Electron source for Linear Colliders

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Introduction

Lepton Collider



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•e+e- collision is a simple interaction.

- •The initial states is well defined.
- •Easy to reconstruct the f nal states.
- •This full reconstruction is powerful and essential for e^+e^- colliders.

Hadron collider and Lepton Collider

Hadron Collider



e+

- Collision between composite particles (protons).
- Initial state is not defined.
- Extremely high energy, high event rate, large noise.

Lepton Colliders

Collision between elementary particles (leptons) The initial state is well defined.

Full reconstruction of events.



Well defined initial states

- Electron and position are spin $\frac{1}{2}$ fermions. Two eigen spin states.
- In SU(2)xU(1) gauge theory, these two spin eigen states are different particles which has different weak Iso-spin and hyper charge.

$$l_{L} \equiv \begin{pmatrix} \mathbf{v}_{eL} \\ e_{L} \end{pmatrix} \quad I_{W} = \frac{1}{2}, \quad Y_{W} = -1$$

$$e_{R} \quad I_{W} = 0, \quad Y_{W} = -2$$

- Ideal well defined initial states means that the beam contains only one spin state.
- Practicaly, the beam should be polarized.

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$$P \equiv \frac{N_R - N_L}{N_R + N_L}$$



Injector

- What is the injector?
 - Generate accelerate-able particle beams;
- What is the accelerate-able beams?
 - Right amount : Charge
 - Right shape : Beam size, emittance, bunch length
 - Right direction: along beam line
 - Right time : timing, phase



Electron Chun

- Generate electron beam
 - Right amount : Charge
 - Right shape : Beam size, emittance, bunch length
 - Right direction: beam line
 - Right time : timing, phase



Bunching (1)

- Bunching : Bunch the beam. What is the bunch?
 - Beam : collimated particle f bw.
 - Bunch : collimated and clustered particle f bw. The length should be short enough comparing to the RF period for uniform acceleration.



Bunching (2)

- Bunching: Shorten the longitudinal length of the beam.
 - Right amount : Charge
 - Right shape : Beam size, emittance, bunch length
 - Right direction: beam line
 - Right time : timing, phase



Bunching



Electron Emission



Electronic States

- Electrons are confined in a well potential.
- At T=0, electrons are in ground states.
- At T>0, some electrons are excited by thermal energy.



Electronic States

- Electrons are distributed according to Fermi-Dirac Distribution.
- Fermi energy : the maximum electron energy state at T=0.
- Work-function : height of the vacuum cliff from the Fermi energy.



Peaceful Cliff



Electrons in grond states

Once they are excited....

Some extreme guys are extracted as beam

Hot Electrons

Fermi Level

Storm a Brewing (RF/08)

Electronic States (2) Electron density in a metal is product of state density $D(\varepsilon)$ and distribution function $f(\varepsilon)$, $n(\epsilon) = D(\epsilon) f(\epsilon)$ (1-1) State density in phase space $(x, v_x) - (x+dx, v_x+dv_x)...$ İS $D(\epsilon) = \frac{2m^2}{k^3} dx \, dy \, dz \, dv_x \, dv_y \, dv_z \qquad (1-2)$ Distribution function $f(\varepsilon)$ is given by Fermi-Dirac function $f(\epsilon) = \frac{1}{\exp\left(\frac{\epsilon - \mu}{kT}\right) + 1} \qquad (1 - 3)$ Number of electron with energy $\varepsilon < E$ is $N(\epsilon) = \int_{0}^{E} f(\epsilon) D(\epsilon) d\epsilon \qquad (1-4)$

Thermal Electron Emission

- ► If the temperature is suff ciently high, so that electrons are distributed up to more than the vacuum level (E_0) , the electrons escape out to the outside.
- The gap between the vacuum level and the Fermi energy is Work function, φ, which characterize the thermal emission.



 $E > E_0 = E_f + \phi$

Emission Density (1)

Number of emitted electron: In depth (z-direction)

z <

$$v_z \Delta t$$
 (1-5)

Kinetic energy for z-direction must be more than vacuum potential energy, $\mu+\Phi$

$$v_z \ge v_{vac} \equiv \sqrt{\frac{2(\mu + \phi)}{m}}$$
 (1-6)

Number of electron emitted from the cathode is give by

$$N = \int dx \int dy \int_{0}^{v_{z} \Delta t} dz \int_{-\infty}^{+\infty} dv_{x} \int_{-\infty}^{+\infty} dv_{y} \int_{v_{vac}}^{+\infty} dv_{z} f(\epsilon) D(\epsilon) \quad (1-7)$$

e dx dy dy

material

vacuum

Emission Density (2)

By integrating x, y, z and inserting distribution function,

$$N = \Delta x \Delta y \Delta t \frac{2m^3}{h^3} \int_{-\infty}^{+\infty} dv_x \int_{-\infty}^{+\infty} dv_y \int_{v_{vac}}^{+\infty} dv_z \frac{v_z}{\exp\left(\frac{\epsilon - \mu}{kT}\right) + 1}$$
(1-8)

From this equation, emission density per unit time is obtained

$$\sigma \equiv \frac{N}{\Delta x \Delta y \Delta t} = \frac{2m^3}{h^3} \int_{-\infty}^{+\infty} dv_x \int_{-\infty}^{+\infty} dv_y \int_{v_{vac}}^{+\infty} dv_z \frac{v_z}{\exp\left(\frac{\epsilon - \mu}{kT}\right) + 1} \quad (1 - 9)$$

Emission Density (4)

Because $\varepsilon - \mu \gg kT$, $f(\varepsilon)$ is approximated as

$$\frac{1}{\exp\left(\frac{\epsilon - \mu}{kT}\right) + 1} \sim \exp\left(\frac{\mu - \epsilon}{kT}\right)$$
(1-10)

The density is simplif ed as

$$\sigma = \frac{2m^3}{h^3} \int_{-\infty}^{+\infty} dv_x \int_{-\infty}^{+\infty} dv_y \int_{v_{vac}}^{+\infty} dv_z v_z \exp\left(\frac{\mu - \epsilon}{kT}\right) \qquad (1 - 11)$$

Replacing the energy with the velocity,

$$\epsilon = \frac{m}{2} \left(v_x^2 + v_y^2 + v_z^2 \right)$$

$$\sigma = \frac{2m^3}{h^3} \exp\left(\frac{\mu}{kT}\right) \int_{-\infty}^{+\infty} dv_x \int_{-\infty}^{+\infty} dv_y \int_{v_{vac}}^{+\infty} dv_z v_z \exp\left(\frac{-m(v_x^2 + v_y^2 + v_z^2)}{2kT}\right) \quad (1-12)$$

Emission Density (5)

Integral for v_x and v_y can be performed as

$$\int_{-\infty}^{+\infty} dv_x \int_{-\infty}^{+\infty} dv_y \exp\left(\frac{-m(v_x^2 + v_y^2)}{2kT}\right) = \frac{2\pi k T}{m} \qquad (1-13)$$

and for v_z as

$$\int_{v_{vac}}^{+\infty} dv_z v_z \exp\left(\frac{-mv_z^2}{2kT}\right) = \frac{kT}{m} \exp\left(\frac{-mv_{vac}^2}{2kT}\right) \qquad (1-14)$$

we obtain

$$\sigma = \frac{4\pi m k^2 T^2}{h^3} \exp\left(-\frac{\Phi}{kT}\right) \qquad (1-1)$$

Electric current density J is given by

$$U = \frac{4\pi e m k^2 T^2}{h^3} \exp\left(-\frac{\Phi}{kT}\right) \qquad (1-16)$$

Richardson-Dushman Equation $J = AT^2 e^{-\frac{\Phi}{kT}}$ (1-17)

$$A = \frac{4 \pi emk^2}{h^3} = 1.20 \times 10^6 [A/m^2 K^2]$$

A : thermionic emission constant

T: Temperature (K)

- k : Boltzmann constant ; 1.38E-23 (J/K)
- e : electronic charge
- m : electron mass
- h : Plank constant ; 6.63E-34 (Js)

Field Emission (1)

- FE is electron emission observed from cold (not hot) material when a high electric f eld is applied.
 - Large surface f eld makes the potential barrier very thin.
 - The tunnel current becomes signif cant with >1E+8 V/m.





Field Emission (3)

By Taylor expansion,

$$(E_0 - \epsilon_z)^{3/2} = \left[\phi + (\mu - \epsilon_z) \right]^{3/2} = \phi^{3/2} + \frac{3}{2} \phi^{1/2} (\mu - \epsilon_z) \qquad (1-21)$$

In the low temperature limit, the current density is

$$J(F) = \frac{4\pi em}{h^3} \int_0^\infty d\epsilon_z (\mu - \epsilon_z) \exp\left[-8\pi \frac{\sqrt{2m}}{3heF} (E_0 - \epsilon_z)\right]$$
$$= \frac{4\pi em}{h^3} \exp\left[\frac{-8\pi \sqrt{2m}}{3heF} \varphi^{3/2}\right] \int_0^\infty d\epsilon \epsilon \exp\left[-4\pi \frac{\sqrt{2m}}{heF} \varphi^{1/2} \epsilon\right] \quad (1-22)$$

where '= z-. $J = \frac{e^{3}F^{2}}{8\pi\phi} \exp\left(-\frac{8\pi\sqrt{2m}}{3heF}\phi^{3/2}\right) \qquad (1-23)$

(Fowler-Nordheim formula)

Fowler-Nordheim Plot

Fowler-Nordheim formula with field enhancement factor

$$J = \frac{e^3 \kappa^2 F^2}{8 h \pi \phi} \exp\left(-\frac{8 \sqrt{2m}}{3 h e \kappa F} \phi^{3/2}\right) \qquad (1-24)$$

H: local f $\dot{\mathbf{e}}$ ld enhancement by surface condition, Taking ln(J/F²) and plotting as a function of 1/F,

$$\ln(J/F^2) = \ln\left(\frac{e^3\kappa^2}{8h\pi\phi}\right) - \left(\frac{8\sqrt{2m}}{3he\kappa}\phi^{3/2}\right)\frac{1}{F} \qquad (1-25)$$

The gradient gives information on the surface condition, H.

(RF case)

$$\ln\left(J/F^{2.5}\right) = \ln\left(\frac{e^{3}\kappa^{2}}{8\,h\,\pi\,\phi}\right) - \left(\frac{8\sqrt{2m}}{3\,he\,\kappa}\,\phi^{3/2}\right)\frac{1}{F} \qquad (1-25\,')$$



Emission Densiy (1)

Photo-electron current density is given by

$$J = \frac{4\pi emkT}{h^3} P \int_{E_0 - h\nu}^{\infty} d\epsilon_z \ln \left[1 + \exp \frac{(\mu - \epsilon_z)}{kT} \right] \qquad (1 - 27)$$

where P is transition probability by photon excitation. For further manipulation, replacing $y=(z+h -E_0)/kT$ and =h(-0)/kT,

$$J = \frac{4\pi emkT}{h^3} P \int_{E_0 - hv}^{\infty} d\epsilon_z \ln\left[1 + \exp\frac{(\mu - \epsilon_z)}{kT}\right]$$
$$= \frac{4\pi emk^2T^2}{h^3} P \int_0^{\infty} dy \ln\left[1 + \exp(\delta - y)\right] \qquad (1 - 29)$$

Emission Density (2) $f(\delta) = \int_{0}^{\infty} dy \ln[1 + e^{\delta - y}] \quad (1 - 30)$ (a) =h(- 0)/kT <0 (ph. energy is less than FE) $f(\delta) = \sum_{n=1}^{\infty} (-1)^{n-1} \frac{e^{n\delta}}{n} \int_{0}^{\infty} dy e^{-ny}$ $= \sum_{n=1}^{\infty} (-1)^{n-1} \frac{e^{n\delta}}{n^{2}} \quad (1 - 31)$

since

$$\ln(1+x) = \sum_{n=1}^{\infty} (-1)^{n-1} \frac{x^n}{n} \qquad (1-32)$$
$$\ln(1+e^{\delta-y}) = \sum_{n=1}^{\infty} (-1)^{n-1} \frac{e^{n(\delta-y)}}{n} \qquad (1-33)$$

Photo-electron Emission

- Electron emission by photoelectron effect.
 - Photons excite electrons into higher energy states.
 - If the states are higher than the vacuum level, the electrons goes to vacuum.
 - Condition for photo-emission is approximately,

F е Vacuum level 0 Ef Photon N(E)

 $h\nu > \phi$ (1-26)

Emission Density (3)
(b) =h(- 0)/kT >0 (ph. energy is more than FE),

$$f(\delta) = \left| \int_{0}^{\delta} dy + \int_{\delta}^{\infty} dy \right| \left[\ln \left(1 + e^{\delta - y} \right) \right]$$
(1-34)

(b-1) f ist integral, w= -y $\int_{0}^{\delta} dy \ln (1 + e^{\delta - y}) = \int_{0}^{\delta} dw \ln (1 + e^{w})$ $= \int_{0}^{\delta} dw \left[w + \ln (1 + e^{-w}) \right]$ $= \left[\frac{w^{2}}{2} \right]_{0}^{\delta} + \sum_{n=1}^{\infty} (-1)^{n} \frac{1}{n^{2}} [e^{-nw}]_{0}^{\delta}$ $= \frac{\delta^{2}}{2} + \frac{\pi^{2}}{12} + \sum_{n=1}^{\infty} (-1)^{n} \frac{e^{-n\delta}}{n^{2}} \qquad (1-35)$

Emission Density (4)
(b-2) second integral, w=y-

$$\int_{\delta}^{\infty} dy \ln(1+e^{\delta-y}) = \int_{0}^{\infty} dw \ln(1+e^{-w})$$

$$= \left[w \ln(1+e^{-w})\right]_{0}^{\infty} + \int_{0}^{\infty} dw \frac{w}{1+e^{w}} \quad (1-36)$$
the first term of rhs is 0 and the second term is

$$\int_{0}^{\infty} dw \frac{w}{1+e^{w}} = \frac{\pi^{2}}{12} \qquad (1-37)$$

Finally, sum of (b-1) + (b-2) gives f()

$$f(\delta) = \frac{\delta^2}{2} + \frac{\pi^2}{6} + \sum_{n=1}^{\infty} (-1)^n \frac{e^{-n\delta}}{n^2} \qquad (1-38)$$

Quantum Eff tiency

Quantum Eff ciency, , is practically used to qualify the photoelectron emission

$$\eta = \frac{number \, of \, photo \, electrons}{number \, of \, photons} \tag{1-40}$$

With practical units,

$$\eta[\%] = 124 \frac{J[nA]}{P[\mu W]\lambda[nm]} \qquad (1-41)$$

Fowler Equation

$$J = AT^{2}P \begin{vmatrix} \sum_{n=1}^{\infty} (-1)^{n-1} \frac{e^{n\delta}}{n^{2}} & \delta < 0 \\ \frac{\delta^{2}}{2} + \frac{\pi^{2}}{12} + \sum_{n=1}^{\infty} (-1)^{n} \frac{e^{-n\delta}}{n^{2}} & \delta > 0 \end{vmatrix}$$

$$A = \frac{4\pi e mk^2}{h^3}$$

- Fowler equation gives photo-current spectrum.
- The absolute density is hard to estimate because *P* depends on the surface condition.



 $\left(1\right)$
Photo-cathode

- Basically, all solid material can be used as photocathode.
- The light wave length has to be shorter than the threshold wavelength of the photo-electron effect.
- Metal is popular as photo-cathode for accelerator.
- Semi-conductor is popular as photo-cathode for Phototube, since the high QE and operable for wide wavelength region.
- Semi-conductor becomes popular as photo-cathode for accelerator too, because the high QE, longer wavelength, and polarization.
- Insulator is hardly used as photo-cathode because it is operable only with tiny current. Otherwise, it is charged up.

Metal Cathode



 Fermi level is in a band.

- Emission threshold = work function.
- Work-function is in UV.
- QE is generally low, 0.01% 0.001%.
- Temporal response is fast <ps.
- Cu, Mg, Ag, are popular.

Semiconductor Cathode

band gap.

10%.

slow > ps.

work function.

from VL to UV.

material, more than

NaK₂Sb, LaB₆, etc.



Polarized electron

- Polarized Electron is generated by photo-emission with GaAs semiconductor cathode.
- It is essential for polarization that GaAs is direct transition type semiconductor.
- Transition from the valence band (VB) to conduction band (CB) by circularly polarized photon is spin dependent.



Excitation

Transition probability ~ Fermi's golden rule

$$W_{i \to f} = \frac{2\pi}{\hbar} M^2 D(\hbar \omega) f(E)$$

- M: Matrix element
- D: joint density of states of ħω photon
- *f: f*ermi distribution function
- Considering only near the band gap, the transition probability is proportional to M^2 .





Right handed polarization



Polarization Enhancement

GaAs

- Further enhancement by breaking the degeneration.
- It is achieved by GaAs/GaAsP Strained Super-lattice Crystal.



Polarized Electron from GaAs

- Super-lattice structure to break the degeneration.
- The polarization is maximized when the laser wavelength is matched to the band gap.





NEA surface (1)

- To extract the excited electron in CB to vacuum, surface strucure is important.
- NEA (Negative Electron Affnitiy) surface is artif cially made.
- NEA surface : vacuum potential is lower than CB bottom.



NEA surface (2)

- NEA surface is made by evaporation of Cs and O₂/NF₃ on cleaned GaAs.
- GaAs: chemical etching by H₂SO₄ and treatment by HCl-Isopropanol solution followed by heat cleaning.
- Alternating deposition of Cs and O₂/NF₃.
- The process should be made in extremely low vacuum pressure, <5.0E-9Pa.



Related Physics Process

Roll of the field

Electrons in cathode is tightly bond by the potential.
The external f eld on the cathode surface is important not only to lead the beam, but also to extract the beam from the cathode.

Surface f eld modif es the work function of cathode.
 (Schottky effect)

•The emittable current density is limited by the coulomb potential of the beam and the external field. (Space charge limitation)

Schottky Effect (1)

Force by mirror charge

$$F_m(z) = -\frac{1}{4\pi\epsilon} \frac{e^2}{(2z)^2} \qquad (2-1)$$

Potential of the mirror charge

$$V_m(z) = -\frac{1}{4\pi\epsilon} \int_z^\infty \frac{e}{4z'^2} dz'$$
$$= -\frac{e^2}{16\pi\epsilon z} (2-2)$$



Schottky Effect (2)

Mirror charge potential and external f eld give

$$V(z) = \phi_0 - \frac{e^2}{16\pi \epsilon z} - eEz \qquad (2-3)$$

Maximum $at \quad z_{max} = \frac{1}{4} \sqrt{\frac{e}{\pi \epsilon E}}$

$$V_{max} = V_0 - e \sqrt{\frac{eE}{4\pi\epsilon}} \quad (2-4)$$

Effective work function

$$\phi(E) = V_{max} - \mu = \phi_0 - e \sqrt{\frac{eE}{4\pi\epsilon}} \quad (2-5)$$



Space Charge Limit (2)

Poisson equation is

$$\frac{d^2 V(z)}{dz^2} = -\frac{\rho(z)}{\epsilon_0} \qquad (2-7)$$

The current density J is given by the charge density and velocity v,

 $J = -\rho(z)v(z)$ (2-8) According energy conservation,

$$\frac{d^2 V(z)}{dz^2} = \frac{J}{\epsilon_0} \sqrt{\frac{m}{2e}} V(z)^{-1/2} \quad (2-10)$$

Anode Cathode $(z=d, V=V_A)$ (z=0, V=0) 7 Charge density Ξ(Z) $\frac{1}{2}mv(z)^2 = eV(z) \quad (2-9)$

Space Charge Limit

- Electron terminates the electric f lux (Gauss's law).
- Electric f eld is weakened by the space charge.
- When all f lix is terminated by the charge, the f eld at the cathode surface is disappeared (no further emission).



SC Limited Current (3)

Multiplying 2(dV/dz) and integrating both sides,

$$\left.\frac{dV(z)}{dz}\right|^2 = \frac{4J}{\epsilon_0} \sqrt{\frac{m}{2e}} V(z)^{1/2} \qquad (2-11)$$

Taking square root of both sides and integrate it again,

$$\frac{4}{3}V^{3/4} = \sqrt{\frac{4J}{\epsilon_0}} \sqrt[4]{\frac{m}{2e}} z \qquad (2-12)$$

Extract J

$$U = \frac{4\epsilon_0}{9} \sqrt{\frac{2e}{m}} \frac{V(z)^{3/2}}{\frac{Z^2}{2}}$$

= 2.33×10⁻⁶ $\frac{V^2(z)^{3/2}}{z^2}$ (2-13)

SC Limited Current (3)

Substituting the anode conditions, the space charge limited current density is obtained as

$$J(V_A, d) = 2.33 \times 10^{-6} \frac{V_A^{3/2}}{d^2} \qquad (2-14)$$

V(z), E(z), (z) are expressed as a function of z

$$V(z) = V_{A} \left(\frac{z}{d}\right)^{3/4}$$
(2-15)

$$E(z) = -\frac{dV(z)}{dz} = -\frac{4}{3} \frac{V_{A}}{d^{4/3}} z^{1/3}$$
(2-16)

$$\rho(z) = -\frac{4\epsilon_{0}}{9} \frac{V_{A}}{d^{4/3}} z^{-2/3}$$
(2-17)

Child-Langmuir Law

If the cathode emission density is more than the space charge limit, the current is given by C-L law

$$I = 2.33 \times 10^{-6} \frac{S V^{3/2}}{d^2} = P V^{3/2} (A) \qquad (2-18)$$

- V and d : voltage and distance between two electrodes.
- S: cathode area
- **P** : perveance defined as;

$$P = 2.33 \times 10^{-6} \frac{S}{d^2} (AV^{-3/2}) \qquad (2-19)$$

DC Gun design (2D SC Limited Flow) 2D case solution for SC limited f bw;

$$V(z, y) = V_{A} \frac{\Re \left[(z+iy)^{4/3} \right]}{d^{4/3}} \qquad \mathbf{y}$$
$$= V_{A} (z^{2}+y^{2})^{2/3} \cos \frac{4}{3} \theta \quad (2-22)$$

V=0 equi-potential line:

$$\cos\frac{4}{3}\theta = 0 \rightarrow \theta = \frac{3}{8}\pi$$

By setting an electrode (Wehnelt) with this angle, SCL f bw is produced.

 $\nabla \cdot \nabla V(z) = 0$ $\frac{3}{8}\pi$ $V(z) = V_A \left(\frac{z}{z} \right)$

DC Gun design : Real geometry

•By setting Wehnelt and anode electrodes to reproduce the potential, SC limited current is extracted from the cahode. •This is Pierce type gun; •Conventional type,

Cathode

- •DC bias voltage,
- •Thermionic cathode,
- •Continous beam.

Space Charge Force (1)

The space charge force causes various beam quality degradations, e.g. bunch lengthening, emittance growth, tune shift, etc. The effect is suppressed by acceleration because it scaled as $1/\gamma^2$.

Consider a cylindrical beam with a constant density.

$$E_r = \frac{N e}{2\pi a^2 \epsilon_0} r \qquad (2-23)$$

magnetic f lux density by the current,

$$B(r) = \frac{\mu_0}{r} \int_0^r r' J(r') dr' \qquad (2-24)$$

Space Charge Force (2)

Current density is

The magnetic f lix is given as

The Lorentz force to electron is

$$J(r) = \frac{Ne}{\pi a^2} \beta c \qquad (2-25)$$

$$B(r) = \frac{\mu_0 N e \beta c}{2 \pi a^2} r$$
 (2-26)

$$\boldsymbol{F} = e \, \boldsymbol{E} + e \, \beta \, c \, \boldsymbol{B} = \frac{N e^2 \, r}{2 \, \pi \, a^2 \, \epsilon_0} (1 - \beta^2) \, \vec{e}_r$$

which is scaled as $1/\gamma^2$.

$$=\frac{Ne^2r}{2\pi a^2\epsilon_0\gamma^2}\vec{e}_r\qquad(2-27)$$

Beam Emittance

Emittance is defined as area in the phase space where particles occupy. The phase space is defined x and x'=dx/ds

$$\dot{x} = \frac{dx}{ds} = \frac{v_x}{v} = \frac{p_x}{p} \sim \frac{p_x}{p} \qquad (2-28)$$

In general, RMS emittance is given as

$$\epsilon_x = \sqrt{\langle x^2 \rangle \langle \dot{x}^2 \rangle - \langle x \dot{x} \rangle^2}$$
 (2-29)

If there is no correlation between x and x',

$$\epsilon_x = \sqrt{\langle x^2 \rangle \langle x^2 \rangle}$$
 (2-30)

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ps

рх

Normalized emittance

In acceleration, transverse momentum p_x is conserved, but the total momentum p is increased as

Px P1 P2
$$p_s = \gamma \beta mc$$
 (2-31)
The emittance is inversely scaled. To avoid the energy dependence
() on the emittance, the normalized emittance is defined
 $\epsilon_{nx} = \gamma \beta \epsilon_x$
 $= \gamma \beta \frac{R}{2} \sqrt{\left|\left(\frac{p_x}{\gamma \beta m c}\right)^2\right|} = \frac{R}{2mc} \sqrt{\langle p_x^2 \rangle}$ (2-32)

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What is matter on Emittance?

- •Emittance shows the quality of the beam.
- •Small emittance beam can be focused down to a small spot size.
- •Small emittance beam can be extremely parallel.
- •The shape of the beam depends on the optics, but the emittance is invariant in the frame of linear optics.



Linear

What is the fundamental limit on the emittance?

Everybody wants small emittance beam, but what is the limit?
One of the limit is the intrinsic emittance which the emitted beam from the cathode already has.

•The source of the intrinsic emittance of cathode is thermal energy and laser energy (photo-cathode case).

Emittance of Beam from Thermionic Cathode (1)

Thermionic electron emission density is already obtained

$$N = \frac{4\pi m}{h^3} k^2 T^2 \exp\left(-\frac{\Phi}{kT}\right) \qquad (2-33)$$

Total transverse energy of emitted electron is obtained with a similar calculation as

$$E_{t} = \frac{4\pi m}{h^{3}} \int_{\mu+\phi}^{\infty} d\epsilon_{z} \int_{0}^{\infty} d\epsilon_{t} \epsilon_{t} \exp\left(-\frac{\epsilon_{z}+\epsilon_{t}-\mu}{kT}\right)$$
$$= \frac{4\pi m}{h^{3}} k^{3} T^{3} \exp\left(-\frac{\Phi}{kT}\right) \qquad (2-34)$$

The average transverse energy per electron is

$$\langle \epsilon_t \rangle = \frac{E_t}{N} = kT$$
 (2-35)

Emittance of Beam from Thermionic Cathode (2)

Thermal energy is,

$$\langle \epsilon_x \rangle = \frac{kT}{2}$$
 (2-36)

The transverse emittance is

 $\varepsilon_{x} = \sqrt{\langle x^{2} \rangle \langle x^{2} \rangle} = \frac{1}{\gamma \beta mc} \sqrt{\langle x^{2} \rangle \langle p_{x}^{2} \rangle} \qquad (2-37)$ Substituting the thermal energy $\frac{\langle p_{x}^{2} \rangle}{2m} = \langle \epsilon_{x} \rangle = \frac{kT}{2}$, emittance is

$$\varepsilon_{x} = \frac{1}{\gamma \beta} \sqrt{\langle x^{2} \rangle \frac{kT}{mc^{2}}} = \frac{1}{\gamma \beta} \frac{R}{2} \sqrt{\frac{kT}{mc^{2}}} \qquad (2-38)$$
$$\varepsilon_{nx} = \gamma \beta \varepsilon_{x} = \frac{R}{2} \sqrt{\frac{kT}{mc^{2}}} \qquad (2-39)$$

Emittance of Beam from Photo-cathode (1)

Transverse energy from photo-emission is

$$E_{t} = \frac{4\pi m}{h^{3}} \int_{\mu+\phi-h\nu}^{\infty} d\epsilon_{z} \int_{0}^{\infty} d\epsilon_{t} \epsilon_{t} \left[\exp\left(\frac{\epsilon_{z}+\epsilon_{t}-\mu}{kT}\right) + 1 \right]^{-1} \qquad (2-40)$$

With T=0 approximation,

$$E_{t} = \frac{4\pi m}{h^{3}} \int_{\mu+\phi-h\nu}^{\mu} d\epsilon_{z} \int_{0}^{\mu-\epsilon_{z}} d\epsilon_{t}\epsilon_{t}$$
$$= \frac{4\pi m}{h^{3}} \frac{(h\nu-\phi)^{3}}{6} \qquad (2-41)$$

Emittance of Beam from Photo-cathode (2)

Average of the transverse energy is

$$N = \frac{4\pi m}{h^3} \int_{\mu+\phi-h\nu}^{\mu} d\epsilon_z \int_0^{\mu-\epsilon_z} d\epsilon_t = \frac{4\pi m}{h^3} \frac{(h\nu-\phi)^2}{2} \qquad (2-42)$$

$$\epsilon_{x,y} = \frac{E_t}{2N} = \frac{h\nu-\phi}{6} \qquad (2-43)$$

The momentum is

Emittance is

$$\langle p_x^2 \rangle = 2m \epsilon_{x,y} = m \frac{h \nu - \phi}{3} \quad (2 - 44)$$

$$\epsilon_{x} = \frac{1}{\gamma \beta} \frac{R}{2} \sqrt{\frac{h\nu - \phi}{3mc^{2}}} \qquad (2 - 45) \qquad \epsilon_{nx} = \frac{R}{2} \sqrt{\frac{h\nu - \phi}{3mc^{2}}} \qquad (2 - 46)$$

Emittance of Beam from Photo-cathode (3)

Acounting thermal energy, the transverse energy becomes

$$\epsilon_{x,y} = \frac{E_t}{2N} = \frac{h\nu - \phi}{6} + \frac{kT}{2} \qquad (2-47)$$

The transverse emittance is

$$\varepsilon_{x} = \frac{1}{\gamma \beta} \frac{R}{2} \sqrt{\frac{h\nu - \phi}{3mc^{2}} + \frac{kT}{mc^{2}}} \qquad (2-48)$$
$$\varepsilon_{nx} = \frac{R}{2} \sqrt{\frac{h\nu - \phi}{3mc^{2}} + \frac{kT}{mc^{2}}} \qquad (2-49)$$

Bunch Compression (1)

- In any RF accelerators, the beam should be concentrated in a short period of longitudinal space for small energy spread;
 - $E=E_0\cos(\omega t-ks)$, $k\int s \ll 1$ for eff cient acceleration.
- Bunch compressor(buncher) shorten the bunch length down to an adequate size for acceleration.



Bunch Compression (2)

- There are two ways for bunch compression:
 - Velocity Bunching
 - Magnetic Bunching
- Velocity bunching is effective only for low energy;
 - Some particle source can generate only long bunch or continuous beam.
 - It should be bunched for RF acceleration.
- Magnetic bunching is effective for all energy region.
 - It is employed sometimes to get extremely short buhc after acceleration.
 - It is also used to compensate the bunch lengthning in DR for Linear colliders.

Velocity Bunching (1)

- Bunch compression is performed by velocity modulation within a bunch;
 - Bunch head is decelerated.
 - Bunch tail is accelerated.
- Velocity is modulated by energy modulation according to

$$c\beta = c\sqrt{1 - \frac{1}{\gamma^2}} \qquad (2 - 54)$$

• Velocity is saturated to c at $\gamma >>1$. Then, it works only for low energy particle ($\beta <1$).
Velocity Bunching (2)

Energy modulation by RF cavity,

 $dE = eV_0 \frac{d\sin(\omega t)}{dt} dt \qquad (2-55)$

In linear approximation,

$$\frac{dE}{E_0} \sim \frac{eV_0}{E_0} \omega \, dt \qquad (2-56)$$

Next higher order

$$\frac{dE_3}{E_0} \sim -\frac{eV_0}{E_0} \frac{1}{6} (\omega \, dt)^3 \quad (2-56')$$



Velocity Bunching (3)

► After energy modulation, drift the beam

If $d\tau$ equals to -dt, all particles are gathered at the bunch center.

► Because all electrons concentrate at t=0 position, RF phase of bunching determines the bunch longitudinal position.

► It works only for low energy.





Magnetic Bunching (1)

- Energy Modulation : RF cavity.
- Dispersive section : different path for different energy.
- Bunch head (tail) travels longer (shorter) path and bunch length becomes shorter.



Magnetic Bunching (2)

- Bunch compression is performed by energy modulation with dispersive path length difference.
 - Chicane, Wiggler, Arc, etc.
- A path length difference by a dispersive section, Δz is

$$\Delta z = \eta_l \frac{\Delta P}{P} \qquad (2-59)$$
$$\eta_l = \int_L ds \frac{\eta}{\rho} \qquad (2-60)$$

It works well for any energy particle.

Common formalism (1)

- Bunching can be formalized with transfer matrix in linear approximation.
- Energy modulation is made by RF (acc- and deceleration).
- Drift space (velocity bunching) or drift through a dispersive section (magnetic bunching) rotates the beam in phase space.
- The bunch rotates 90 deg.



Common formalism (1)

- Bunching can be formalized with transfer matrix in linear approximation.
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Common formalism (2) **R**-matrices $\begin{bmatrix} z(s) \\ \delta(s) \end{bmatrix} = \begin{bmatrix} 1 & R_{56} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} z(0) \\ \delta(0) \end{bmatrix} \quad (2-60)$ Drift space: $R_{56} = -\frac{L}{\gamma^2 \beta^2}$ (2-61) $\begin{bmatrix} z(s) \\ \delta(s) \end{bmatrix} = \begin{bmatrix} 1 & R_{56} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} z(0) \\ \delta(0) \end{bmatrix} \quad (2-62)$ Dispersive section: $R_{56} = \eta_l = \int ds \frac{\eta}{\Omega} \quad (2 - 63)$ $\begin{bmatrix} z(s) \\ \delta(s) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} z(0) \\ \delta(0) \end{bmatrix} \quad (2-64)$ $R_{65} = \frac{1}{z} \frac{\Delta E}{E} \sim \pm \frac{eV_0}{E} \frac{\omega}{\beta c} \quad (2-65)$ **RF** Energy modulation



Common formalism (4)

 $\delta(\Delta E/E)$

 R_{65}

 R_{56}

•When the bunching condition is satisf ed,

$$\begin{bmatrix} z(s_2) \\ \delta(s_2) \end{bmatrix} = \begin{bmatrix} 0 & R_{56} \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} z(s_0) \\ \delta(s_0) \end{bmatrix} \quad (2-68)$$

•The position z(s₂) does not depends on z(s₀).

•This is a good mechanism to stabilize the bunch position.

Common formalism (5)

 $\delta(\Delta E/E)$

Ζ

Final bunch length after an optimized BC section (1+R₅₆R₆₅=0) is determined by the initial energy spread;

$$z_2 = R_{56} \delta_0$$
 (2-69)

The actual bunch length is also limited by non-linearity.

$$z_{nl} = R_{56} \frac{dE_{nl}}{E}$$

Energy Compression

Energy compression is a reverse process of the bunch compression. Bean transfere by dispersive section (R_{56}) and energy modulation (R_{65}) is

$$\begin{aligned} \begin{bmatrix} z(s_2) \\ \delta(s_2) \end{bmatrix} &= \begin{bmatrix} 1 & 0 \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} 1 & R_{56} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} z(s_0) \\ \delta(s_0) \end{bmatrix} \\ &= \begin{bmatrix} 1 & R_{56} \\ R_{65} & 1 + R_{56} R_{65} \end{bmatrix} \begin{bmatrix} z(s_0) \\ \delta(s_0) \end{bmatrix} (2-71) \end{aligned}$$

Matching condition for energy compression is $1+R_{56}R_{65}=0$ (2-72) The final energy spread is

$$\delta(s_2) = z(s_0) R_{65} \qquad (2-73)$$



 $\delta(\Delta E/E)$

Electron Gun

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Electron Cun

	Cathode	Extraction Field	Comments
Pierce type (thermionic DC)	Thermal	Static	Still conventional
Photo Cathode DC Gun	Photo-electron	Static	For special cathode
Photo-cathode RF Gun	Photo-electron	RF	Advanced
Thermionic RF Gun	Thermal	RF	Advanced

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Thermionic DC gun

- Thermionic cathode with DC bias.
- It is a conventional gun widely used.
- Continous beam or
- Bunched beam by grid switching, but the bunch length is down to ~1ns.
- Energy at the gun exit is

$$K = (\gamma - 1)mc^2 = eV \qquad (3 - 1)$$



Thermionic Gun: A typical conf guration (1)

- The beam emission is controlled by grid bias. The primary bunching and bunch repetition is determined by the grid pulse duration and repetition.
- The bunch length is shortened by bunchers for further acceleration.



Thermionic Gun: A typical conf guration (2)

- Electron beam is extracted from thermionic gun continuously.
- RF cavity (Pre-Buncher) modulates the velocity of the electron beam. After some drift, the beam is bunched.
- The bunch repetition is determined by the Pre-Buncher frequency.
- Further bunching is made by SHB and Buncher.



Thermionic Cathode

- According to Richardson-Dushman equation, material with low work-function operated at high temperature is favor to generate high density electron beam.
- Practical operation temperature is limited by the operable temperature T_e which 10 atomic layers are lost per second at.
- Figure of merit of thermionic cathode is

$$\eta = \frac{\Phi}{T_e} \qquad (3-2)$$

Thermionic Cathode

- $/T_e < 2.0$ is practically used as thermionic cathode.
- Impregnated type BaO cathode is widely used for conventional accelerator.
- CeB₆ and LaB₆ have advantage for high-brightness beam generation.

Material	A(ev)	Te (K)	A/Te(x1E+3)
W	4.5	2860	1.57
Та	4.1	2680	1.53
Мо	4.2	2230	1.88
Cs	1.9	320	5.94
Th-W	2.6	1800	1.44
BaO	1.0	1400	0.71
CeB ₆	2.5	1400	1.79
LaB ₆	2.5	1400	1.79

Photo-Cathode DC Gun (1)

- Electron beam is generated by Photo-emission with laser.
- The bunch structure (repetition and duration) is determined by the laser.
- Beam extraction by a static electric f eld.
- Beam energy at the gun exit is determined by the bias voltage,



 $K = (\gamma - 1)mc^2 = eV \qquad (3 - 3)$

Photo-Cathode DC Gun (2)

- Because the velocity at the gun exit is slow, the f ist cavity is "low cavity", which synchronizes with the low speed beam.
- Time duration, in which the bunch travels cell length, L, has to be synchronize to the phase advance per cell.



Photo-Cathode DC Gun (3)

- In some case, SHB is placed for bunching.
- Low-beta cavity followed by accelerator.



HV Operation (1)

- Since the bunch length at the gun exit is determined by the space charge limit, higher voltage operation makes a higher peak current and bunch length can be shorter.
- Short bunch length from gun has merits
 - Simpler bunching section,
 - Energy spread after acceleration is smaller,
- For higher voltage operation, dark current by field emission from electrode surface should be suppressed.

HV Operation (2) \ddot{Y} . '• $\in \bullet \in \epsilon t \in c \ldots$ F• $d t \in c \notin i$



Only 7mm² area exposed maximum field gradient.

ILCWS2005, Snowmass

HV Operation (3)

Future light source based on ERL employs PC-DC gun. HV terminal Guard ring • For extremely low emittance, HV operation is essential. Support rod Ceramic insulator Electron beam Anode Cathode

HV operation (4)

- Segmented ceramic.
- Guard ring for FE electron.
- HV conditioning up to 550kV.
- 8 hour stable operation at 500kV without any damage.
- It is a world record of PC DC gun.



R. Nagai, RSI(81)033304(2010)

<u>RF</u> <u>Gun</u> (1)

- RF field for beam extraction.
- Electron beam is generated inside of the cavity.
- Laser photo-cathode type is popular.
- Beam from thermionic cathode type has a wide energy spred.



RF Gun(2)

- Typical cavity configuration is 1.5 cells.
- TM01, pi-mode.
- Energy at the gun exit is given by

K

$$= (\gamma - 1)mc^{2} = \int e E(z, t) c \beta(t) dt$$
$$= \int e \sqrt{RP} \cos(\omega t - \phi) c \beta(t) dt \qquad (3 - 4)$$

P: RF input power, R:shunt impedance

Electron source for Linear Colliders

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ILC Requirements

Parameters	
Pulse length	0.9ms
Pulse repetition <i>frep</i>	5Hz
# of bunches in a pulse <i>n</i> ^₅	2625 (1310)
Bunch separation	369(670)ns
# of electrons in a bunch N	2x10 ¹⁰
Micro bunch length at source	1ns
Peak current	3.2A
Electron Polarization	80%



Basic Concept

- NEA GaAS cathode with circularly polarized laser is the only solution for polarized electrons.
- Beam extraction by a static electric f eld (DC photocathode gun) because RF gun is not compatible with GaAs cathode.



Bunch extraction Required Laser Pulse Energy

•From QE vs Polarization curve, required laser pulse energy is decided.

 $E_{L}[\mu J] = \frac{124 \times Q[nC]}{\eta[\%] \times \lambda[nm]}$



T. Nishitani et al., J of Appl. Phy. 97,094907(2005)

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Bunch extraction Bunch shape

tь

S

•GaAs cathode is only operable in DC bias gun structure. The space charge limit gives possible charge density, J.

•Assuming a resonable spot size, the bunch length in time *t_b* is decided to extract 3.2nC bunch charge.

$$J[A/m^{2}] = 2.33 \times 10^{-6} \frac{V^{3/2}}{d^{2}}$$

I[A] = JS



Injector Design

- If the bunch length at gun *t*^b is adequate for RF acceleration, any bunching section is not needed.
- Otherwise, we need a bunching section.
- RF period for the bunching should be long enough comparing to *t_b* for linear modulation.
- RF frequency for the bunching should be harmonics of bunch repetition, i.e. RF of the main linac.

 $T_{bunching} \gg t_b$

 $T_{bunching} = n T_{mainRF}$ $n \in N$

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Surface Charge Limit (1)

- For Linear colliders, multibunch electron beam are generated.
- Anomalous charge limit phenomena is observed (Surface Charge Limit) for high intensity and multi-bunch beam generation.



GaAs with a Be-dope 5E+18cm³

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K. Togawa, NIM A 414 (1998) 431-445
Surface Charge Limit (2)

- The surface charge limit is caused by Photo-voltage effects;
- Some electrons, J_{surface} is captured at BBR(Band Bending Region).
- By the captured electrons, the effective vacuum level is increased.
- Photo-voltage effects decrease size of EA and limit the current.



K. Togawa, NIM A 414 (1998) 431-445

Surface Charge Limit (3)

- SCL was compensated by enhancement of the recombination of the captured electron.
- The recombination was boosted by increasing the positive carrier density in VB by high p-doping.
- Finally, 5.0A/cm² is achieved. It is more than the requirement of ILC gun.

(a) sample 1b(Na=0.5),
(b) sample 2a(Na=1.0), and
(c) sample 3(Na=2.0). The laser
intensity is 1 to 150 W/cm2.

G.A. Mulhollan, Phy. Lett. A 282 (2001)

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Surface Charge Limit (4)

- Super-lattice Cathode has an advantage against SCL.
- J_{escape} is proportional to the size of NEA.
- The effective size of NEA in Super-lattice cathode is larger than that of bulk-GaAs.
- The escape probability, J_{esacape}/J_{total} is larger for Super-lattice cathode. SCL current should be higher for Super-lattice cathode.



Super-Lattice Cathode

- GaAs/GaAsP super lattice cathode for high polarization (90%) and high QE (0.5%).
- Heavy P (Zn) -doped GaAs surface layer to suppress SCL.
- Cathode is operated in Space charge limit regime.



Bunching(1)

- According Child-Langmuir law, peak current of ILC Electron gun (120kV, d~5cm, and 1cm diameter) is ~3A.
- To generate ILC bunch (3.2nC), 1.1ns is necessary.
- It is signif cantly longer than RF acceleration and should be shorten down to 10ps.
- A special section for this purpose is placed at downstream of Electron gun: Bunching section
- SHB(Sub Harmonic Buncher)
 - 216.7 MHz (1/6 of 1.3 GHz)
 - 433 Mhz (1/3 of 1.3 GHz)
 - Buncher : 1.3 G Hz NC tube.

Bunching (2)

- Bunch length is 1ns at the exit of Electron gun.
- Velocity bunching to shorten the bunch length for RF acceleration.
- Acceleration by high gradient RF cavity for the whole bunch, compensates the velocity modulation and the beam becomes rigid.



ILC and CLIC comparison

Accelerator Beam parameter	CLIC (ACC.)	ILC
Pulse length	156ns	0.86
Pulse reputation	50Hz	5Hz
# of micro bunches in a pulse	312	2625
Bunch separation	500ps	369ns
Bunch charge	0.9nC	3.2nC
Polarization	80%	80%
Bunch length at gun	100ps	1ns
Peak current	9A	3A

• A similar system to ILC based on Polarized electron source with GaAs cathode is assumed.

Less bunch charge, but high repetition rate and high average current in a pulse are challenging.

•

Summary

- Fundamentals of electro-emission and electron gun are explained.
- Polarized electron is generated by photo-emission from NEA GaAs cathode with circularly polarized laser.
- ILC and CLIC electron sources are DC bias gun with NEA GaAs.