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Collective Effects in Damping Rings
A variety of collective effects can limit DR performance

- Key damping ring performance specifications are:
  - High beam current
  - Low emittance of extracted beam
  - Low orbit jitter

- As a first approximation, we can consider beam dynamics in the low-current limit, for example:
  - Frequency map analysis for acceptance studies
  - Dispersion and betatron coupling for emittance studies

- For operation at the specified currents, many other effects must be considered:
  - Interaction between particles in a single bunch, either directly, or via vacuum chamber
  - Interaction between different bunches
  - Interaction between particles in the beam and ions/electrons in the path of the beam

- Consequences of collective effects are varied, and include:
  - Particle loss (or current limits)
  - Emittance growth
  - Increased orbit jitter
We shall briefly consider some of the following effects:

- **Short-range wake fields**
  - Electromagnetic fields from a bunch affect the distribution of particles within the bunch

- **Long-range wake fields**
  - Electromagnetic fields from one bunch drive coherent oscillations of following bunches

- **Space-charge**
  - Particles see a focusing force dependent on their position within the bunch

- **Intra-beam scattering**
  - Particles within a bunch scatter off each other, leading to a growth in emittance

- **Fast ion instability**
  - The beam ionizes residual gas in the vacuum chamber: the ions affect the dynamics of the beam

- **Electron cloud effect**
  - The secondary electron yield of the vacuum chamber leads to a rapid increase in electron density within the chamber
Short-range wake fields affect beam dynamics

- Electromagnetic wake fields depend on:
  - Bunch charge and shape
  - Vacuum chamber material
  - Vacuum chamber geometry and length

Electric field following a point charge traveling along the axis of a vacuum chamber of circular cross-section.


- The wake field can be described by a Green’s function:

\[
\Delta \delta(z) = \frac{NCr_0}{\gamma} \int_{z}^{\infty} \lambda(z')W_{\parallel}(z - z')dz'
\]
In NLC MDR, instability appears at $5 \times$ nominal bunch charge

- Include only resistive wall wake field
- Track 5000 turns, starting from close to zero-charge equilibrium distribution
- Take the final 2000 turns, and perform Fourier analysis
- Plot amplitude of peak at the quadrupole frequency against bunch charge
Instability appears as distortion of particle distribution.
The impedance can be used to indicate thresholds

- For practical purposes, it is easier to work in frequency space
  - The Fourier transform of the wake function (integrated over the circumference) is the **impedance** $Z(\omega)$
  - The energy loss per turn $\sim I(\omega)Z(\omega)$
  - A crude characterization of the impedance is the “impedance per unit length”, $Z/n = Z(n\omega_0)/n$

- An indication of the *microwave instability threshold* is given by the Boussard criterion:

$$\frac{Z}{n} \leq \frac{(2\pi)^{3/2} E / e \sigma_0^2 \sigma_{\alpha} \alpha_p}{N_{ec}}$$

- This expression gives thresholds for the damping rings:
  - 100 mΩ for TESLA
  - 660 mΩ for NLC MDR

- Compare with some measured values:
  - $Z/n \sim 600$ mΩ for DAΦNE
    - A. Ghigo et al, EPAC 2002
  - $Z/n \sim 75$ mΩ for KEK-B (5× design value)
Long-range wake fields drive multibunch oscillations

- For NLC MDR, track $3 \times 192$ bunches through the full lattice
  - Represent each bunch as a single macroparticle, with only transverse dynamics
  - Include long-range resistive wall wake field
  - Include synchrotron radiation damping
- Start with only one bunch train having horizontal jitter
A feedback system will be needed to damp instabilities
Space-charge forces can drive betatron oscillations

Particles with smaller synchrotron amplitudes see larger vertical defocusing

no vertical emittance increase in straight sections
vertical emittance increased in straight sections with local coupling bump

Average CS Invariant versus initial $\Delta p/p$

Simulations for TESLA DR from Winni Decking, Snowmass 2001
Intra-beam scattering can cause emittance growth

- Scattering rate depends on:
  - Beam energy
  - Bunch charge
  - Emittance
- Measurements are difficult
  - Significant effects only at very low emittance
- Results from KEK-ATF support predictions of Bjorken-Mtingwa
- Expect no significant effects in TESLA DR
- Expect NLC MDR horizontal emittance growth from 2.4 μm to ~ 3 μm
Gas ionization can lead to a coupled-bunch instability

- Results from KEK-ATF
- Yosuke Honda, presented at ISG 11
Ion effects depend on pressure and on charge
Summary

- Vacuum chamber impedance can lead to single-bunch and multi-bunch instabilities
  - Concerns for both NLC and TESLA
  - Should be possible to build vacuum chamber to stay below single-bunch instability thresholds
  - Should be possible to use feedback systems to suppress multi-bunch instabilities

- Space-charge forces are a concern for TESLA
  - Large circumference means relatively large tune shifts
  - Use of “coupling bumps” should minimize effects

- Intra-beam scattering is a concern for NLC MDR
  - Effect is strongly dependent on energy
  - Present lattice may have sufficient margin in emittance

- Ion effects are a concern
  - Various effects in TESLA and NLC
  - More work needed to specify necessary vacuum pressure

- Electron cloud is the most serious concern
  - See talk by Mauro Pivi...