Particle Physics Phenomenology

April 13, 2004
Accelerator Theory

- Longitudinal stability (synchrotron oscillations)
- Strong focusing (alternating quadrupoles)
- Betatron oscillations (transverse oscillations)
- Instabilities
- Luminosity lifetime

Bergstrom and Goobar, Cosmology and Particle Astrophysics
M. Sands, SLAC-121, 1970
ACCELERATOR PHYSICS OF COLLIDERS - Revised August 2001
by K. Desler and D.A. Edwards (DESY), Particle Data Group
Circular Accelerator Theory - Stability

- Longitudinal stability (synchrotron oscillations)

\[ V = V_0 \sin(2\pi f_c + \phi_s) \]
Circular Accelerator Theory - Stability

- Betatron oscillations (transverse oscillations)

\[ x(s) = A\sqrt{\beta(s)} \cos(\psi(s) + \delta), \quad 1/\beta = d\psi/ds \]

- Tune:

\[ \nu = \frac{1}{2\pi} \int \frac{ds}{\beta} \]

- Resonances (particularly critical for storage rings):
  - If \( \nu \) is an integer, tiny perturbations will drive beam out of stable orbit
    - eg. the smallest imperfection in the guide field
      (and there will surely be at least one!)
      will act as a perturbation which is synchronous with the oscillation frequency.
  - More generally, a resonance occurs when \( mn_x + n\nu_y = r \), for integers \( m, n, \) and \( r \).
Storage Ring - Stability

- A resonance occurs when for certain “tunes” \( mv_x + nv_y = r \), for integers \( m, n, \) and \( r \).
- Significant effects are usually observed for small integers.
- The operating point of a storage ring is specified by giving both \( v_x \) and \( v_y \); and must be chosen to avoid the serious resonances.
Storage Ring - Typical Orbit

\[ x = A \cos\left(\frac{s}{\beta_n} + \theta\right) \]

\[ \int \frac{ds}{\beta} = \frac{L}{\beta_n} \]

BETATRON TRAJECTORY

APPROXIMATE SINUSOID

\[ 2\pi \beta_n \]
Storage Ring - Tune Shift

- The field gradient in the storage ring is never the ideal of the design.
- These gradient errors change the function of the betatron oscillations from the ideal orbit.
- And the betatron number is changed from its nominal value \( \nu \), to another value, \( \nu + \Delta \nu \). (\( \Delta \nu \) is called the tune shift)
- The tune shift \( \Delta \nu \) must be controlled to keep the operating point away from resonances.

\[
2\pi \Delta \nu = - \int \frac{\Delta \beta(s)}{\beta^2} \, ds
\]

- BEAM-BEAM TUNE SHIFT

\[
\Delta \nu_y = \frac{r_e}{2\pi} \frac{N B y}{\gamma \sigma_z (\sigma_x + \sigma_z)}
\]

\[
\Delta \nu_x = \frac{r_e}{2\pi} \frac{N B x}{\gamma \sigma_x (\sigma_x + \sigma_z)}
\]

\[
r_e = \frac{e^2}{4\pi \epsilon_0 mc^2}
\]
Luminosity

- If two bunches containing \( n_1 \) and \( n_2 \) particles collide with frequency \( f \), then the luminosity is

\[
\mathcal{L} = f \frac{n_1 n_2}{4\pi\sigma_x \sigma_y}
\]

- But recall beam size is a function of the tranverse emittance, \( \varepsilon \), and the \( \beta \) function

\[
\varepsilon = \pi \sigma^2 / \beta
\]

- So

\[
\mathcal{L} = f \frac{n_1 n_2}{4 \sqrt{\varepsilon_x \beta_x^* \varepsilon_y \beta_y^*}}
\]
Luminosity Lifetime

\[ \mathcal{L} = f \frac{n_1 n_2}{4 \sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}} \]

Storage ring luminosity lifetime is limited by:
- interactions of the two beams at the IPs
- beam size blowup due to intra-beam scattering
- reduction in the beam intensity due to rest gas scattering
- beam size reduction due to synchrotron radiation damping
- beam size blowup due to the non-linear beam-beam interactions

Different effects will dominate in different colliders

Future Super-B Factory (requires continuous injection)

<table>
<thead>
<tr>
<th>Lifetime Contribution</th>
<th>HER</th>
<th>LER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity lifetime (min)</td>
<td>15</td>
<td>58</td>
</tr>
<tr>
<td>Vacuum lifetime (min)</td>
<td>100</td>
<td>30</td>
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<tr>
<td>Touschek lifetime (min)</td>
<td>300</td>
<td>30</td>
</tr>
<tr>
<td>Beam-beam tune shift lifetime (min)</td>
<td>10</td>
<td>10</td>
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<td>Dynamic aperture lifetime (min)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Overall lifetime (min)</td>
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<td>4.1</td>
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</table>
# Luminosity Lifetime - PEP II

<table>
<thead>
<tr>
<th>HER I</th>
<th>LER I</th>
<th>Luminosity Spec Lumin</th>
<th>HER E</th>
<th>E LER E</th>
<th>E CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>018.87</td>
<td>mA</td>
<td>mA</td>
<td>3504</td>
<td>2.71</td>
<td>3802</td>
</tr>
<tr>
<td></td>
<td>10**30/Sec</td>
<td>N10<strong>30 / mA</strong>2/Sec</td>
<td>3120</td>
<td>10608</td>
<td></td>
</tr>
<tr>
<td>HER N Buckets / Pattern</td>
<td>LER N Buckets / Pattern</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>993</td>
<td>by3_trains_of_20</td>
<td>993 by3_trains_of_20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Last Owl/Day/Swing/24hr</td>
<td>81.9 53.0 66.3 201.2 Shift: 0.21 /pb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Luminosities</td>
<td>3845 3872 3882 3555</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![PEP-II Luminosity and Currents](image)

01/22/2003 00:00:33
Luminosity Lifetime - continuous injection

<table>
<thead>
<tr>
<th>I HER</th>
<th>I LER</th>
<th>Luminosity</th>
<th>Spec Lun</th>
<th>E HER</th>
<th>E LER</th>
<th>E CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1213.53</td>
<td>2146.17</td>
<td>7423</td>
<td>3.90</td>
<td>3823</td>
<td>3119</td>
<td>10551</td>
</tr>
</tbody>
</table>

mA  mA  10**30/Sec  N*10**30  /  mA*2/Sec  MeV  MeV  MeV

HER N Buckets / Pattern  LER N Buckets / Pattern
1369 by2_t14_t15_her_no_fb_m  1369 by2_t14_t15_ler_no_fb_m

Last Owl/Day/ Swing/24hr  152.3  142.0  201.5  495.8  Shift:  0.44 /pb

Peak Luminosities  8022  7878  8091  7493

PEP-II Luminosity and Currents

03/02/2004  00:00:42
Accelerators

- High Impedance Microwave Devices
- Superconducting Technology
- Electron Synchrotrons
- Electron Linear Accelerators
- Storage Rings
- Large Hadron Collider
- Linear Colliders
- Muon Collider
- VLHC
- Beam Cooling
- RF Separated Beams
- Synchrotron Radiation Facilities

  Bergstrom and Goobar, Cosmology and Particle Astrophysics
High-impedance Microwave Devices

- EM cavities were invented as a way to generate high voltage at moderate input power
  - Amplifiers
  - Oscillators
  - Cavities
  - Disk-loaded waveguides
Klystrons

- The klystron was invented at Stanford in 1937. The klystron served as an oscillator in radar receivers during WW II. After the war, however, very high-power klystrons were built at Stanford for use in the first linear accelerators. This opened the way for the use of klystrons not only in accelerators and radar, but also in UHF-TV, satellite communications, and industrial heating.

- Klystrons are high-vacuum devices based on the interaction of a well-focused pencil electron beam with a number of microwave cavities that it traverses, which are tuned at or near the operating frequency of the tube. The principle is conversion of the kinetic energy in the beam, imparted by a high accelerating voltage, to microwave energy. Conversion takes place as a result of the amplified RF input signal, causing the beam to form "bunches." These give up their energy to the high level induced RF fields at the output cavity. The amplified signal is extracted from the output cavity through a vacuum window.
Klystron

The electron gun (1) produces a flow of electrons. The bunching cavities (2) regulate the speed of the electrons so that they arrive in bunches at the output cavity. The bunches of electrons excite microwaves in the output cavity (3) of the klystron. The microwaves flow into the waveguide (4), which transports them to the accelerator. The electrons are absorbed in the beam stop (5).

http://www2.slac.stanford.edu/vvc/accelerators/klystron.html
Klystron

"Applegate Diagram"
Klystron

MAGIC SIMULATION (OUTPUT SECTION OF 8-CAVITY PPM KLYSTRON)

TIME DOMAIN

CURRENT PULSES INTO OUTPUT CAVITY

FREQUENCY DOMAIN (FOURIER TRANSFORM)

FREQUENCIES INTO OUTPUT CAVITY

\[ f_0 = \frac{1}{2 \pi \sqrt{LC}} \]
Klystron

X-Band:
75 Megawatts at 11.4 GHz, with 1.6 microsecond pulses
Superconducting Technology

- Superconducting materials added to the technology base of accelerators
- Niobium-titanium
  - multistrand cables
  - Niobium-tin for higher fields, but brittle
- Niobium coatings inside RF cavities
  - now practical and reliable
Simplified RF System Accelerator Layout

Low Level RF

Klystron

RF Distribution

RF Pulse

Modulator

Beam

Accelerator Structure
Superconducting RF System

Length = 50 m, Filling Fraction with Quads = 75%

Future: 2 x 9 Superstructure
One Feed per Pair, 6% Shorter
Superconducting RF Accelerating Structure

- Typical cylindrically symmetric cavity, showing the fundamental, or lowest RF frequency, mode (TM 010).
- The electric field is roughly parallel to the beam axis, and decays to zero radially upon approach to the cavity walls.
- Boundary conditions demand that the electric surface be normal to the metal surface.
- The peak surface electric field is located near the iris, or region where the beam tube joins the cavity.
- The magnetic field is azimuthal, with the highest magnetic field located near the cavity equator. The magnetic field is zero on the cavity axis.
X-Band (warm) RF System

NLC/JLC-X Linac RF Unit

75 MW PPM Klystrons (1.6 µs Pulses)

Solid State Induction Modulator
(500 kV, 2 kA, 1.6 µs Pulses)

150 MW
1.6 µs

475 MW
400 ns

Dual Mode SLED-II Delay Lines
(500 kV, 2 kA, 1.6 µs Pulses)

Accelerator Structures
(0.9 m, 65 MV/m Unloaded, 50 MV/m Loaded)
X-Band (warm) Accelerating Structure
X-Band Pulse Compression Achieved - 2003

Output Load Tree

Compressed output > 600 MW 400 ns.

Dual mode waveguide carrying 200 MW

Single mode waveguide input to the pulse compression system; 100 MW/Line for 1.6 μs

NLC experimental rf pulse compression system

Dualmode Resonant Delay Lines ~30 m

RF Input to the 4 50 MW klystrons

Physics 663, lecture 3
CLIC Drive Beam Power Source and 30 GHz Accelerator

Accelerated Beam

Drive-Beam

230 MW, 30 GHz

2 m

Accelerated Beam

Drive Beam Accelerator

937 MHz - 3.9 MV/m - 1.18 GeV

182 Modulators / Klystrons
50 MW - 92 µs

x2

Drive Bunch Compression (x 32)
and Distribution