Outline

■ Introduction of KEK injector Linac
■ Positron source
  ○ Introduction
  ○ Target
  ○ AMD
  ○ Positron source for SupreKEKB
■ Summary
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Positron production target

KEK electron/positron injector LINAC
Google street view is available
Accelerator complex in KEK Tsukuba

Beam from Injector and Storage Current
- **SuperKEKB**: 7 GeV e⁻ 2600 mA
- 4 GeV e⁺ 3600 mA
- **PF**: 2.5 GeV e⁻ 450 mA
- **PF-AR**: 6.5 GeV e⁻ 60 mA

**Notes**:
- Low emittance RF-gun
- Damping Ring
- PF 2.5 GeV
- 2x beam current
- PF-AR 6.5 GeV
- HER 7 GeV
- LER 4 GeV
- Belle II

**Icons**:
- Injector Linac 600 m
- High efficiency e⁺ generator
- e⁻ BT
- e⁺ BT
- SuperKEKB HER
- SuperKEKB LER
- linac
- PF
- PF-AR

**Figure Description**:
- The diagram illustrates the layout of the KEK Tsukuba accelerator complex, with various beam lines and storage rings.
- Key elements include the injector linac, damping rings, and high energy electron beams.
- Beam currents and energies are specified for different sections of the complex.
Accelerator complex in KEK Tsukuba

- 4 rings and 1 linac
  - Two light source rings
    - PF, PF-AR
  - Two collider rings
    - SuperKEKB LER, HER
- Parallel configuration
  - No booster ring
- All storage rings
  - Full energy injection
- Top-up injection
  - Keep intensity of photon constant
  - Compensate short life time (360 sec.)
- Two electron guns
  - RF gun for low emittance injection to SuperKEKB HER
  - Thermionic gun for high charge (10 nC) to produce large number of positrons
- Positron injection to LER

Our linac is an all-in-one injector

**Beam from Injector and Storage Current**

<table>
<thead>
<tr>
<th>Storage Ring</th>
<th>Energy</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>SuperKEKB</td>
<td>7 GeV e-</td>
<td>2600mA</td>
</tr>
<tr>
<td>PF:</td>
<td>4 GeV e+</td>
<td>3600mA</td>
</tr>
<tr>
<td>PF-AR:</td>
<td>6.5 GeV e-</td>
<td>60mA</td>
</tr>
<tr>
<td>PF-AR:</td>
<td>2.5 GeV e-</td>
<td>450mA</td>
</tr>
</tbody>
</table>
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Positron source for HEP

- Accelerate electron beam
- Inject electron beam into the target material
- Electron positron pairs are created
- Effectively collect positrons
- Accelerate positrons
- To increase the number of positron
  - Increase power of primary beam
  - Increase collection efficiency
Positron sources in the world

- Positron source is necessary for electron positron collider experiment
- Examples of positron source for previous, present and future high energy experiment in the world
- Specifications for positron source is determined from experiment

<table>
<thead>
<tr>
<th>Facility</th>
<th>SLC</th>
<th>LEP (LIL)</th>
<th>KEKB</th>
<th>BEPC</th>
<th>Super KEKB</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Institute</td>
<td>SLAC</td>
<td>CERN</td>
<td>KEK</td>
<td>IHEP</td>
<td>KEK</td>
<td>CERN</td>
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<tr>
<td>Country</td>
<td>U.S.A.</td>
<td>Switzerland</td>
<td>Japan</td>
<td>China</td>
<td>Japan</td>
<td>Switzerland</td>
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<tr>
<td>Max. repetition</td>
<td>Hz</td>
<td>120</td>
<td>100</td>
<td>50</td>
<td>50</td>
<td>50</td>
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<tr>
<td>Primary electron energy on target</td>
<td>GeV</td>
<td>33</td>
<td>0.2</td>
<td>4</td>
<td>0.14</td>
<td>3.2</td>
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<tr>
<td>Number of Primary electron per bunch</td>
<td>nC</td>
<td>8</td>
<td>0.5</td>
<td>10</td>
<td>0.86</td>
<td>10</td>
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<tr>
<td>Bunch per pulse</td>
<td></td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Primary electron beam power</td>
<td>kW</td>
<td>20</td>
<td>1</td>
<td>4</td>
<td>0.12</td>
<td>3.2</td>
</tr>
<tr>
<td>Beam size on target</td>
<td>mm</td>
<td>0.6 - 0.8</td>
<td>&lt; 2</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
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<tr>
<td>Target thickness</td>
<td>X₀</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Target material</td>
<td></td>
<td>W-25Re</td>
<td>W</td>
<td>W</td>
<td>W</td>
<td>W</td>
</tr>
<tr>
<td>Capture system</td>
<td></td>
<td>AMD</td>
<td>QWT</td>
<td>QWT</td>
<td>AMD</td>
<td>AMD</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>T</td>
<td>6</td>
<td>1</td>
<td>2</td>
<td>2.6</td>
<td>4.5</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>T</td>
<td>0.5</td>
<td>0.36</td>
<td>0.4</td>
<td>0.35</td>
<td>0.4</td>
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<tr>
<td>Mirror ratio</td>
<td></td>
<td>12</td>
<td>3</td>
<td>5</td>
<td>7.43</td>
<td>11.25</td>
</tr>
<tr>
<td>Aperture of 1st cavity</td>
<td>mm</td>
<td>18</td>
<td>25/18</td>
<td>20</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Gradient of 1st cavity</td>
<td>MV/m</td>
<td>30-40</td>
<td>10</td>
<td>20</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Frequency of cavity</td>
<td>MHz</td>
<td>2856</td>
<td>2998</td>
<td>2856</td>
<td>2856</td>
<td>2856</td>
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<tr>
<td>Positron yield @ linac end</td>
<td></td>
<td>1.78</td>
<td>0.0059</td>
<td>0.1</td>
<td>0.00196</td>
<td>0.4</td>
</tr>
<tr>
<td>Positron yield per primary energy @ linac end</td>
<td>/GeV</td>
<td>0.054</td>
<td>0.0295</td>
<td>0.025</td>
<td>0.014</td>
<td>0.125</td>
</tr>
<tr>
<td>DR energy</td>
<td>GeV</td>
<td>1.15</td>
<td>0.5</td>
<td>no DR</td>
<td>no DR</td>
<td>1.1</td>
</tr>
<tr>
<td>Number of positron per bunch</td>
<td>nC</td>
<td>10.7</td>
<td>0.035</td>
<td>1</td>
<td>0.0008</td>
<td>4</td>
</tr>
<tr>
<td>Number of positron per second</td>
<td>nA</td>
<td>1280</td>
<td>3.5</td>
<td>100</td>
<td>0.04</td>
<td>400</td>
</tr>
</tbody>
</table>
- World’s highest intensity positron source for HEP ever build
- Used for electron positron linear collider (SLC) in 1990s
- 100 times more positron compared with the source for LEP at the same time
  - SLC : linear collider
  - LEP : circular collider
- Model of many positron source including SuperKEKB positron source
History of positron source in KEK

TRISTAN (1985-1994)  primary electron / positron

KEKB (1998-2010)

SuperKEKB (2016-)
Requirement for SuperKEKB positron source

- Large number of positron in small emittance is needed for SuperKEKB
  - 50 time more positrons in total compared with that of previous experiment KEKB
  - 4 times more bunch charge
  - Higher duty (a few% → 100%)
  - Emittance should be better one order of magnitude → damping ring
  - Positron yield normalized by primary electron energy is highest among positron source ever build.

<table>
<thead>
<tr>
<th>Table 2 Injection parameters of positron</th>
<th>KEKB</th>
<th>Super KEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy in ring</td>
<td>3.5 GeV</td>
<td>4.0 GeV</td>
</tr>
<tr>
<td>stored current</td>
<td>1.6 A</td>
<td>3.6 A</td>
</tr>
<tr>
<td>life time</td>
<td>150 min</td>
<td>6 min</td>
</tr>
<tr>
<td>Norm. emittance (Hori. / Vert.)</td>
<td>1400 / 300</td>
<td>100 / 15</td>
</tr>
<tr>
<td>energy spread</td>
<td>0.125%</td>
<td>0.16%</td>
</tr>
<tr>
<td>bunch / pulse</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>bunch charge</td>
<td>1 nC</td>
<td>4 nC</td>
</tr>
<tr>
<td>circulation</td>
<td>$10^5$ Hz</td>
<td>$10^5$ Hz</td>
</tr>
<tr>
<td>frequency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>repetition rate</td>
<td>50 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td>injection efficiency</td>
<td>50%</td>
<td>50%</td>
</tr>
</tbody>
</table>
Requirement for SuperKEKB positron source

- Estimation of required positron amount

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Life</td>
<td>360 s</td>
</tr>
<tr>
<td>Current</td>
<td>3.6 A</td>
</tr>
<tr>
<td>Injection bunch charge</td>
<td>4 nC</td>
</tr>
<tr>
<td>Injection rate</td>
<td>25 Hz x 2 bunch</td>
</tr>
<tr>
<td>Injection efficiency</td>
<td>50 %</td>
</tr>
<tr>
<td>Circulation frequency</td>
<td>$10^5$</td>
</tr>
</tbody>
</table>

\[
\frac{dI}{dt} = \frac{3.6 [A]}{360 [s]} = 10 [mA/s]
\]

\[
4 [nC] \times 25 [Hz] \times 2 [bunch] \times 50[\%] \times 10^5[Hz] = 10 [mA/s]
\]
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Target material

- Inject accelerated electron to the target material
- Production cross section is roughly proportional to $Z^{2}$ (atomic number)$^{2}$
- Material is determined from the viewpoints of availability, machinability, melting point, activated species and so on
- W and Ta are usually used
Heat load to target

- Too much heat will damage the target
- Empirical formula was extracted from previous several experiments at SLAC
- More detailed consideration taking into account the energy deposition in depth is known as PEDD (peak energy deposition density) < 35 J/g
- When heat load is too high, to avoid concentration of the heat in a small area, target will be moved or rotated.

\[ \rho_{\text{max}} = \frac{NE}{\pi r^2} = 2 \times 10^{12} \text{ [GeV/mm}^2\text{]} \]

- \( \rho_{\text{max}} \): energy density
- \( N \): number of primary electron
- \( E \): energy of primary electron beam
- \( r \): radius of primary electron beam

<table>
<thead>
<tr>
<th>Beam power</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLC</td>
<td>20 kW</td>
</tr>
<tr>
<td>SuperKEKB</td>
<td>3.2 kW</td>
</tr>
<tr>
<td>ILC</td>
<td>( \sim 100 \text{ kW} )</td>
</tr>
</tbody>
</table>

Knowledge about target destruction is limited due to difficulty of experiment...
Target for SuperKEKB

- Made of W
- Target is implanted in Cu block and combined by HIP (Hot Isostatic Pressing) for cooling
- Cu pipe is brazed with the Cu block for cooling
- Small hole for electron beam beside the target
- Thickness of the target is $4X_0 = 14$ mm
- Diameter of the target is 4 mm
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AMD (adiabatic matching device)

- Spot size of the positron beam from the target is similar to the size of primary electron beam
- But divergence angle is very large
- To reduce beam loss in the following section, matching device is necessary
- Reduce angle at the expense of beam size

- Electron hit small point of the target.
- Positron comes from small spot.
- Angle distribution is large.

- Adiabatically expand position distribution.
- Angle distribution decrease.
- Matched to the aperture of the following section.
Motion of a charged particle in the uniform magnetic field

\[ F = m \frac{d\mathbf{v}}{dt} = q \mathbf{v} \times \mathbf{B} \]

Circular motion around magnetic field line

\[
\begin{align*}
    v_x &= v_\perp \cos(\omega_c t + \delta) \\
    v_y &= -v_\perp \sin(\omega_c t + \delta) \\
    x - x_0 &= r_c \sin(\omega_c t + \delta) \\
    y - y_0 &= r_c \cos(\omega_c t + \delta)
\end{align*}
\]

frequency \( \omega_c = \frac{|q|B}{m} \)

radius \( r_c = \frac{mv_\perp}{|q|B} \)
Motion of a charged particle in the gradient magnetic field

Radius is proportional to $1/B$
- In the high (low) field region, radius is small (large)
- When the magnetic field has gradient, center of motion drift
- Direction of the drift is perpendicular to both magnetic field and its gradient

Particle drift across the magnetic field lines
Motion of a charged particle in the gradient magnetic field

\[ \mathbf{F} = m \frac{d\mathbf{v}}{dt} = q\mathbf{v} \times \mathbf{B} \]

\[ F_x = m \frac{dv_x}{dt} = q(v_y B_z - v_z B_y) \]
\[ F_y = m \frac{dv_y}{dt} = q(v_x B_z - v_z B_x) \]
\[ F_z = m \frac{dv_z}{dt} = q(v_x B_y - v_y B_x) \]

\[ \mathbf{B} = (0, 0, B_z) \]

\[ F_x = m \frac{dv_x}{dt} = q v_y B_z \]
\[ F_y = m \frac{dv_y}{dt} = q v_x B_z \]
\[ F_z = m \frac{dv_z}{dt} = 0 \]
Motion of a charged particle in the gradient magnetic field

\[ F_x = m \frac{dv_x}{dt} = qv_y B_z \]

\[ F_y = m \frac{dv_y}{dt} = qv_x B_z \]

\[ F_z = m \frac{dv_z}{dt} = 0 \]

\[ v_x = v_\perp \cos(\omega_c t + \delta) \]

\[ v_y = -v_\perp \sin(\omega_c t + \delta) \]

\[ F_x = m \frac{dv_x}{dt} = -v_\perp \sin(\omega_c t + \delta) B_z \]

\[ F_y = m \frac{dv_y}{dt} = qv_\perp \cos(\omega_c t + \delta) B_z \]

\[ F_z = m \frac{dv_z}{dt} = 0 \]
Motion of a charged particle in the gradient magnetic field

\[ B_z(y) = B_0 + \frac{\partial B(y)}{\partial y} (y - y_0) \]

Bz is function of y
Taylor series of Bz in the 1st order

substitute \( y - y_0 = r_c \cos(\omega_c t + \delta) \)

\[ B_z(y) = B_0 + \frac{\partial B(y)}{\partial y} r_c \cos(\omega_c t + \delta) \]
Motion of a charged particle in the gradient magnetic field

\[ F_x = m \frac{dv_x}{dt} = -qv_{\perp} \sin(\omega_c t + \delta)B_z \]

\[ F_y = m \frac{dv_y}{dt} = qv_{\perp} \cos(\omega_c t + \delta)B_z \]

\[ F_z = m \frac{dv_z}{dt} = 0 \]

\[ B_z(y) = B_0 + \frac{\partial B(y)}{\partial y} r_c \cos(\omega_c t + \delta) \]

\[ F_x = m \frac{dv_x}{dt} = -qv_{\perp} \sin(\omega_c t + \delta) \left\{ B_0 + \frac{\partial B(y)}{\partial y} r_c \cos(\omega_c t + \delta) \right\} \]

\[ F_y = m \frac{dv_y}{dt} = qv_{\perp} \cos(\omega_c t + \delta) \left\{ B_0 + \frac{\partial B(y)}{\partial y} r_c \cos(\omega_c t + \delta) \right\} \]

\[ F_z = m \frac{dv_z}{dt} = 0 \]
Motion of a charged particle in the gradient magnetic field

\[ F_x = m \frac{dv_x}{dt} = -qv_\perp \sin(\omega_c t + \delta) \left\{ B_0 + \frac{\partial B(y)}{\partial y} r_c \cos(\omega_c t + \delta) \right\} \]
\[ F_y = m \frac{dv_y}{dt} = qv_\perp \cos(\omega_c t + \delta) \left\{ B_0 + \frac{\partial B(y)}{\partial y} r_c \cos(\omega_c t + \delta) \right\} \]
\[ F_z = m \frac{dv_z}{dt} = 0 \]

To obtain total amount of force during one cycle of cyclotron motion, integrate each formulae for one cycle \( \omega_c \)

Integral of \( \sin x \), \( \cos x \), \( \sin x \cos x = 0 \) (0 to \( 2\pi \))

\[ \langle F_x \rangle = 0 \]
\[ \langle F_y \rangle = -qv_\perp r_c \frac{\partial B(y)}{\partial y} \int_0^{2\pi/\omega_c} \cos^2(\omega_c t + \delta) dt \]
\[ \langle F_z \rangle = 0 \]

\[ = \frac{1}{2} \]
Motion of a charged particle in the gradient magnetic field

\[ \mathbf{F} = 0 - \frac{1}{2} q v_{\perp} r_c \frac{\partial B(y)}{\partial y} \]

Impulse to the particle during one cycle of cyclotron motion, when \( B \) is \( z \), \( \text{grad} \ B \) is \( y \) direction

Calculate drift speed in \( y \) direction by this force
Motion of a charged particle in the gradient magnetic field

\[ \mathbf{F} = q \mathbf{v} \times \mathbf{B} \]

Multiply \( \mathbf{B} \) from left side to both sides of equal

\[ \mathbf{F} \times \mathbf{B} = q \mathbf{v} \times \mathbf{B} \times \mathbf{B} \]

use \( \mathbf{a} \times \mathbf{b} \times \mathbf{c} = (\mathbf{a} \cdot \mathbf{c})\mathbf{b} - (\mathbf{b} \cdot \mathbf{c})\mathbf{a} \)

\[ \mathbf{F} \times \mathbf{B} = q\{(\mathbf{v} \cdot \mathbf{B})\mathbf{B} - (\mathbf{B} \cdot \mathbf{B})\mathbf{v}\} \]

First term is 0 since \( \mathbf{v} \) is perpendicular to \( \mathbf{B} \)

\[ \mathbf{F} \times \mathbf{B} = -qB^2 \mathbf{v} \]

\[ \mathbf{v} = -\frac{\mathbf{F} \times \mathbf{B}}{qB^2} \]

\[ \langle \mathbf{F} \rangle = \begin{pmatrix} 0 \\ \langle F_y \rangle \\ 0 \end{pmatrix} \]

\[ \mathbf{B} = \begin{pmatrix} 0 \\ 0 \\ B_z (y) \end{pmatrix} \]

\[ \mathbf{v} = \frac{1}{qB(y)^2} \begin{pmatrix} 0 \\ \langle F_y \rangle \\ 0 \end{pmatrix} \times \begin{pmatrix} 0 \\ 0 \\ B(y) \end{pmatrix} = \frac{1}{qB(y)^2} \begin{pmatrix} 0 \\ \langle F_y \rangle B(y) \\ 0 \end{pmatrix} \]
Motion of a charged particle in the gradient magnetic field

\[ \mathbf{v} = \frac{1}{qB(y)^2} \begin{pmatrix} \langle F_y \rangle B(y) \\ 0 \\ 0 \end{pmatrix} \]

\[ \langle F_y \rangle = -\frac{1}{2} q v_r \frac{\partial B(y)}{\partial y} \]

\[ \mathbf{v} = \begin{pmatrix} \frac{1}{2} m v_r^2 \frac{\partial B(y)}{\partial y} \\ \frac{1}{qB^2(y)} \frac{\partial B(y)}{\partial y} \\ 0 \\ 0 \end{pmatrix} \]

drift speed in x direction when B is z, grad B is y direction
Consider magnetic field
  z direction
  symmetric around z axis
  decrease as z in positive direction
Motion of a charged particle in the magnetic mirror

Frist, consider relation among $B_r$, $B_\theta$, $B_z$
From the symmetry, obviously $B_\theta = 0$

Since $\text{div} \mathbf{B} = 0$, 
\[ \frac{1}{r} \frac{\partial}{\partial r} (r B_r) + \frac{\partial B_z}{\partial z} = 0 \]
Motion of a charged particle in the magnetic mirror

\[ \frac{1}{r} \frac{\partial}{\partial r} (rB_r) + \frac{\partial B_z}{\partial z} = 0 \]

From this formula, \( B_r \) is expressed using \( B_z \)

\[ B_r = -\frac{1}{2} r \left[ \frac{\partial B_z}{\partial z} \right]_{r=0} \]

\( B_z \) is function of \( r \) and \( z \), \( B_z(r,z) \)

\[ \mathbf{B} = \begin{pmatrix} B_r \\ B_\theta \\ B_z \end{pmatrix} = \begin{pmatrix} -\frac{1}{2} r \left[ \frac{\partial B_z(r, z)}{\partial z} \right]_{r=0} \\ 0 \\ B_z(r, z) \end{pmatrix} \]
Motion of a charged particle in the magnetic mirror

\[
B = \begin{pmatrix}
    B_r \\
    B_\theta \\
    B_z
\end{pmatrix} = \begin{pmatrix}
    -\frac{1}{2} r \left[ \frac{\partial B_z(r, z)}{\partial z} \right]_{r=0} \\
    0 \\
    B_z(r, z)
\end{pmatrix}
\]

\[
F = \begin{pmatrix}
    F_r \\
    F_\theta \\
    F_z
\end{pmatrix} = \begin{pmatrix}
    q(v_\theta B_z - v_z B_\theta) \\
    q(-v_r B_z + v_z B_r) \\
    q(v_r B_\theta - v_\theta B_r)
\end{pmatrix} = \begin{pmatrix}
    q v_\theta B_z \\
    q(-v_r B_z + v_z B_r) \\
    -q v_\theta B_r
\end{pmatrix}
\]

Focus on \( F_z \)

\[
F_z = q v_\theta \frac{1}{2} r \left[ \frac{\partial B_z(r, z)}{\partial z} \right]_{r=0}
\]

Consider particle whose center of cyclotron motion is on z axis then \( r = r_c \), average over one cycle of cyclotron motion is

\[
\langle F_z \rangle = -\frac{1}{2} q v_\perp r_c \left[ \frac{\partial B_z(r, z)}{\partial z} \right]_{r=0} \quad \text{since } v_\theta = v_\perp = \text{constant}
\]
Motion of a charged particle in the magnetic mirror

\[ \langle F_z \rangle = -\frac{1}{2} q v_\perp r_c \left[ \frac{\partial B_z(r, z)}{\partial z} \right]_{r=0} \]

Substitute \( r_c = \frac{m v_\perp}{|q|B} \)

\[ \langle F_z \rangle = -\frac{1}{2} q v_\perp \frac{m v_\perp}{qB} \left[ \frac{\partial B_z(r, z)}{\partial z} \right]_{r=0} = -\frac{m v_\perp^2}{2B} \left[ \frac{\partial B_z(r, z)}{\partial z} \right]_{r=0} \]

Define magnetic moment as \( \mu = \frac{1}{2} \frac{m v_\perp^2}{B} \)

\[ \langle F_z \rangle = -\mu \left[ \frac{\partial B_z(r, z)}{\partial z} \right]_{r=0} \]

More generally, express component which is parallel to the magnetic field as \( || \)

\[ F_\parallel = -\mu \frac{\partial B}{\partial s} = -\mu \nabla_\parallel B \]
Motion of a charged particle in the magnetic mirror

Explanation about magnetic moment \( \mu = \frac{1}{2} \frac{m v^2}{B} \)

Particle rotate \( \frac{\omega_c}{2\pi} \) turn/s by cyclotron motion

Current flow can be expressed

\[ I = \frac{\omega_c}{2\pi} q \]

Since radius of rotation is \( r_c \), area \( A \) is

\[ A = \pi r_c^2 \]

then \( \mu = \frac{\omega_c q \pi r_c^2}{2\pi} = \frac{q}{2} \omega_c r_c^2 \)

substitute \( \omega_c = \frac{|q|B}{m} \quad r_c = \frac{m v_\perp}{|q|B} \)

\[ \mu = \frac{q qB}{2 \ m} \left( \frac{m v_\perp}{qB} \right)^2 = \frac{1}{2} \frac{m v^2}{B} \]
Consider component parallel to magnetic field

\[ F_{\parallel} = -\mu \frac{\partial B}{\partial s} \]

Equation of motion is

\[ m \frac{dv_{\parallel}}{dt} = -\mu \frac{\partial B}{\partial s} \]

multiply \( v_{\parallel} = \frac{ds}{dt} \) to both side

\[ mv_{\parallel} \frac{dv_{\parallel}}{dt} = -\mu \frac{\partial B}{\partial s} \frac{ds}{dt} \]

\[ \frac{d}{dt} \left( \frac{1}{2} mv_{\parallel}^2 \right) = -\mu \frac{dB}{dt} \]

Conservation of energy

\[ \frac{d}{dt} \left( \frac{1}{2} mv_{\parallel}^2 + \frac{1}{2} mv_{\perp}^2 \right) = 0 \]

Substitute \( \mu = \frac{1}{2} \frac{mv_{\perp}^2}{B} \)

\[ \frac{d}{dt} \left( \frac{1}{2} mv_{\parallel}^2 + \mu B \right) = 0 \]

\[ \frac{d}{dt} \left( \frac{1}{2} mv_{\parallel}^2 \right) + \frac{d}{dt} (\mu B) = 0 \]

\[ -\mu \frac{dB}{dt} + \frac{d}{dt} (\mu B) = 0 \]

To satisfy the equation, \( \frac{d\mu}{dt} = 0 \)
Motion of a charged particle in the magnetic mirror

Direction of magnetic field is $z$
Direction of magnetic field gradient is $r$
Particle drift to the direction of $\theta$
Motion of a charged particle in the magnetic mirror

Speed : $v_1$
Position in $r$ : $r_1$
Angle to $z$ axis : $\varphi_1$

Speed : $v_2$
Position in $r$ : $r_2$
Angle to $z$ axis : $\varphi_2$

conservation of kinetic energy

$$\frac{mv_1^2}{2} = \frac{mv_2^2}{2}$$

then

$$v_1 = v_2$$
Motion of a charged particle in the magnetic mirror

Speed: $v_1$
Position in $r$: $r_1$
Angle to z axis: $\varphi_1$

Conservation of magnetic moment

\[
\frac{mv_{1\perp}^2}{2B_1} = \frac{mv_{2\perp}^2}{2B_2}
\]

Substitute $v_{\perp} = v \sin \varphi$

then

\[
\frac{v_{1\perp}^2 \sin^2 \varphi_1}{B_1} = \frac{v_{2\perp}^2 \sin^2 \varphi_2}{B_2}
\]

Since $v_1 = v_2$, $\sin \varphi_2 = \sin \varphi_1 \sqrt{\frac{B_2}{B_1}}$

If $\varphi$ is small, $\sin \varphi = \varphi$

\[
\varphi_2 = \varphi_1 \sqrt{\frac{B_2}{B_1}}
\]
Motion of a charged particle in the magnetic mirror

Speed : \( v_1 \)
Position in \( r \) : \( r_1 \)
Angle to \( z \) axis : \( \varphi_1 \)

\[ r_2 = \frac{mv_{2\perp}}{|q|B_2} = \frac{mv_2 \sin \varphi_2}{|q|B_2} \]

substitute  \( \sin \varphi_2 = \sin \varphi_1 \frac{B_2}{\sqrt{B_1}} \)

\[ r_2 = \frac{mv_2 \sin \varphi_1}{|q|B_2} \sqrt{\frac{B_2}{B_1}} = \frac{mv_1 \sin \varphi_1}{|q|B_1} B_1 \frac{B_2}{\sqrt{B_1}} \]

(\( v_2 = v_1 \))

\[ r_1 \]

\[ r_2 = r_1 \frac{B_1}{\sqrt{B_2}} \]
Motion of a charged particle in the magnetic mirror

If the particle move from $B_1$ to $B_2$ ($B_2 < B_1$),

\[ v_1 = v_2 \] Velocity does not change

\[ r_2 = r_1 \sqrt{\frac{B_1}{B_2}} \] Radius increase

\[ \varphi_2 = \varphi_1 \sqrt{\frac{B_2}{B_1}} \] Angle to z axis decrease

Angle and position are determined by the ratio of magnetic field
Summary of AMD

- AMD (adiabatic matching device) = A device to convert divergence angle to beam size using slowly changing magnetic field

- Match the positron beam from the target to the following devices

  - Electron hit small point of the target.
  - Positron comes from small spot.
  - Angle distribution is large.
  - Adiabatically expand position distribution.
  - Angle distribution decrease.
  - Matched to the aperture of the following LAS.
Outline

- Introduction of KEK injector Linac
- Positron source
  - Introduction
  - Target
  - AMD
  - Positron source for SupreKEKB
- Summary
Positron source setup 1

Positron target and capture section
Positron source setup 2

FC head + BC + target = FC assembly

BC (bridge coil)  
FC (flux concentrator) head  
LAS (large aperture S-band)  
solenoid

target
Positron source setup 3

- Temp sensor
- Cooling water pipe
- W target
- φ2 mm hole for electron
- Beam
Flux concentrator

- Originally developed by SLAC in 1980s
- Consists of Cu block with tapered hole inside and Cu pipe brazed to the block.
- Cu pipe works as both current path and cooling pipe
- Coil shape with 0.2 mm width spiral slit
- Pulse current produce strong magnetic field (∼a few T) inside the tapered hole
Flux concentrator

- Peak magnetic field is 3.5 T at 12 kA, 6 us
- Current flows only surface of the block due to skin effect
  - Skin depth is about 0.2 mm in present parameters
- Shape of the magnetic field is determined by the shape of the tapered hole
After large discharge... 

Slit gap got narrow. Not possible to apply high voltage unless the gap will be expanded.
To suppress discharge

- Reduce voltage by snubber circuit
- Cu-alloy material for FC head
\[ V \sim L \frac{dI}{dt} \]

Due to resonance by capacitance of the cable and inductance of the load

High voltage probe

\[
I[kA] = \pi r^2
\]

\[ V_{\text{supply}} \]

\[ V_{\text{return}} \]

\[ V_{\text{supply}} - V_{\text{return}}[kV] \]

\[ \sim 3\text{MHz} \]
Snubber circuit

Avoid discharge
→ Reduce electric field between gap
→ Reduce voltage keeping current
→ Suppress rapid current change

Resister 3 Ω
Capacitor 100 x 4 nF

\[ V \sim L \frac{dl}{dt} \]
Current and voltage waveform w or w/o snubber circuit

- w/o snubber circuit
- w snubber circuit
New material for FC head

- Increase yield strength of the material
- Work hardening process was tested
  - Result was not clear
- Another approach using Cu-alloy

Requirements for material of the FC head are
- Good brazing characteristic
- High yield strength even after brazing
- High electric and thermal conductivity
Cu alloys

Cu, Cu-Zr, Cu-Cr, Cu-Ni-Si were tested.
Evaluation of brazing characteristic

Cu-Zr(SH-2)
Cu-Cr(SH-1)
Cu-Ni-Si(NC50)

P:Palladium
C1020
A:Silver
# Measured properties of materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Cu (C1020)</th>
<th>Cu-Cr (SH-1)</th>
<th>Cu-Zr (SH-2)</th>
<th>Cu-Si-Ni (NC50)</th>
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<tbody>
<tr>
<td><strong>Conductivity</strong></td>
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<tr>
<td>%IACS</td>
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<td>48.8</td>
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<td><strong>Hardness</strong></td>
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<td></td>
<td>45.9</td>
<td>55.8</td>
<td>95.3</td>
<td>61.2</td>
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<tr>
<td></td>
<td>95.3</td>
<td>61.2</td>
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<tr>
<td><strong>Tensile strength</strong></td>
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<tr>
<td>Mpa</td>
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<td>238.3</td>
<td>648.7</td>
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<td></td>
<td>658.8</td>
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<tr>
<td><strong>Elongation</strong></td>
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<td>%</td>
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<td><strong>Yield strength</strong></td>
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<td>Mpa</td>
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<td>513.1</td>
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</table>
Strain-stress curve for C1020 and NC50

- **C1020**
- **NC50**

![Graph showing the strain-stress curve for C1020 and NC50](image)

- **Y-axis:** Stress (MPa)
- **X-axis:** Strain (%)

The graph indicates the stress versus strain for C1020 and NC50 materials. The curve for NC50 starts at a lower stress level compared to C1020 and shows a steeper increase in stress with strain, reaching a peak and then stabilizing at a higher stress level compared to C1020.
Strain-stress curve for C1020 and NC50
Strain-stress curve for C1020 and NC50

NC50 after aging (precipitation hardening)
Strain-stress curve for C1020 and NC50

- C1020 after brazing
- NC50 after brazing
- NC50 after aging (precipitation hardening)
Yield strength

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1020</td>
<td>322.3</td>
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<tr>
<td>SH-1</td>
<td>293.6</td>
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<tr>
<td>SH-2</td>
<td>348.2</td>
</tr>
<tr>
<td>NC50</td>
<td>551.8</td>
</tr>
</tbody>
</table>

Positron source made of NC50 is now under test
Outline

- Introduction of KEK injector Linac
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  - Introduction
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Summary and outlook

- KEK electron positron injector Linac has been providing electron and positron for many years.
- AMD is a key device for efficient positron source
- Intense positron source for SuperKEKB is under development
  - To suppress discharge,
    - Snubber circuit
    - New Cu alloy
- Medical and industrial use of positron is increasing, however intense positron source for high energy physics experiment is decreasing
  - SuperKEKB is nearly the only experiment in operation now
- Several future project such as ILC, FCCee, CLIC, CEPC require high power positron source.
  - As long as electron positron collider experiment continue, succession of know-how is important

Thank you for your attention!!