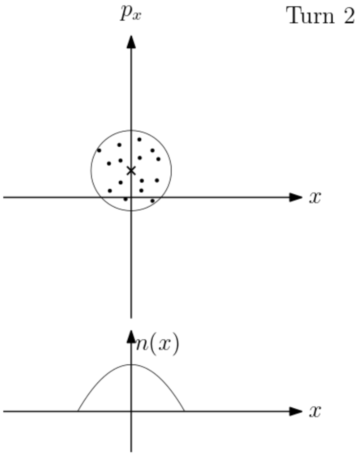
A common technique to measure tune is to use a kicker to increase p_x on a single turn, which will cause the beam's average position to oscillate.



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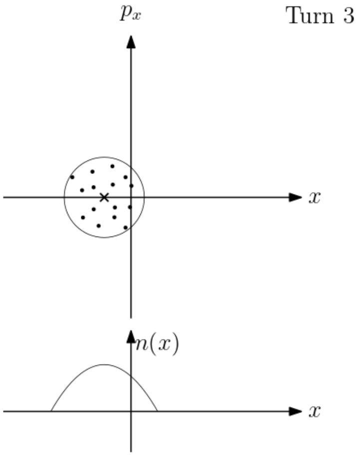

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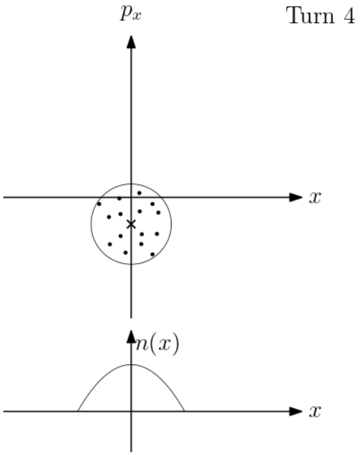

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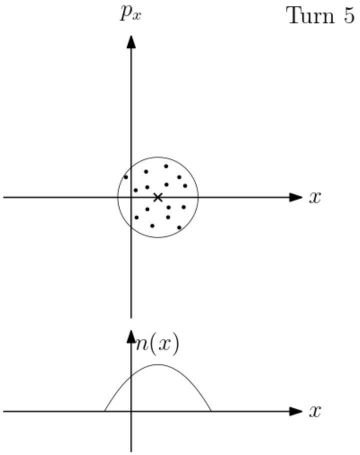

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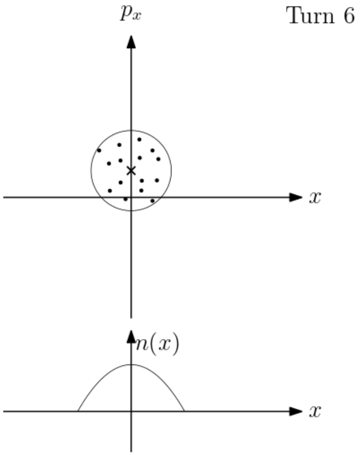

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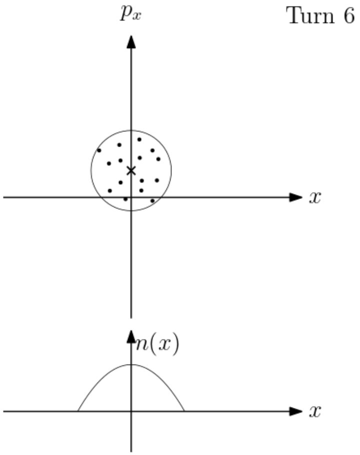
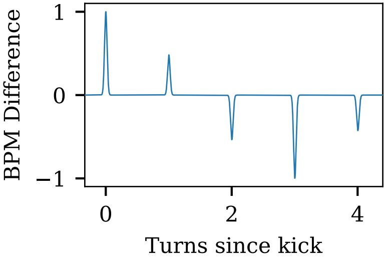
Oscillation frequency gives non-integer tune.



Betatron Tune

An idealised BPM difference signal will resemble a beam pulse, with its amplitude modulated by transverse offset. For non-integer tunes, amplitude changes on each turn.



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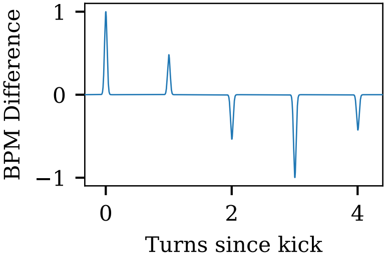
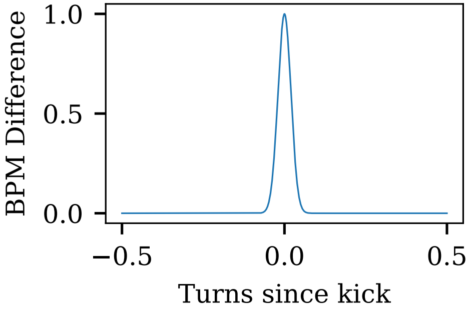


To understand how to obtain the tune, let's write down an ideal BPM difference signal.

Betatron Tune

If $y(t)$ is the longitudinal charge distribution of a bunch, assume signal will resemble $y(t)$.



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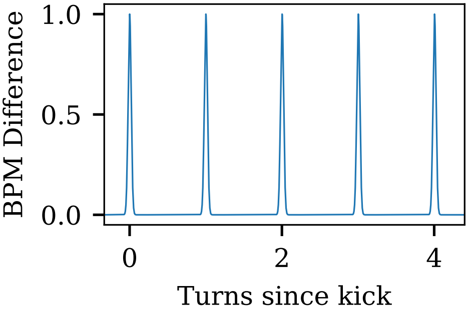
With one bunch we'd see that signal repeated every revolution period, T_p. Temporarily neglecting the oscillation, we could express the signal as

$$V(t) = A \sum_{n=-\infty}^{\infty} y(t - nT_p)$$



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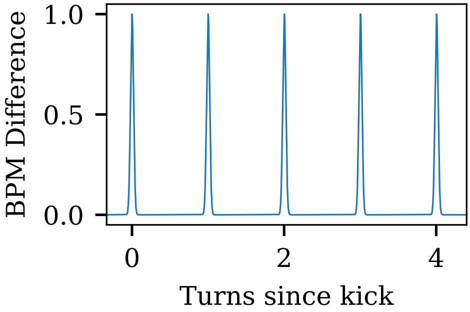
$$= A \sum_{n=-\infty}^{\infty} \delta(t - nT_p) * y(t)$$



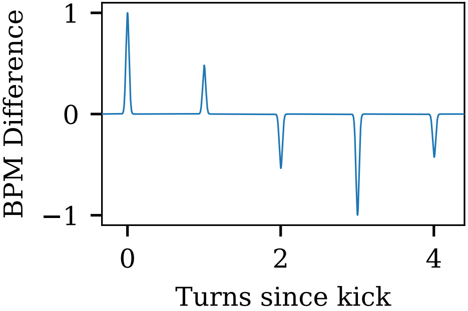
where $*$ is a convolution

Betatron Tune

To include the transverse oscillations, we write

$$V(t) = y(t) * A\cos(\omega_\beta t)\sum_{n=-\infty}^{\infty}\delta(t - nT_p),$$

where $\omega_\beta = 2\pi\frac{Q}{T_p}$ is the angular betatron frequency.



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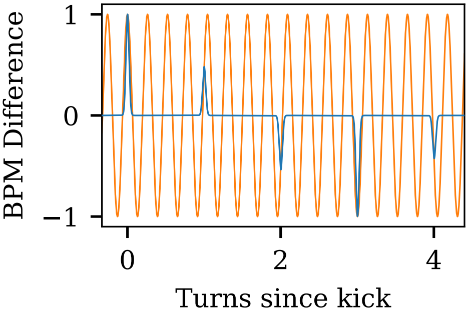

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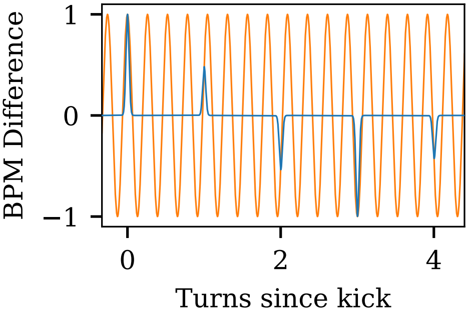
If the integer part of the tune > 1, there are full, undetectable oscillations between turns.



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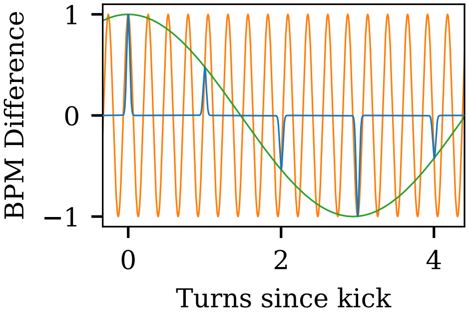

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Betatron Tune from Fourier Transform

I define the Fourier transform and its inverse as

$$\mathcal{F}\left(f(t)\right) = \tilde{f}(\omega) = \int_{-\infty}^{\infty} f(t)e^{-i\omega t}\,\mathrm{d}t, \qquad \mathcal{F}^{-1}\left(\tilde{f}(\omega)\right) = f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{f}(\omega)e^{i\omega t}\,\mathrm{d}\omega$$

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Find the Fourier transform (FT) of $V(t)$ with the convolution theorem of FT's

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and its inverse $\mathcal{F}\left(h(t)k(t)\right) = \frac{1}{2\pi}\mathcal{F}\left(h(t)\right) * \mathcal{F}\left(k(t)\right)$, plus the important result

$$\mathcal{F}\left(\sum_{n=-\infty}^{\infty} \delta(t - nT_p)\right) = \frac{2\pi}{T_p} \sum_{n=-\infty}^{\infty} \delta\left(\omega - n\frac{2\pi}{T_p}\right).$$

The result is

$$\tilde{V}(\omega) = \frac{A}{2}\mathcal{F}\left[y(t)\right]\omega_0 \sum_{n=-\infty}^{\infty} \left[\delta(\omega - n\omega_0 - \omega_\beta) + \delta(\omega - n\omega_0 + \omega_\beta)\right]$$

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We can't distinguish the integer part of the tune from a single monitor, because $\omega_\beta = \omega_0(m + q)$ where m is an integer. The delta-functions become $\delta(\omega - (n \pm m)\omega_0 \pm q\omega_0)$. Since this appears in an infinite sum, we can't distinguish between n and $n \pm m$.

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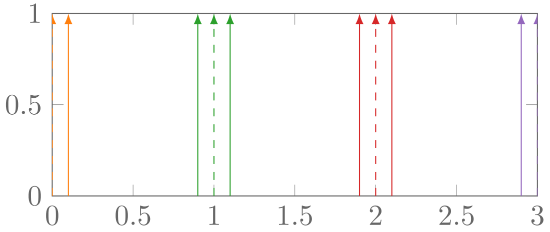
The quantity of interest, q can then be found by measuring the difference in frequency between the revolution harmonics and the sidebands and dividing by $f_0 = \frac{1}{T_p}$

$$\tilde{V}(\omega) = \frac{A}{2}\mathcal{F}\left[y(t)\right]\omega_0 \sum_{n=-\infty}^{\infty}\left[\delta(\omega - n\omega_0 - \omega_\beta) + \delta(\omega - n\omega_0 + \omega_\beta)\right]$$

We can also get an intuitive picture of why it is that we can only measure up to the half-integer. Plot $\tilde{V}(\omega)$ for increasing values of fractional tune:

$$\tilde{V}(\omega) = \frac{A}{2}\mathcal{F}[y(t)]\,\omega_0 \sum_{n=-\infty}^{\infty} [\delta(\omega - n\omega_0 - \omega_\beta) + \delta(\omega - n\omega_0 + \omega_\beta)]$$

We can also get an intuitive picture of why it is that we can only measure up to the half-integer. Plot $\tilde{V}(\omega)$ for increasing values of fractional tune: $q = 0.1$.



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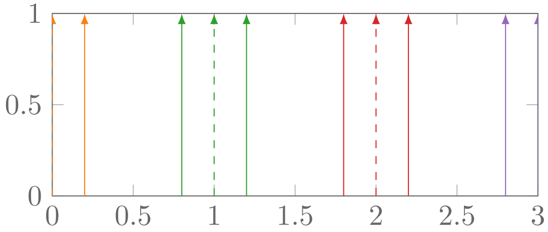
$$\tilde{V}(\omega) = \frac{A}{2}\mathcal{F}\left[y(t)\right]\omega_0 \sum_{n=-\infty}^{\infty} \left[\delta(\omega - n\omega_0 - \omega_\beta) + \delta(\omega - n\omega_0 + \omega_\beta)\right]$$

We can also get an intuitive picture of why it is that we can only measure up to the half-integer. Plot $\tilde{V}(\omega)$ for increasing values of fractional tune: $q = 0.2$.



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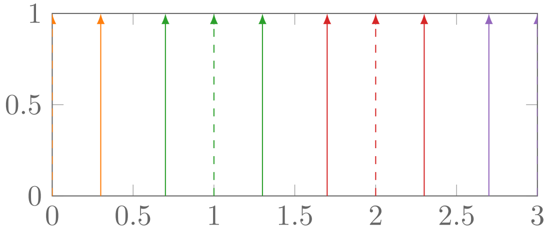

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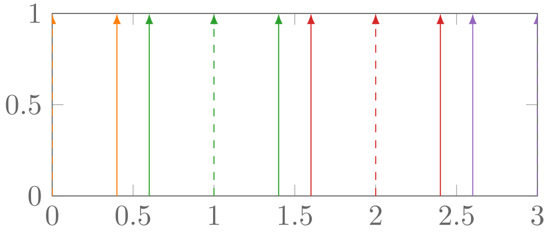
$$\tilde{V}(\omega) = \frac{A}{2}\mathcal{F}\left[y(t)\right]\omega_0 \sum_{n=-\infty}^{\infty} \left[\delta(\omega - n\omega_0 - \omega_\beta) + \delta(\omega - n\omega_0 + \omega_\beta)\right]$$

We can also get an intuitive picture of why it is that we can only measure up to the half-integer. Plot $\tilde{V}(\omega)$ for increasing values of fractional tune: $q = 0.4$.



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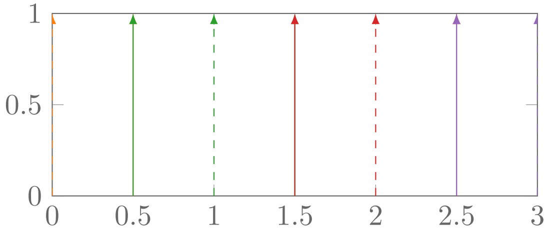
We can also get an intuitive picture of why it is that we can only measure up to the half-integer. Plot $\tilde{V}(\omega)$ for increasing values of fractional tune: $q = 0.5$.



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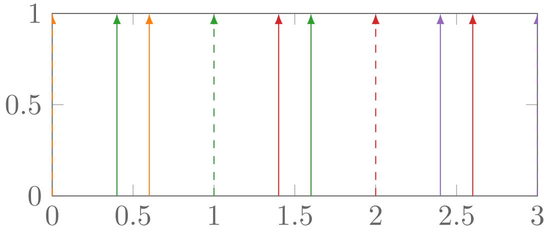
We can also get an intuitive picture of why it is that we can only measure up to the half-integer. Plot $\tilde{V}(\omega)$ for increasing values of fractional tune: $q = 0.6$.



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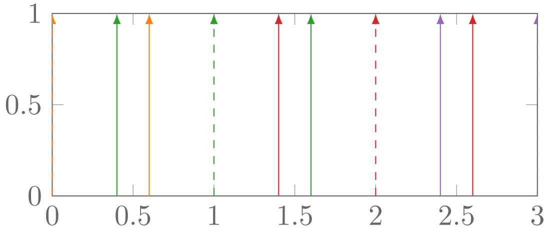
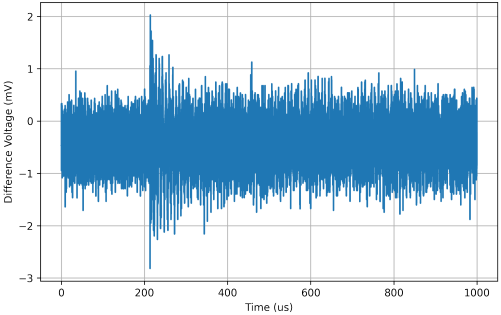


Sidebands have swapped places! **We can't know if $q = 0.4$ or $1 - 0.4 = 0.6$.**

Tune Measurement Example

This is an example BPM difference signal during a tune measurement on the ISIS synchrotron.
A kick was applied at around $200\,\mu s$.



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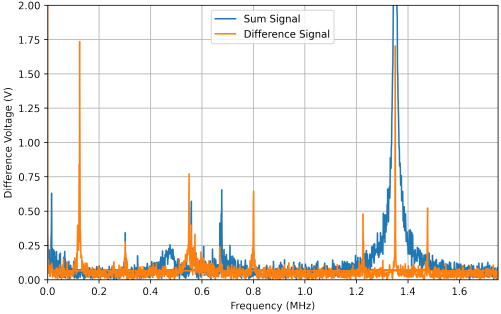
A kick was applied at around $200\,\mu s$.

Use an FFT to obtain a spectra of this signal.



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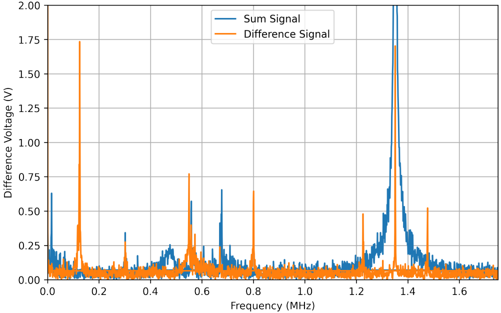

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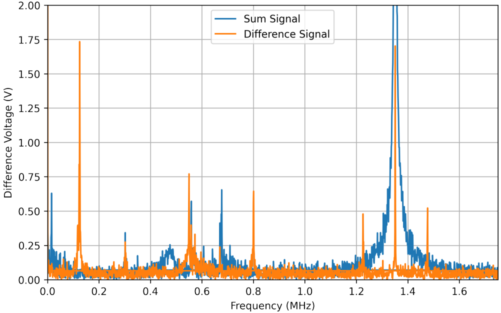

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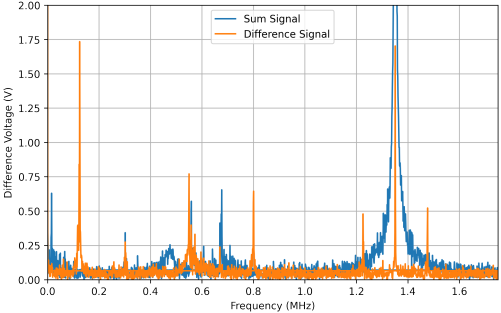

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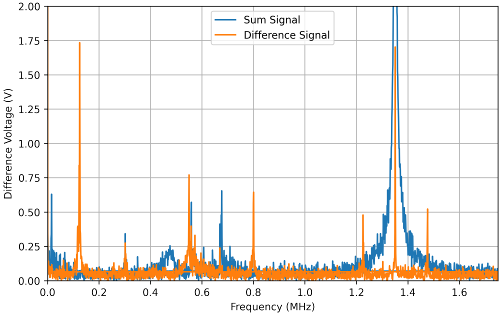

Fractional tune is either 0.19 or 0.81.

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Questions?

Other Diagnostic Systems

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But there are two systems I haven't mentioned which are very important, and I would like to mention them, even without much detail.

Like some of the more detailed examples, they can be used in combination with other equipment and techniques to measure a range of beam and machine parameters.

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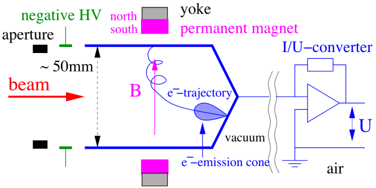

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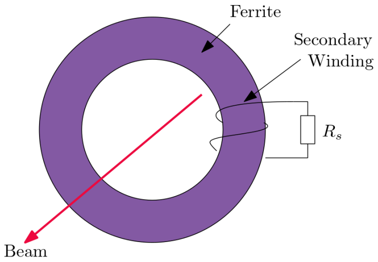

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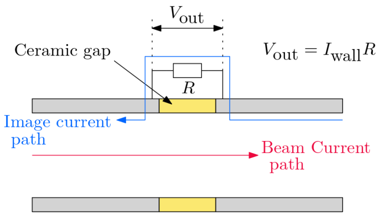
Wall current monitors generate a voltage from the image current flowing in the vacuum vessel.



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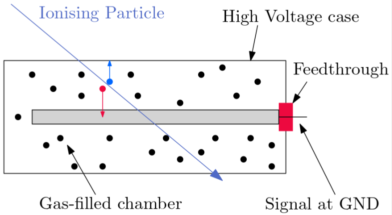

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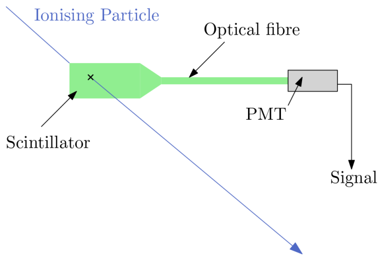
In a scintillator BLM, light is generated when an incoming particle passes through its sensitive volume. The light signal is converted into an electrical signal.



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- Sometimes the quantity of interest can be obtained directly from the spectra.
- Please review some of the excellent references for more detail.

References

[1] R. E. Shafer. *Beam position monitoring*. DOI: 10.1063/1.39710.

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Extra: Data Acquisition and Sampling

Sampling

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There are a few things that it is good to be aware of.

What can go wrong? - Aliasing

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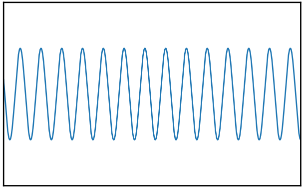

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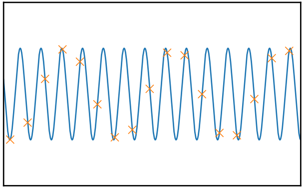

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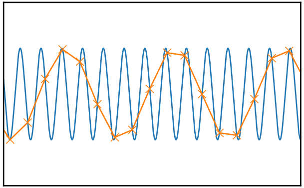

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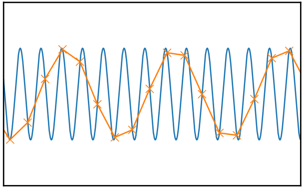

After a signal has been sampled, there is no general correction method. Must be considered in advance!

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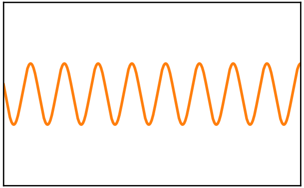

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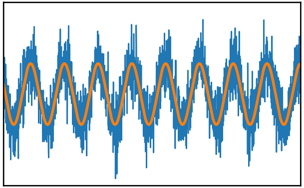

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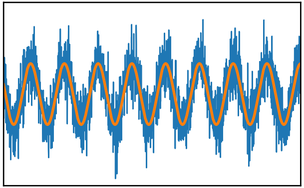

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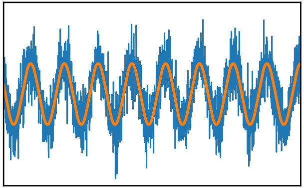

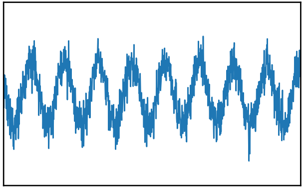

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