Instabilities

JAI lectures - Hilary Term 2022

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References

- H. Wiedemann, Particle Accelerator Physics, Springer.
- G. Romulo, Beam Instabilities, CAS lectures.
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- S. Sheehy, Instabilities, JAI lectures.

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Goals of this course

- To give an overview of the mechanisms that drive to instabilities.
- Understand that the beam couples with the accelerator environment throughout the concepts of wake fields and impedance.
- Identify different types of instabilities in the transverse and longitudinal planes.
- Identify single-bunch and multi-bunch instabilities.

Approach

The deep treatment of wakefields/impedances/instabilities requires a detailed mathematical treatment. In this course a qualitative approach is given. Details can be found in the references.

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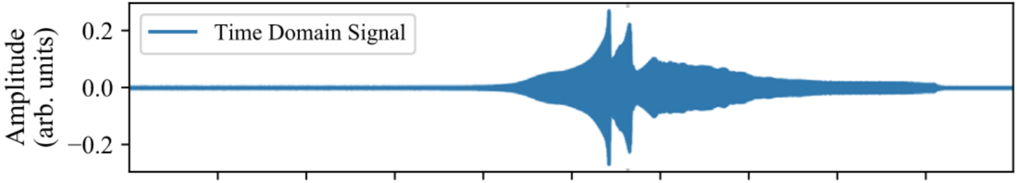

Observables

- Increase of oscillation amplitude.
- Beam losses.
- Intensity loss.

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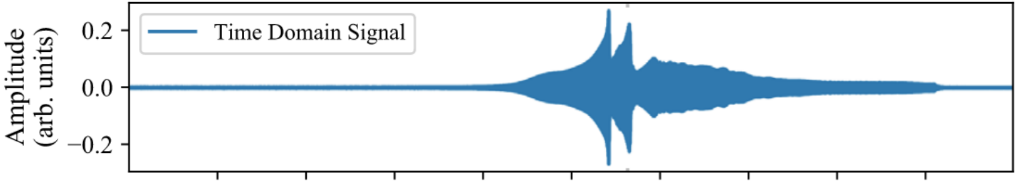

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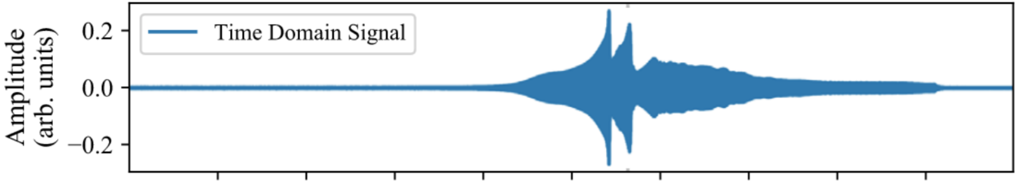

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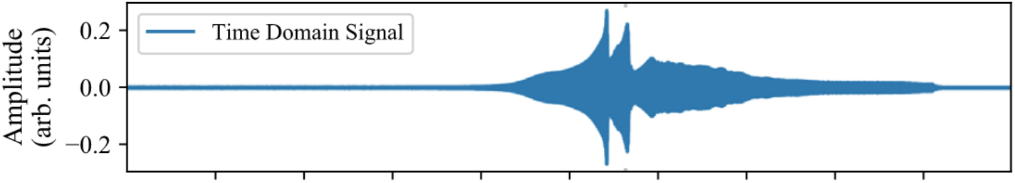

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- Beam losses.
- Intensity loss.

Impedance

- We have studied the single particle dynamics (transverse dynamics lectures).
- We have seen what happens when the bunches are treated as distribution of self-interacting charges (beam-beam and space charge lectures).
- A circulating beam resembles an electric circuit.
- Impedance plays an important role in determining the induced voltage on circulating current.

Impedance

Fourier transform of the electromagnetic waves induced by the passing charged particle beam (wakefield).

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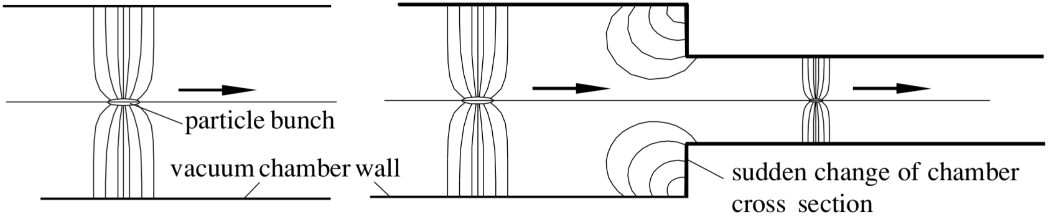
Origins

Accelerator components such as resistive wall vacuum chamber, space charge, image charge on vacuum chamber, broad-band impedance due to bellows, vacuum ports, and BPMs, and narrow-band impedance due to high-Q resonance modes in rf cavities, septum and kicker tanks.



Impedance

- The particle beam covers a wide frequency spectrum from the kHz regime to the order of the revolution frequency up to many GHz limited only by bunch length.
- The vacuum chamber environment consitutes an impedance which can become significant in the same frequency regime and efficient coupling can occur leading to collective effects.
- Strong coupling between RF-cavity and beam.
- The ultimate beam intensity is limited by instabilities caused by electromagnetic interaction of the beam current with the environment of the vacuum chamber.

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Impedance and wake fields

- Wake fields are created after the interaction of the beam charge with the environment.
- They have the ability to pull or push the charges of the distribution.
- Energy losses and gains of a single or collection of particles can cause modifications in the beam dynamics, eventually driving to a beam instability.
- Transverse wakefields: $W_{||}$.
- Longitudinal wakefields: $W_{\perp}$.

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Impedance

- In time domain, the interaction is described by wake fields that act on charges.
- In frequency domain, vacuum chamber components can be represented as a frequency dependent impedance $Z(\omega)$.

$$V(\omega) = -Z(\omega)I(\omega) \tag{1}$$

- The $-$ sign indicates that the induced voltage leads to an energy loss. $Z(\omega) \in \mathbb{C}$.
- All elements can be seen as accidental cavities. Z depends on their shape, material and frequency under consideration.
- Narrow band: $Q \ll 1$ (cavity like).
- Broad band: $Q \approx 1$ (sudden change in chambre cross section).

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Interlude: RLC circuit

A cavity can be modeled as an AC resonant circuit (L: inductance, C: capacitance, R: resistance).

$$\omega_r = \frac{1}{\sqrt{LC}} \tag{2}$$

Quality factor:

$$Q = R\sqrt{C/L} = R/L\omega_r = RC\omega_r \tag{3}$$

Voltage evolution:

$$\ddot{V} + \frac{\omega_r}{Q}\dot{V} + \omega_r^2 V = \omega_r \frac{R}{Q}\dot{I} \tag{4}$$

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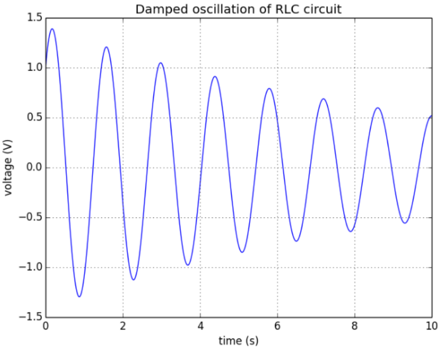
Damped oscillator:

$$V = V_0 e^{-\omega_r/2Q} \sin\left[\omega_r \sqrt{1 - \frac{1}{4Q^2}}\, t\right] + \phi \tag{5}$$

High Q



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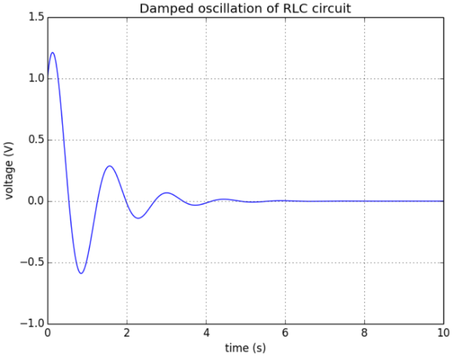

Impedance

Narrow band: $Q \ll 1$

- Persist for a long time.
- Multibunch instabilities (rarely affect single bunch limits).
- Accelerating cavities (fundamental and higher order modes).

Broad band: $Q \approx 1$

- Discontinuities in cross section of vacuum chamber (accelerating cavities, flanges, kicker magnets, BPMs,...)
- Many higher modes can be excited by a passing short particle bunch.
- All modes decohere very fast.
- At the time of arrival of the next particle bunch or the same bunch after one or more revolutions these fields have vanished.
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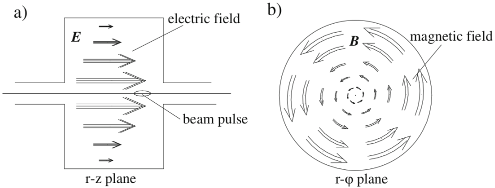
Impedance (Longitudinal vs. Transverse)

A bunch passing through a structure on axis excites a longitudinal electrical field and a transverse magnetic field.

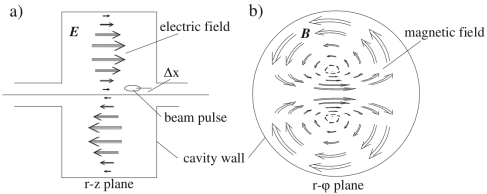
Longitudinal impedance

$$Z_{\|}(\omega) = -\frac{\int \vec{E}_{\|}(\omega) d\vec{z}}{I(\omega)} \qquad (6)$$



Transverse impedance

$$Z_{\perp}(\omega) = i\frac{\int (\vec{E}(\omega) + [\vec{v} \times \vec{B}(\omega)])_{\perp} d\vec{z}}{I(\omega)\Delta x} \qquad (7)$$



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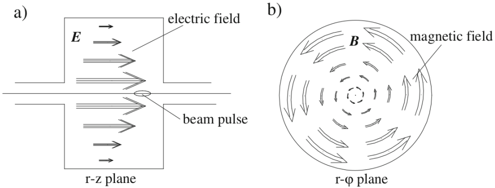

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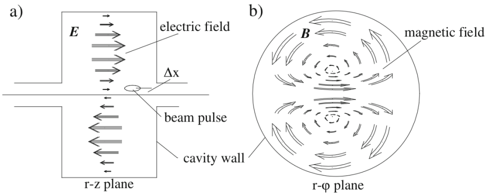

Impedance

In general:

$$Z(\omega) = Z_{\text{Re}}(\omega) + iZ_{\text{Im}}(\omega) = R\left[\frac{1 - iQ\frac{\omega^2-\omega_r^2}{\omega_r\omega}}{1 + iQ\frac{(\omega^2-\omega_r^2)^2}{\omega_r^2\omega^2}}\right] \tag{8}$$

- Resistive part (Z_{Re}): Tune shift.
- Reactive part (Z_{Im}): Damping or antidamping.
  - $\omega < \omega_r$. Inductive: $Z_{\text{Im}} > 0$.
  - $\omega > \omega_r$. Capacitive: $Z_{\text{Im}} < 0$.

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  - $\omega < \omega_r$. Inductive: $Z_{\mathrm{Im}} > 0$.
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Impedance

In general:

$$Z(\omega) = Z_{\text{Re}}(\omega) + iZ_{\text{Im}}(\omega) = R\left[\frac{1 - iQ\frac{\omega^2-\omega_r^2}{\omega_r\omega}}{1 + iQ\frac{(\omega^2-\omega_r^2)^2}{\omega_r^2\omega^2}}\right] \tag{8}$$

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Examples of impedances

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- Space-charge impedance.
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Resistive wall impedance

The particle beam induces an image current in the vacuum chamber wall in a thin layer.

- Since conductivity is not perfect, resistive losses apply a pull or decelerating field on the particles.
- The pull is proportional to the beam current,

$$\frac{Z_{||}(\omega_n)}{n} = \frac{1-i}{n}\frac{\bar{R}}{cr_w}\sqrt{\frac{\mu_r\omega_n}{2\epsilon_0\sigma}} = \frac{1-i}{n}\frac{\bar{R}}{r_w\sigma\delta_{\text{skin}}} \tag{9}$$

- Important role only for low frequencies.

The transverse resistive wall impedance for a round beam pipe is:

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Space-charge impedance

We know that there is an induced voltage leading to an energy gain or loss due to a collection of charged particles.

$$Z_{||,sc}(\omega) = -\frac{i}{\epsilon_0 c}\frac{n}{2\beta\gamma^2}\left(1 + 2\ln\frac{r_w}{r_0}\right) \tag{11}$$

Correct for long wavelength. Purely reactive.

$$Z_{\perp,sc}(\omega) = -\frac{i}{\epsilon_0 c}\frac{\bar{R}}{\beta^2\gamma^2}\left(\frac{1}{r_0^2} - \frac{1}{r_w^2}\right) \tag{12}$$

Specially strong for low energy particle beams.

Cavity-like structure impedance

- Vacuum chamber impedances occur due to sudden changes of cross section.
- Collectively described by a cavity-like impedance with quality factor $Q \approx 1$.
- Broad band impedance.

$$\frac{Z_{||}}{n}_{\text{bb}}(\omega) = \left|\frac{Z_{||}}{n}\right|_0 \frac{1 - i\frac{\omega^2-\omega_r^2}{\omega_r\omega}}{1 + i\frac{(\omega^2-\omega_r^2)^2}{\omega_r^2\omega^2}} \tag{13}$$

- At low frequencies it is almost purely reactive and inductive.
- At high frequencies the impedance becomes capacitive.
- At resonance, purely resistive.
- Transverse broad-band impedance:

$$Z_{\perp}(\omega_n) \approx \frac{2\bar{R}}{r_w^2} Z_{||}(\omega_n) \tag{14}$$

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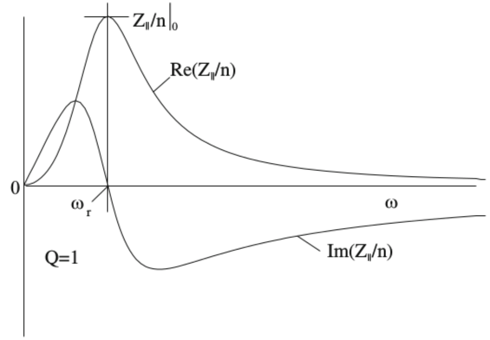

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- Transverse broad-band impedance:

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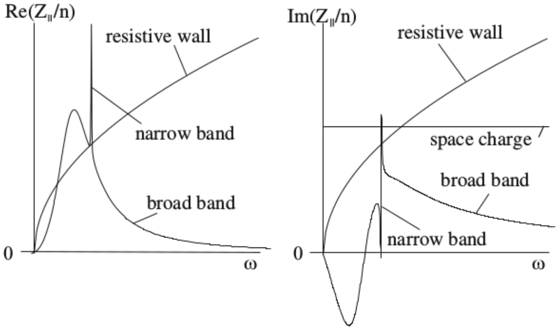
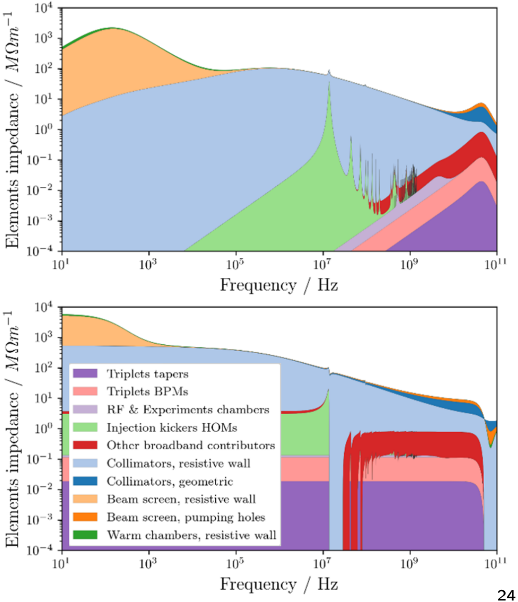
Overall accelerator impedance

- At low frequencies the reactive and the resistive component of the resistive wall impedance dominates.
- Space-charge impedance is independent of frequency.
- The narrow-band cavity spectrum includes the high impedances at the fundamental and higher mode frequencies.



LHC impedance model

- The impedance model summarizes the main impedance contributions from the different elements of the machine.
- In the LHC, the main contribution (for high frequencies) is coming from the collimators.
- New low-impedance collimators under investigation/implementation.



Instabilities

Instability: general concept

Assume some perturbation (i.e. impedance) in the dynamics of the beam motion. If:

- The perturbation is increased: Instability.
- The perturbation is decreased: Stability.

Many types of instabilities:

- Negative-mass instability.
- Robinson instability.
- Head-tail instability.
- Potential well distortion.
- Synchrotron oscillation tune shift.
- Bunch lengthening.
- Multi-bunch instability.
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Negative-mass instability

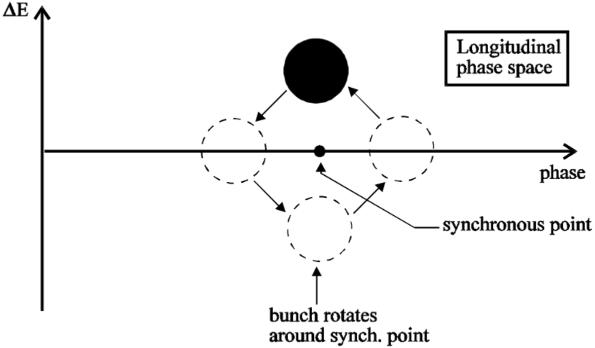
Observed in coasting beams with two possible scenarios:

- Below transition energy:
  - The repulsive electrostatic field from a lump in the distribution causes particles ahead of the lump to be accelerated and particles behind to be decelerated.
  - Stabilizing situation and the lumps smoothes out.
- Above transition energy:
  - Particles ahead gets a slower revolution frequency and it will move closer to the lump.
  - A particle behind will be decelerated and then it will circulate faster.
  - Instability due to a "negative mass".
  - If attractive, then it is stable (Saturn's rings).

It should drive any unbunched beam mode unstable due to the resistivity of the vacuum chamber.

Robinson instability

- Most basic longitudinal instability mechanism that occurs in circular accelerators.
- Induced by longitudinal impedance due to RF accelerating cavities (ω_R).
- Dipole mode oscillation. The whole bunch is moving back and forth around the synchronous position.
- Above transition, the beam will be unstable if ω_R is slightly above $h\omega_0$ and stable if slightly below. Below transition, it is the other way around.



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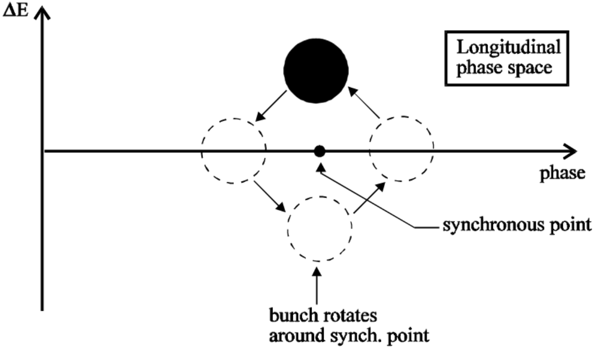

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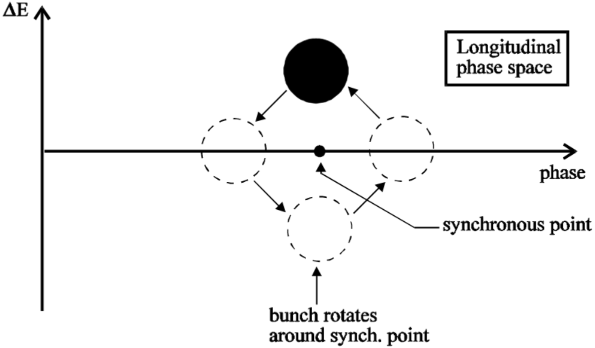

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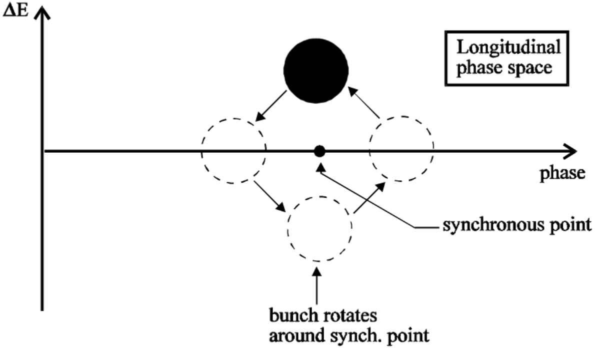

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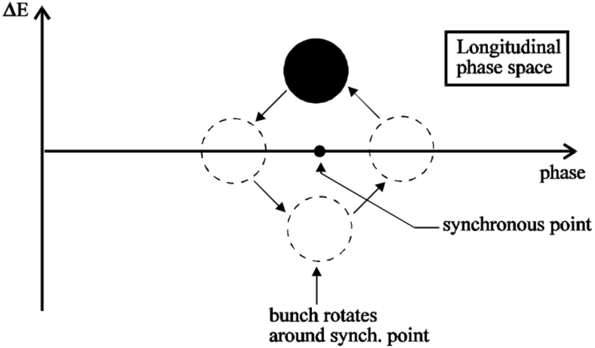

Head-tail instability

In a circular proton accelerator:

- No radiation damping.
- Weak transverse wake fields can lead to transverse bunch blow up and beam loss.
- Particles in the head of a bunch oscillate due to synchrotron oscillations.
- There is an intensity I_b from which the perturbation from wake fields is strong enough to produce instabilities.

$$I_b \leq \frac{4\pi q \gamma \omega_0 \nu_\beta \nu_s}{r_c \beta c \mathrm{Im}(Z_\perp / n)} \tag{16}$$

- Exceeding this limit leads to an immediate loss of the excess current.
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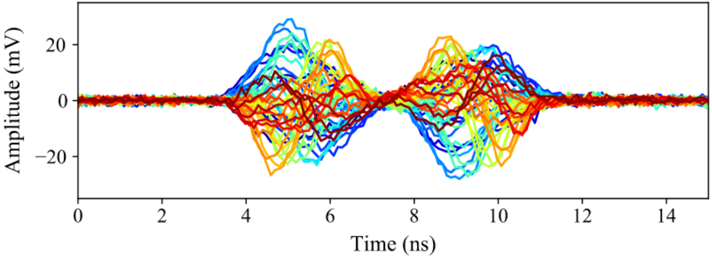
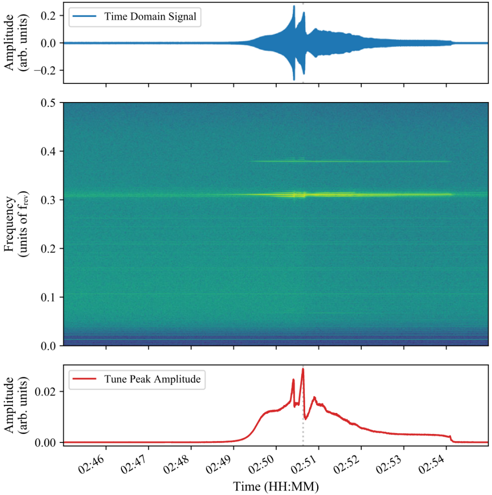
Head-tail instability

- Head and tail start to oscillate while the center of the bunch remains unperturbed.



(a) 8-bit oscillscope

Typical instability in the LHC

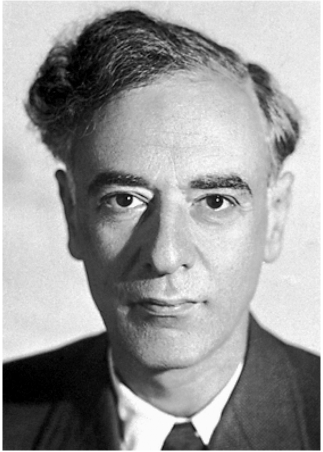


Landau damping

Landau damping

General concept

- Pretty complex topic without a clear/unified description in literature.
- Introduced by Lev Landau (greatest physicist ever) in 1946.
- First introduced in the context of plasmas. Many applications nowadays.
- Quite often, the physical interpretation is unclear.
- Not even for me...



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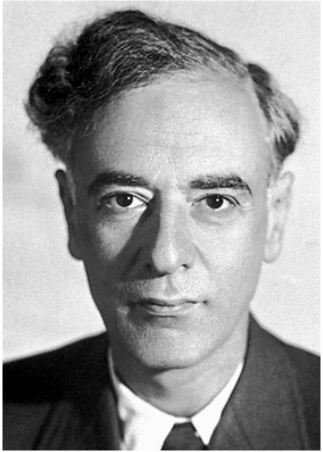

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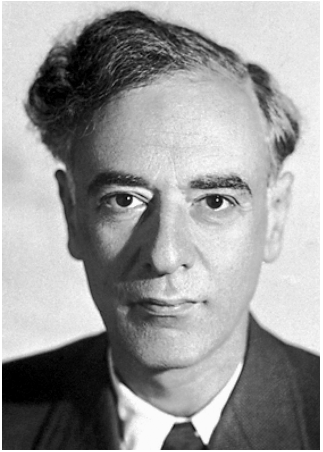

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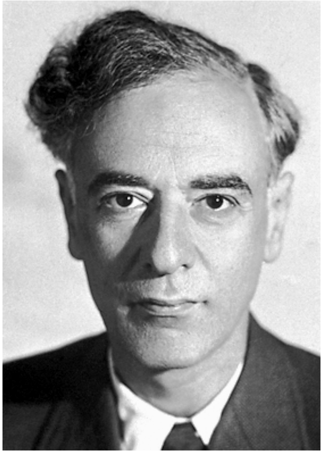

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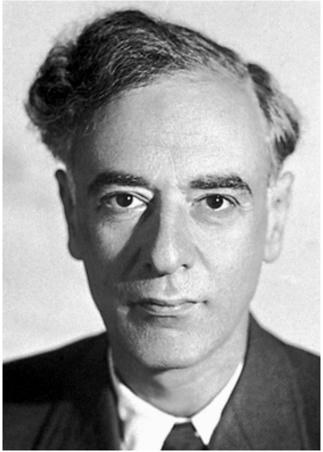

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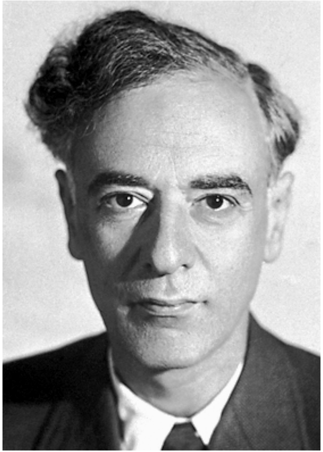

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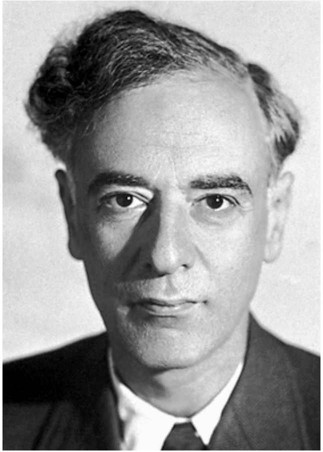

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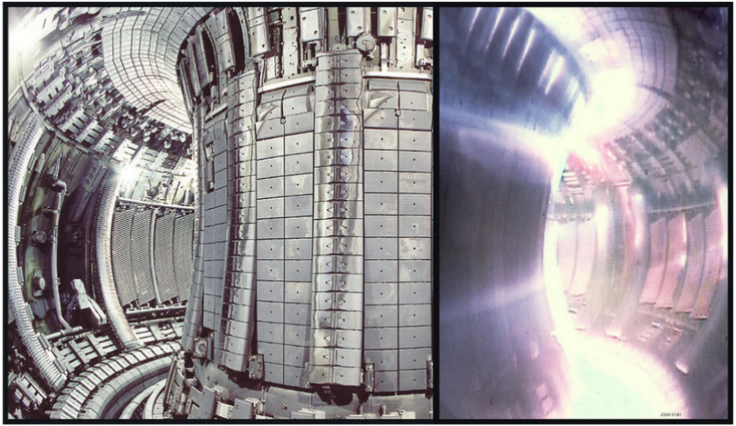
Landau damping in plasmas

- Landau damping dumps collective oscillations.
- Leads to exponentially decaying oscillations.



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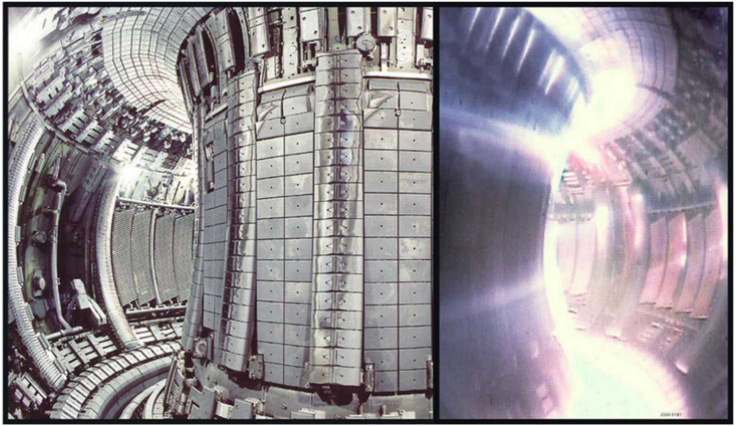

Landau damping in accelerators

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.

- Landau damping does not damp anything.
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- It acts in the longitudinal and transverse planes.
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- Stability diagram may show that we are in the unstable area.
- Octupoles can be used to increase amplitude detuning.
- Check if now we are in a stable region.

Downside

- Octupoles introduce strong non-linearities at large amplitudes.
- Not many particules at large amplitudes $\Rightarrow$ requires large strengths.
- Reduction of dynamic aperture.
- Chromaticity change.

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Recipe to generate Landau damping

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- Stability diagram may show that we are in the unstable area.
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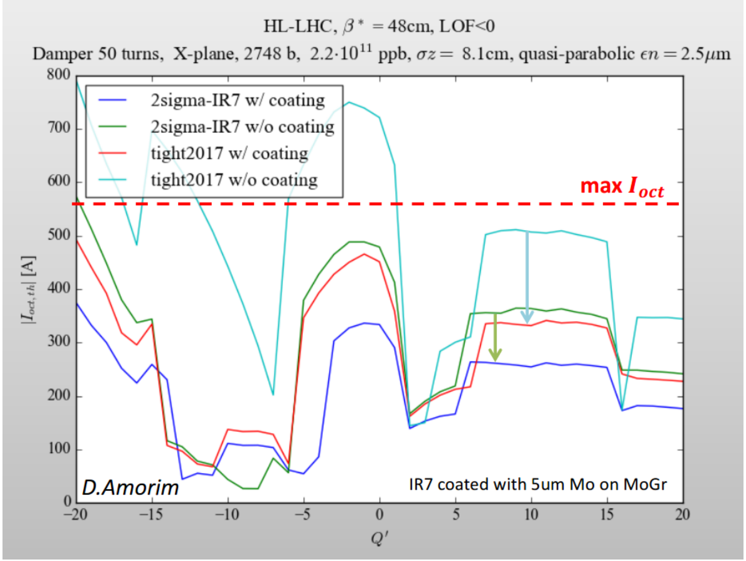
HL-LHC: Stability example



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- They are generated by the interaction/coupling between the beam and the environment.
- Impedances generate wake fields that perturb the beam motion.
- Eventually, this perturbation might lead to unstabilities.
- Different ways to mitigate instabilities (radiation damping, octupoles,...).

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