Accelerators

Lecture IV

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Summary Lecture III

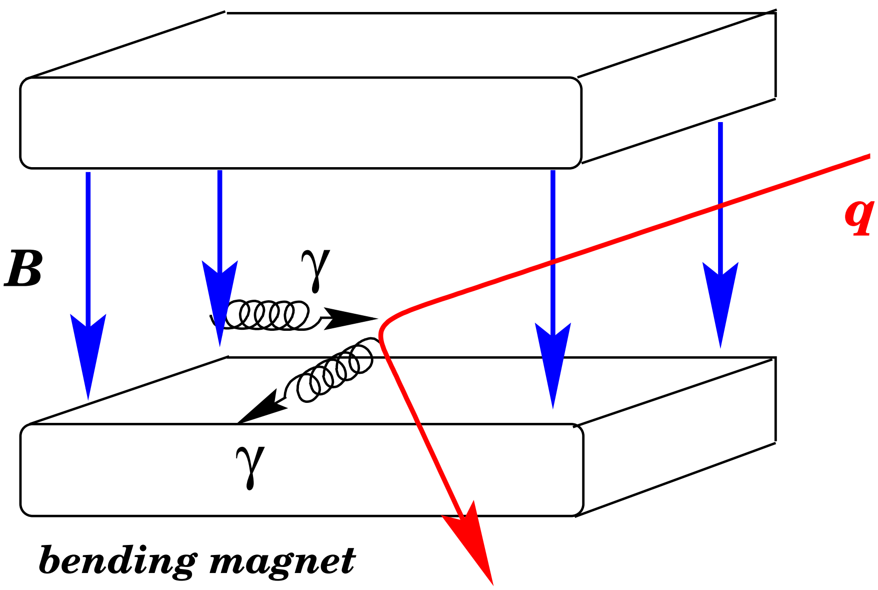
- Orbit Stability
- Linear Resonances
- Chromaticity and Sextupoles
- Non-Linear Resonances and Long Term Stability

IV) Synchrotron Radiation +
Collective Effects

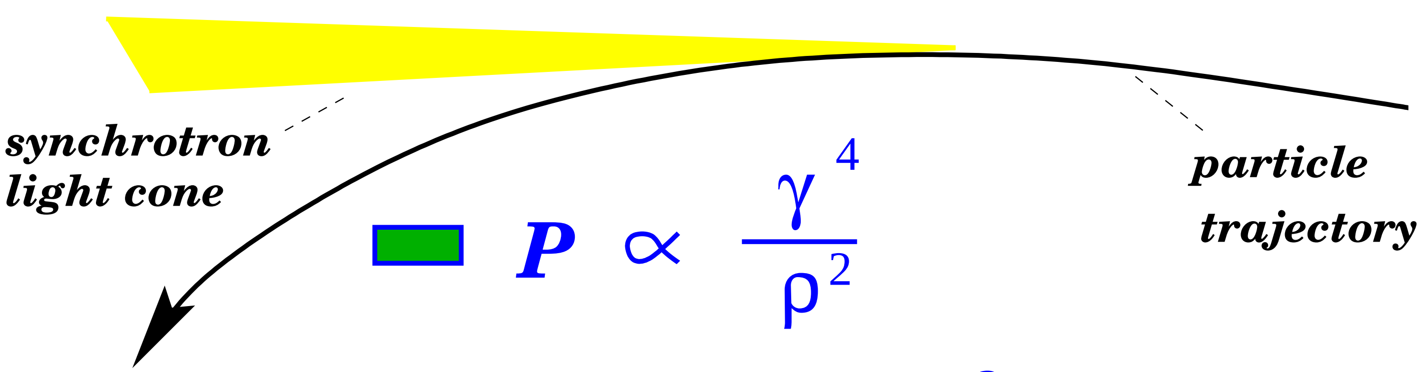
- Synchrotron Radiation
- Acceleration Damping
- Collective Effects
- Feedback and Damping
- Summary

Synchrotron Radiation

Quantum Picture:



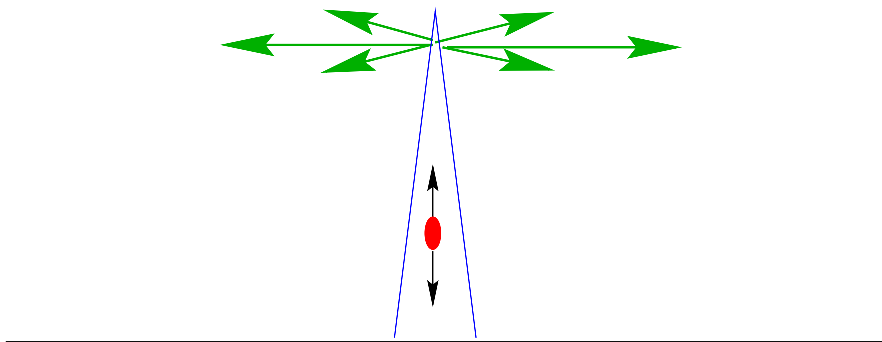
- radiation fan in bending plane
- opening angle $\propto \frac{1}{\gamma}$



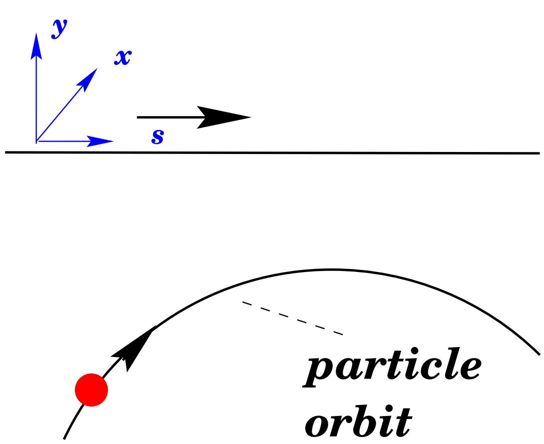
- $P \propto \frac{\gamma^4}{\rho^2}$
- $\langle E_\gamma \rangle \propto \frac{\gamma^3}{\rho}$
- polarised

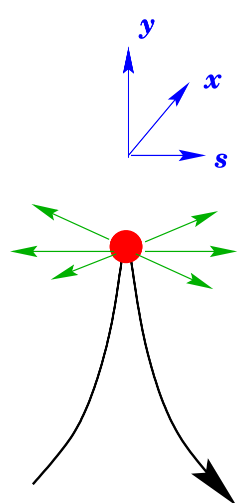
Synchrotron Radiation

Antenna:

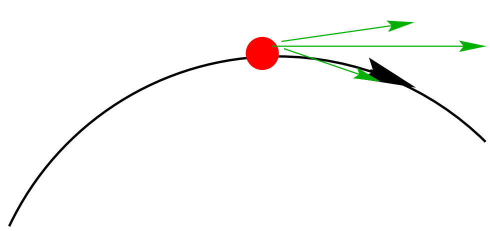


Particle Trajectory:





Lorentz Transformation:



Examples

	E [GeV]	ρ [km]	N [10^{12}]	U [MeV]	P [MW]	u_c [keV]
LEP 1	45	3.1	4.7	260	2.1	90
LEP 2	100	3.1	4.7	2800	23	715
LHC	7000	3.1	312	0.007	0.005	0.04

- γ-rays: Co_{60} → 1.3 MeV
- X-rays: → keV
- Visible Light: → eV

LEP 1 → X-rays

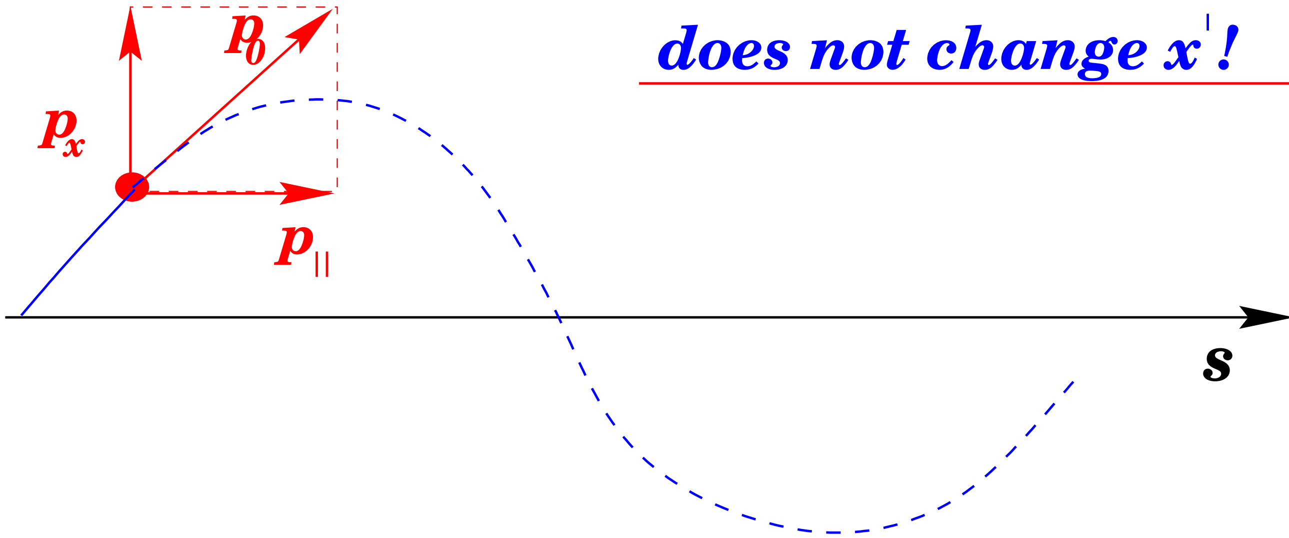
LEP 2 → γ -rays

LHC → UV light

Acceleration Damping I

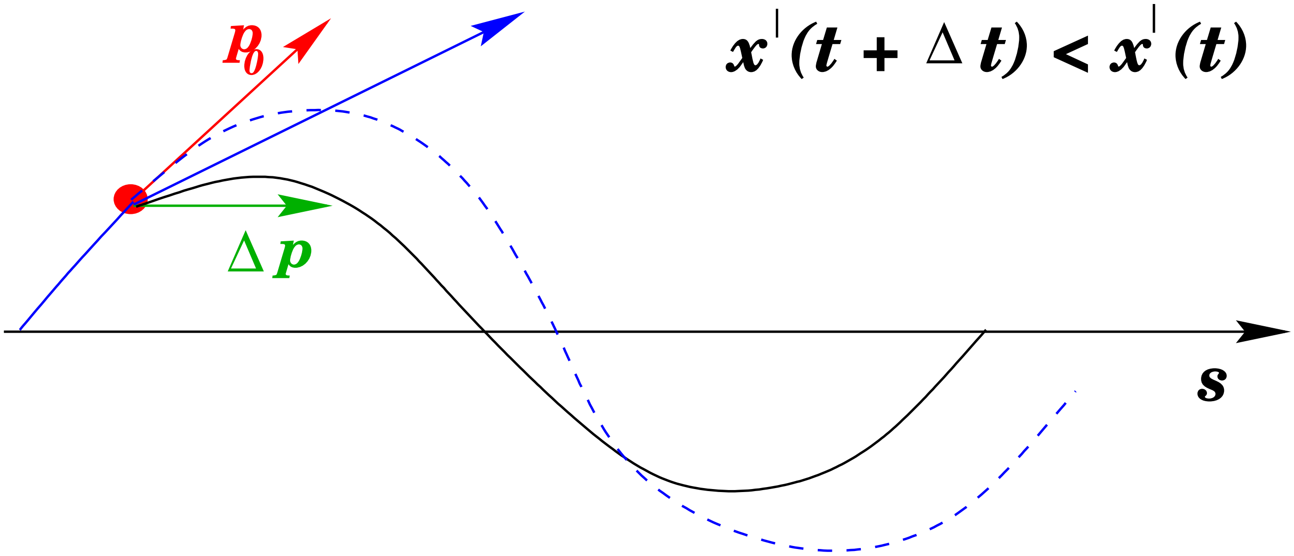
- $x' = \frac{p_x}{p_{||}}$

→ *synchrotron radiation does not change x'!*



- **Acceleration:**

$$x'(t + \Delta t) < x'(t)$$



the beam shrinks as it gets accelerated!

damping $\propto \frac{1}{\gamma}$

Acceleration Damping II

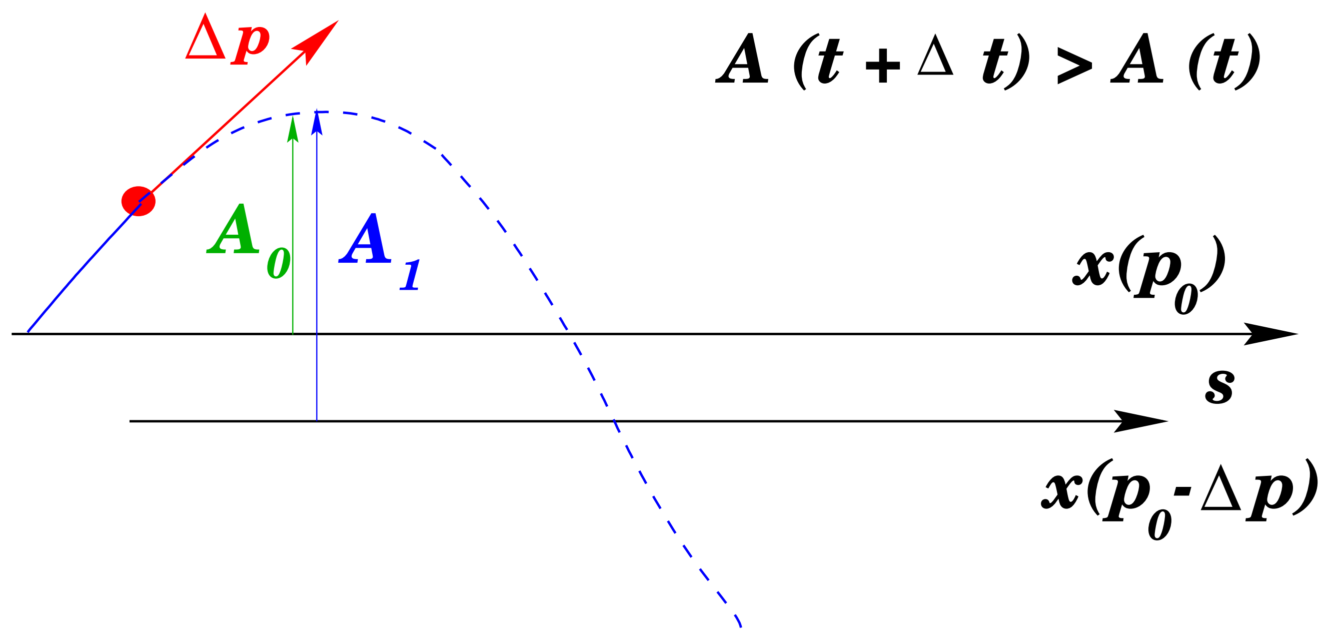
Synchrotron radiation + acceleration

→ continuous damping

- **Limits:**
  - quantum excitations

    → small but finite beam size
  - dispersion
  - orbit curvature

    → synchrotron radiation increases beam size



synchrotron radiation + dispersion

→ excitation

Summary Synchrotron Radiation

- **Pro:**
  - synchrotron radiation
    → dedicated light sources
  - vertical damping
    → flat beams
  - damped motion
    → not sensitive to errors

- **Contra:**
  - power loss
    → large storage ring
    energy limit
  - radiation excitation
    → the horizontal beam size
    increases with γ !

Collective Effects

- **Communication of individual particles via:**
  - *direct coulomb interaction*
  - *residual gas ionisation*
  - *synchrotron radiation*
  - *image charges on the vacuum chamber*

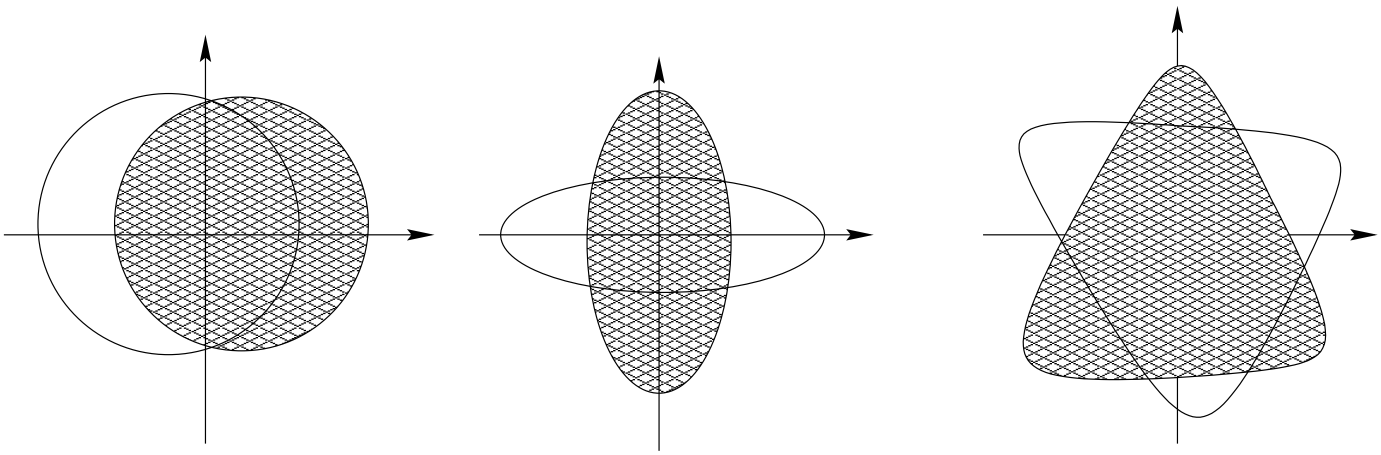
→ **change of individual particle motion**

→ **collective motion**

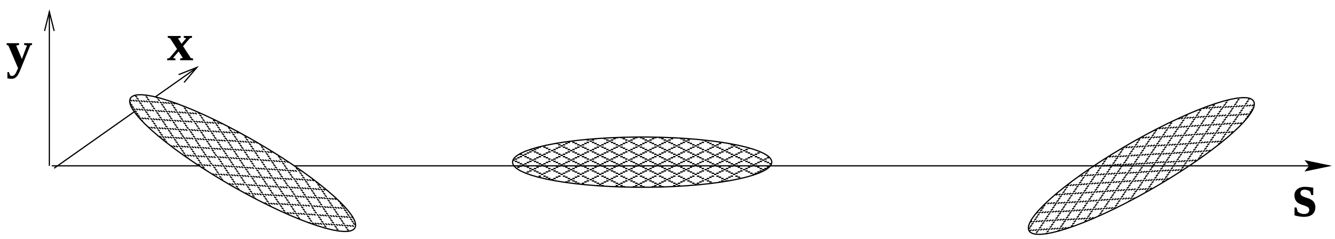
→ **stability?** { beam size, oscillation modes }

Oscillation Modes

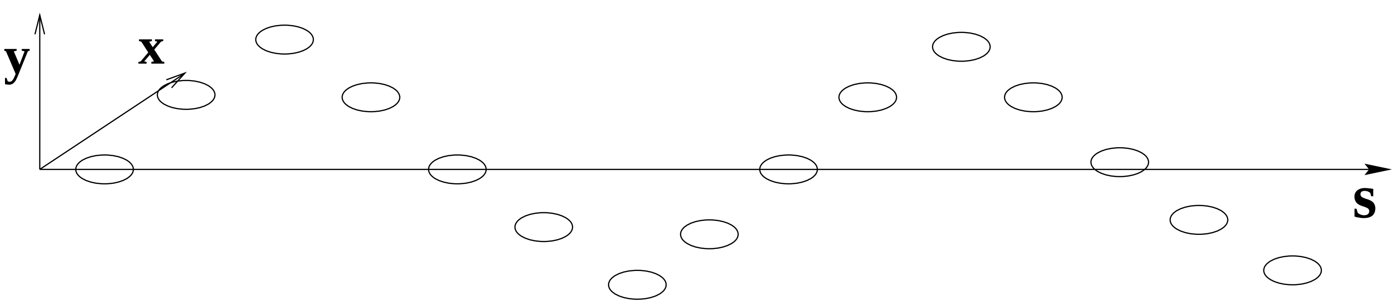
Single Bunch: longitudinal or transverse



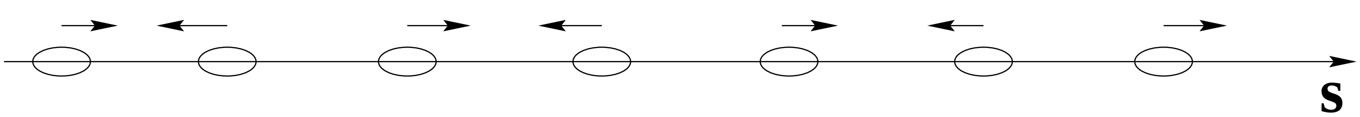
Single Bunch: longitudinal and transverse



Multibunch: transverse



Multibunch: longitudinal

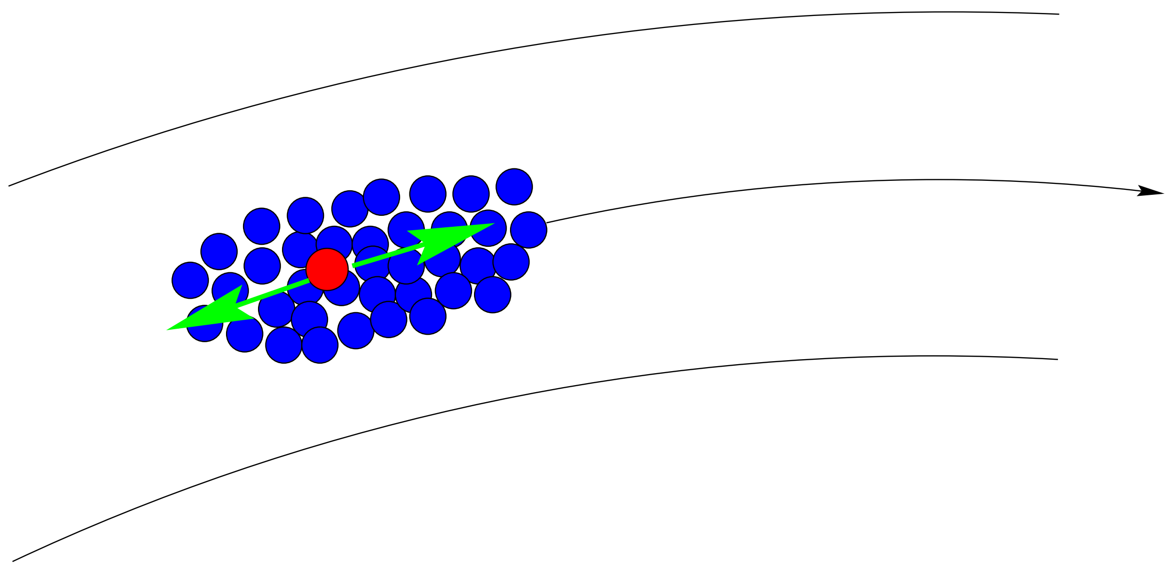


Beam Size

Intra Beam Scattering:

- *each particle performs longitudinal*
  + transverse oscillations
  → *uncorrelated motion!*

Coulomb Scattering → Emittance Growth



- ***Emittance blow-up:***

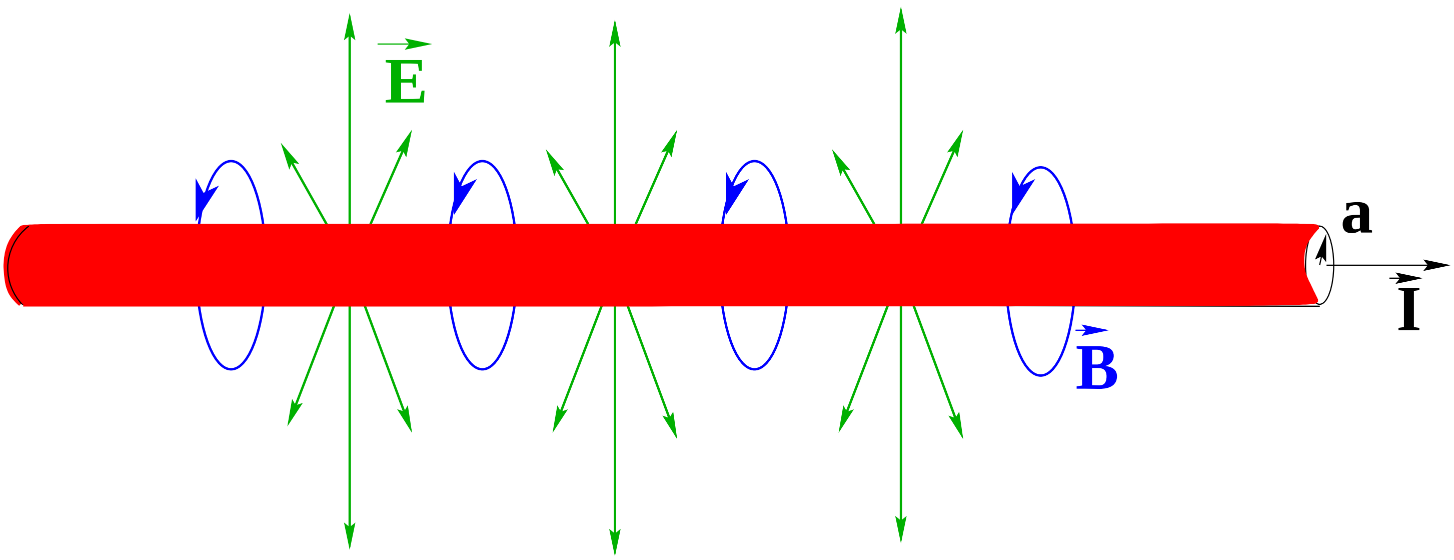
$$\varepsilon(t+\Delta t) = \left(1+\frac{\Delta t}{\tau}\right)\cdot\varepsilon(t)$$

- ***Growth rate depends on beam size:***

$$1/\tau \propto \frac{N}{\varepsilon_t^2 \cdot \varepsilon_l} \cdot A \cdot Z$$

Space Charge

Line Current:



- $E_r = \frac{2\lambda e}{a^2} \cdot r; \quad r < a; \quad \lambda = \frac{N}{2\pi R}$

- $B_\theta = \frac{v}{c^2} \cdot E$

$$x'' + \left(\frac{Q}{R}\right)^2 \cdot x = q \cdot E_r - q \cdot v \cdot B_\theta \cdot \frac{1}{m \cdot v^2}$$

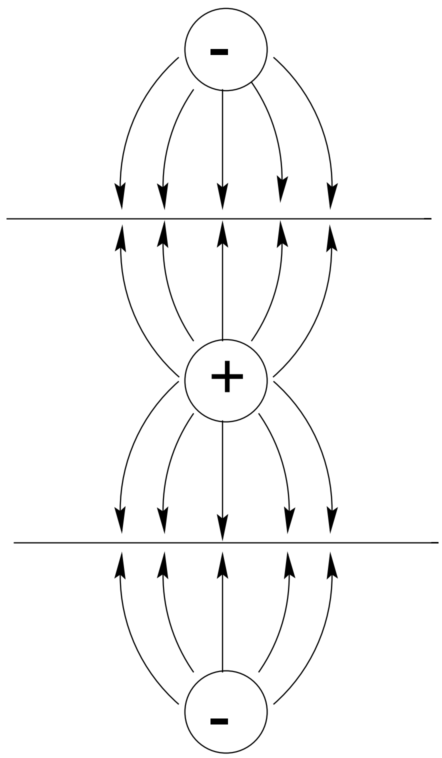
$\propto x$

$$\Delta Q \propto \frac{I \cdot R}{\gamma^2}$$

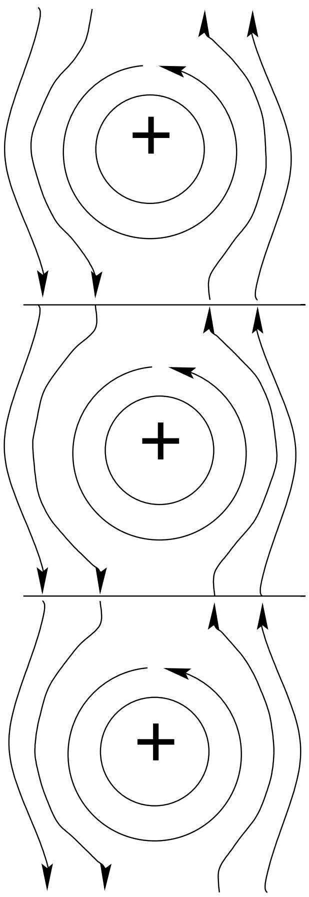
- *resonances limit the total beam current*

Boundary Conditions

Electric:



Magnetic:



- **Different surface currents**

→ *no cancelation of* F_E *and* F_B

→ $\Delta Q \propto \frac{I \cdot R}{\gamma}$

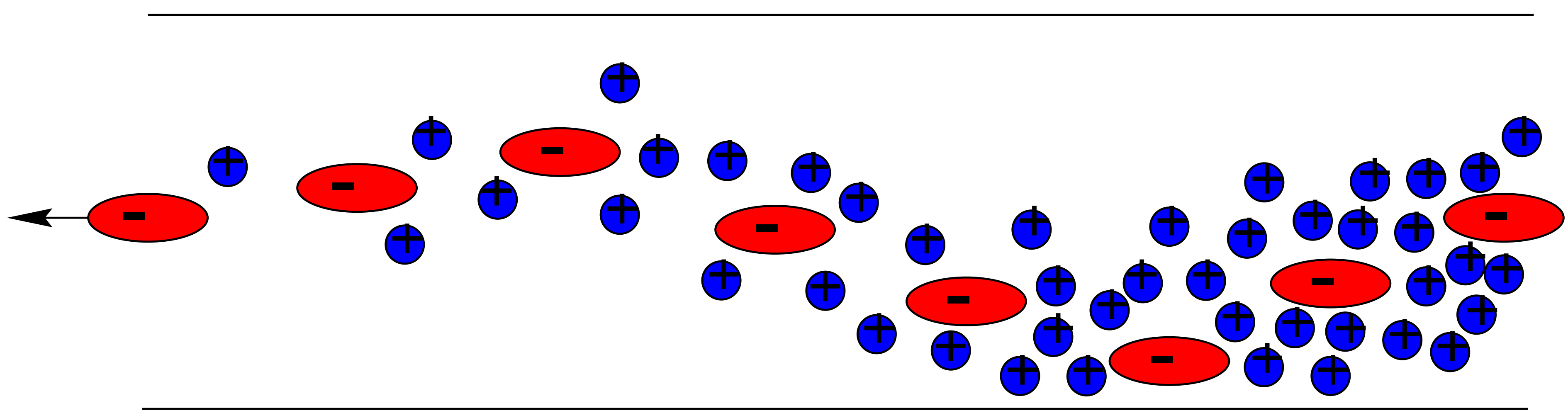
- **Problematic for low energy rings**

→ *small storage rings for* $\gamma \approx 1$

Fast Ion Instability

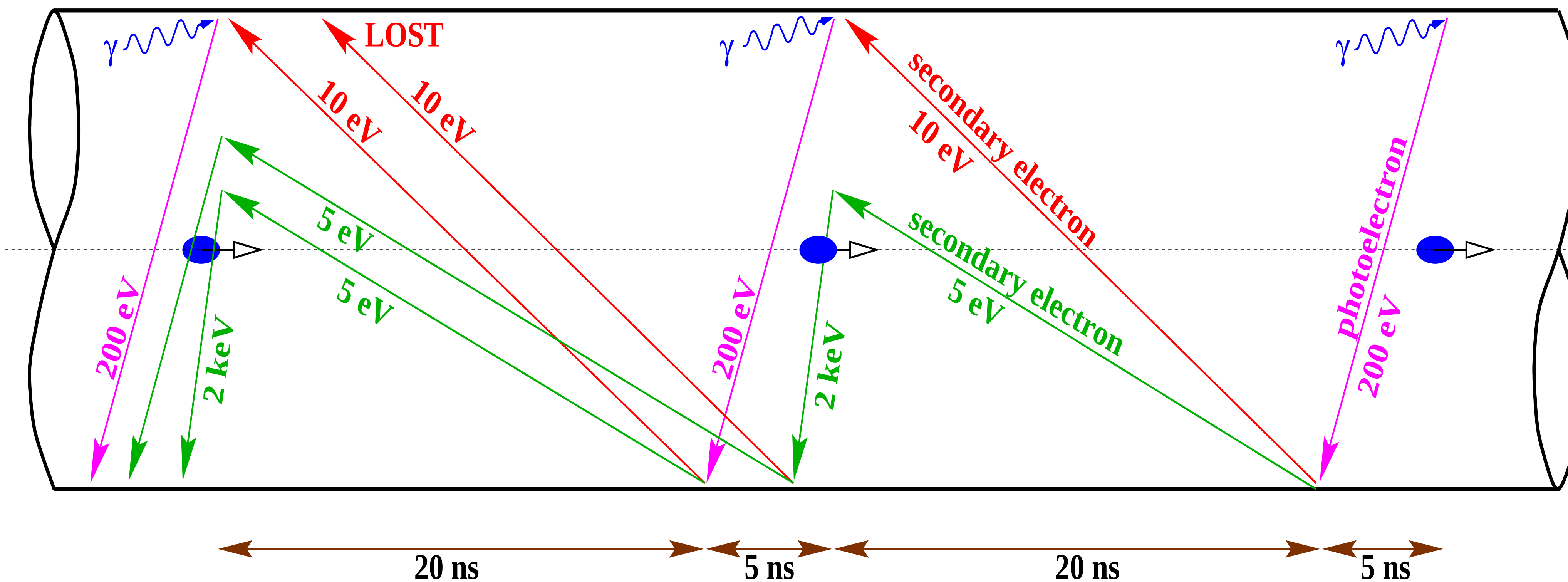
Restgas Ionisation: → **Ion Cloud + Wakefield**

Instability!



Electron Cloud Instability

- Synchrotron light removes electrons from chamber wall
- Electrons are accelerated by the beam
- Electrons hit vacuum chamber and generate more electrons
- Electron cloud → instability and heat losses!



→ ***beam stability depends***

on the surface properties

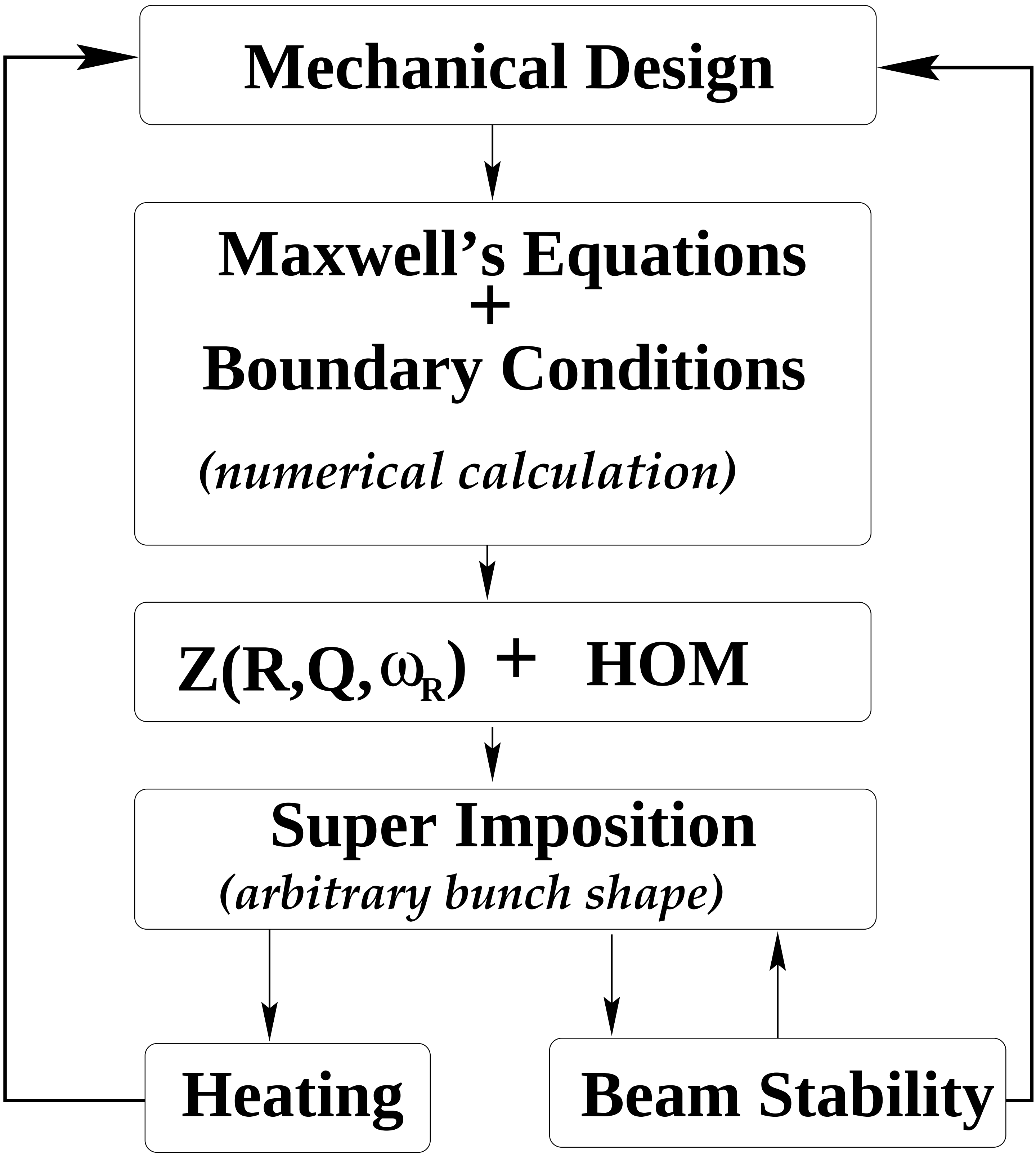
+

geometry of the vacuum chamber

→ ***careful design of all vacuum equipement***

- ***General Rules:***
  - ***smooth transitions***
  - ***shielded discontinuities***

- ***Quantitative Analysis:***
  - ***evaluate E and B for a given test distribution***
  - ***study the beam stability by super-imposition***


Mechanical Design
Maxwell's Equations
+
Boundary Conditions
(numerical calculation)
Z(R,Q,ωR) + HOM
Super Imposition
(arbitrary bunch shape)
Heating
Beam Stability

Summary Instabilities

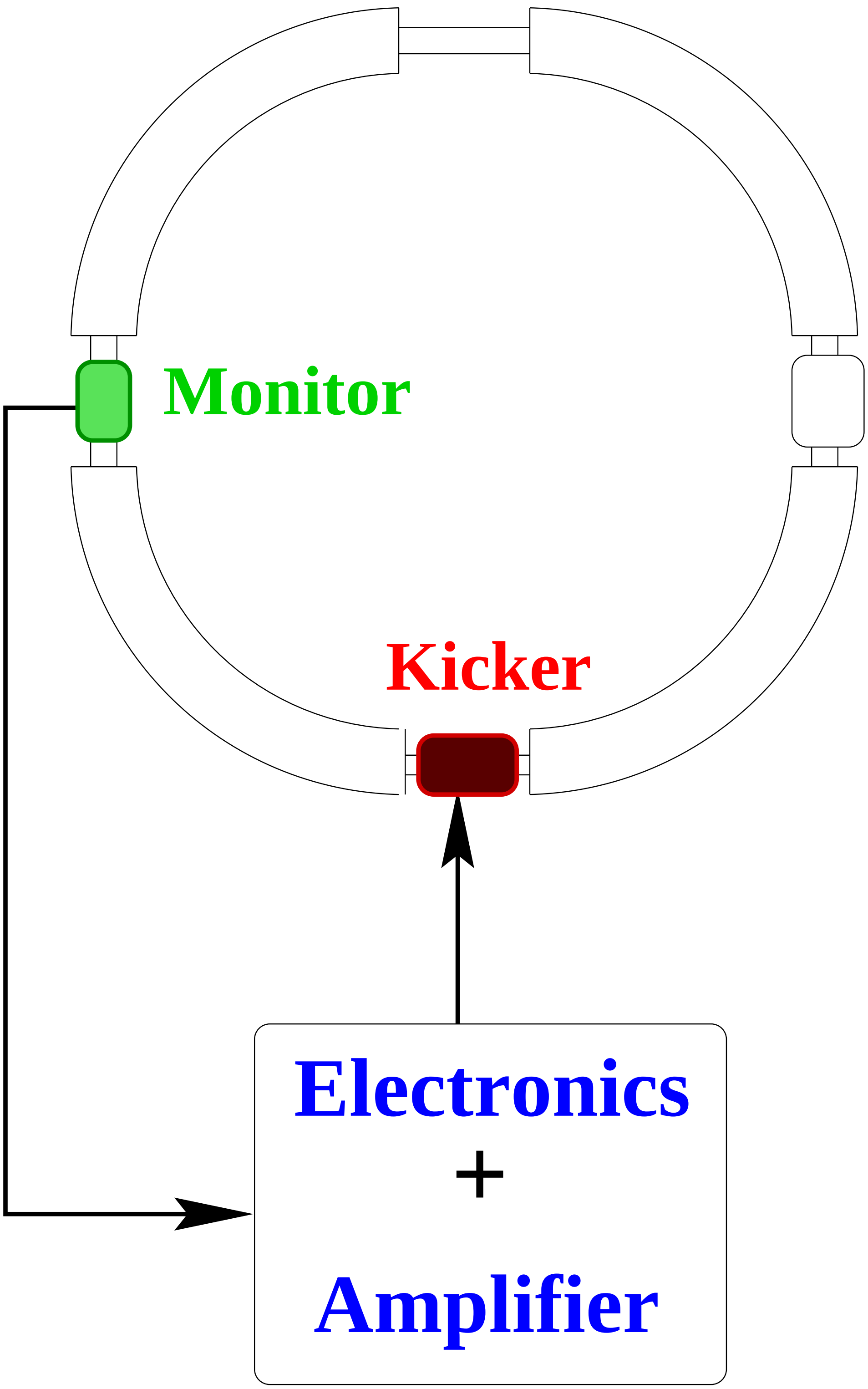
- Particles interact within each bunch
- Bunches interact with each other
  - surface properties
  - chamber geometry
- E and B fields depend on chamber and beam distribution
  - super imposition of multipole moments

→ design of chamber geometry

→ instability estimates

→ threshold currents

Feedback System

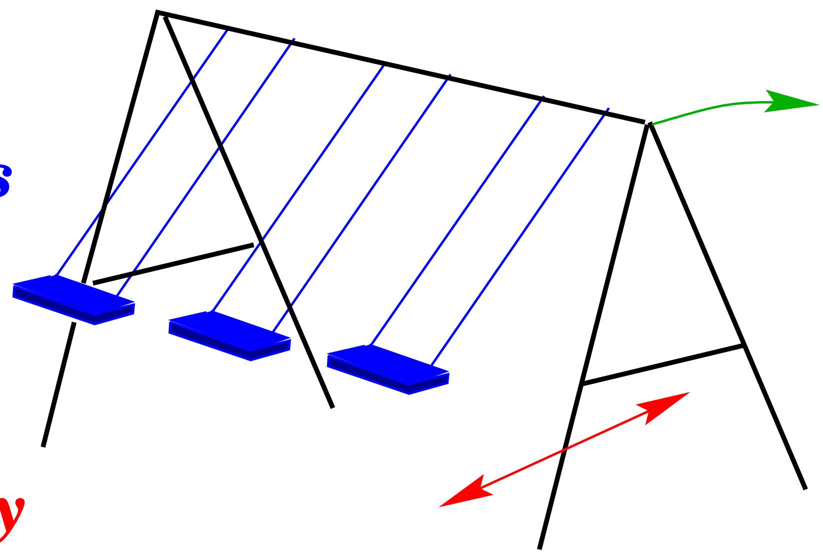


- ***Limit:***

power and bandwidth

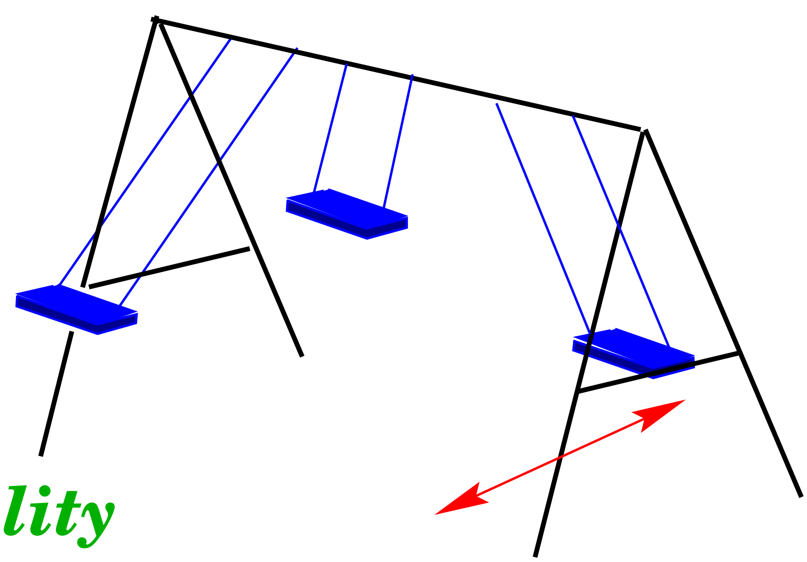
Landau Damping

- **Three Coupled Oscillators:**
  - *equal frequencies*



→ *instability*

- **Three Coupled Oscillators:**
  - *different frequencies*



→ *no instability*

- **Limit:**

→ *frequency spread (tune spread)*

→ *single particle resonances*