Instabilities I & II

JAI Graduate Course

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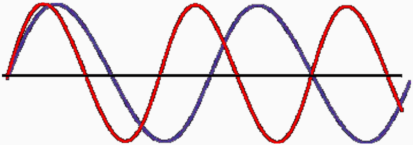
Our Approach

- Propose a physical concept by which a perturbation to the beam might arise
- Try to determine whether this can lead to an instability
- Figure out under which conditions it is unstable

Landau Damping

Landau Damping - the idea

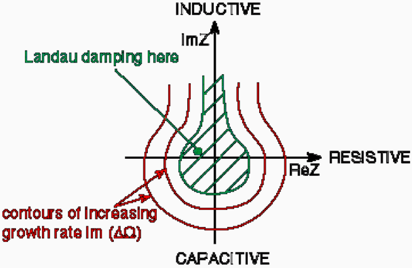
In a real machine, not all particles in the beam have the same frequency. The coherent motion from an instability therefore de-coheres over time, potentially damping the instability.



Two oscillators excited together become incoherent and give zero centre of charge motion after a number of turns comparable to the reciprocal of their frequency difference.

Landau Damping - stability diagram

Landau damping applies not just to longitudinal but also transverse, single and multi-bunch instabilities. Along with active feedback systems, it is a powerful way to overcome coherent beam instabilities



The line defining zero growth rate leads us to a handy approximation for the stability limit of unbunched beams, the 'Keil-Schnell Stability Criterion':

$$\left|\frac{Z}{n}\right| \leq \frac{F m_0 c^2 \beta^2 \gamma \eta}{I_0} \left(\frac{\Delta p}{p}\right)^2_{FWHH} \qquad (19)$$

Types of Instabilities

Types of Instabilities

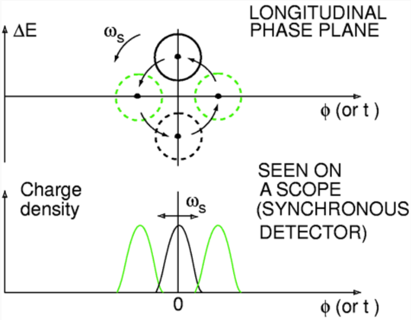
Table 1: A non-exhaustive list of instabilities

	Transverse	Longitudinal
Single bunch	Rigid bunch instability	Negative mass instability Head tail instability Robinson instability Longitudinal microwave instability
Multi-bunch	Coupled bunch modes Resistive wall instability	Coupled bunch modes

For some more detailed discussion on these, [1] and [3] are useful references. Useful books include Wiedemann [5] and Chao [2].

Robinson Instability

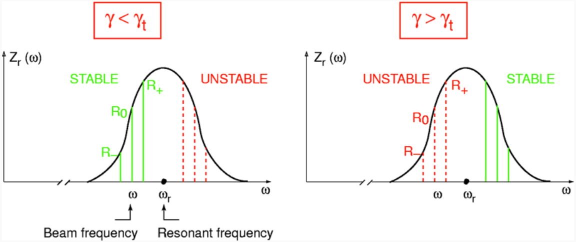
A single bunch and a resonator over multiple turns.



The single bunch in ‘dipole’ or ’rigid bunch’ mode rotates in longitudinal phase plane with ω_s, the phase ϕ and energy ΔE also vary with ω_s.

Robinson Instability

The bunch sees a resonator impedance at $\omega_r \approx \omega_0$



Whenever $\Delta E > 0$, for $\omega < \omega_r$:

- ω increases
- sees a larger real impedance $R+$
- more energy taken from the beam
- STABLE

The opposite is true for $\omega > \omega_r$.

Whenever $\Delta E > 0$, for $\omega < \omega_r$:

- ω decreases (above transition)
- sees a smaller $R+$
- less energy taken from the beam
- UNSTABLE

Robinson Instability

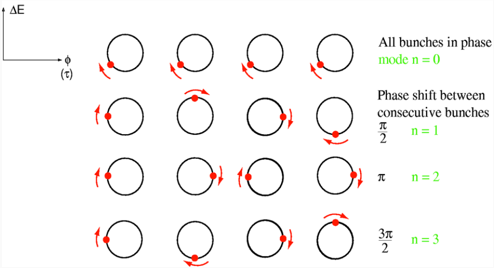
This instability used to be removed just by fine tuning the cavity's resonant frequency ω_r slightly away from the beam frequency $\omega = n\omega_0$

Nowadays a feedback system on the cavity tune is an efficient way of removing it for increased performance.

Multi-bunch coupling instability

In this instability, the fields induced in the resonator hang around long enough to influence subsequent bunches.

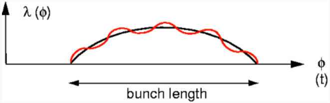
If there are $M = 4$ bunches, they can couple together in 4 ways:



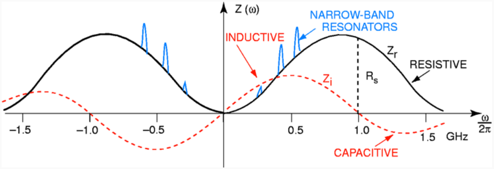
With four possible phase shifts between the four bunches, above transition, n=1 is UNSTABLE.

Longitudinal Microwave instability

This is a single bunch effect, driven by a broad-band impedance, which is caused by discontinuities in the beam pipe.



Typically results in a high-frequency density modulation superimposed on the bunch shape. Has fast growth rates and also affects lepton machines.

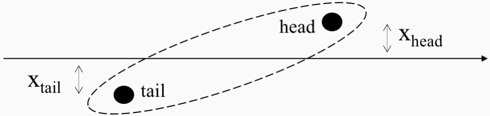


In oder machines, the impedance was as much as $20 - 50\Omega$, whereas it is now $< 1\Omega$ in a modern synchrotron.

Head Tail Instability

- Single bunch effect of transverse wakefields generated by head of the bunch on it's own tail.
- Occurs for broad-band impedances, which act very quickly and decay quickly, so only affects a single bunch.
- In a linear accelerators, can lead to beam break-up, as they have many cavities.

We can represent the head and tail as a two macro-particle model:



This produces a single bunch current $I_b = qNI_b f_{rev}$ limit of:

$$I_b \leq \frac{4\pi q \gamma \omega_0 \nu_\beta \nu_s}{r_c \beta c \left(Z_\perp / n\right)_{imag}} \tag{20}$$

Severe limitation on single-bunch currents in storage rings - special care must be taken to minimize transverse impedance of the vacuum chamber

Summary

- Broad-band impedances are mainly responsible for single-bunch beam instabilities.
- Narrow-band impedances can cause multibunch instabilities but usually don't affect single bunch intensity limits.
- Both can cause longitudinal or transverse instabilities.

Questions?

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