Electron source for Linear Colliders

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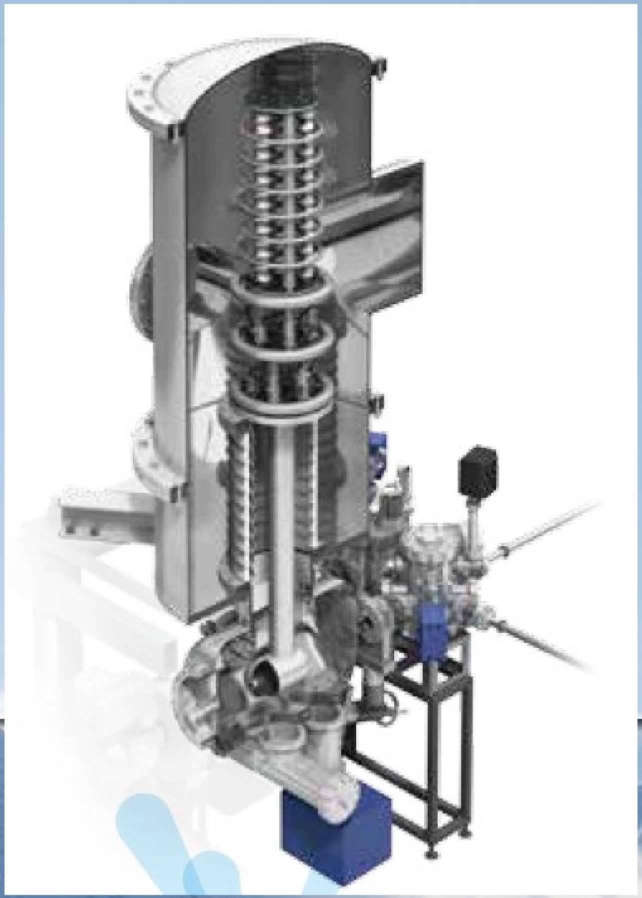

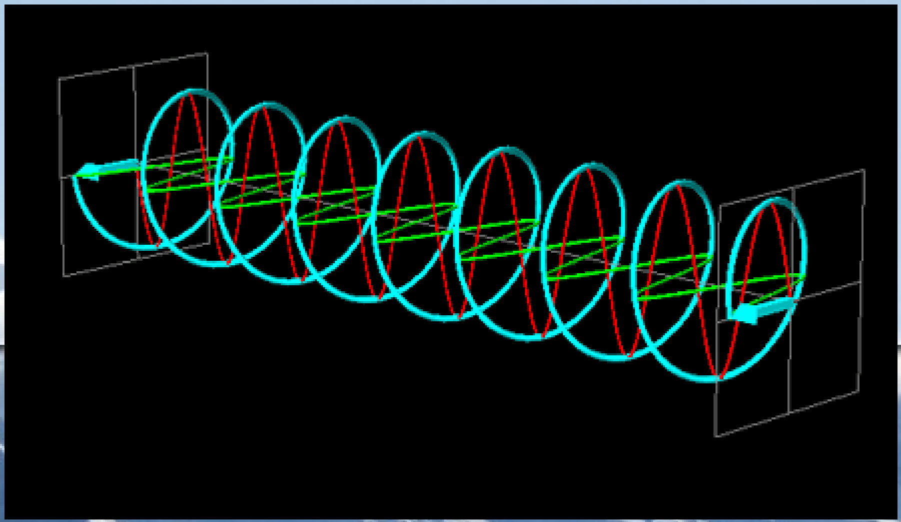

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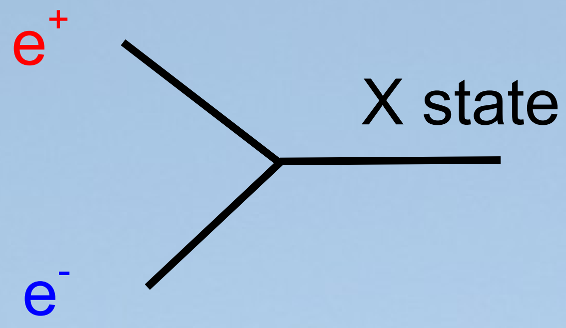
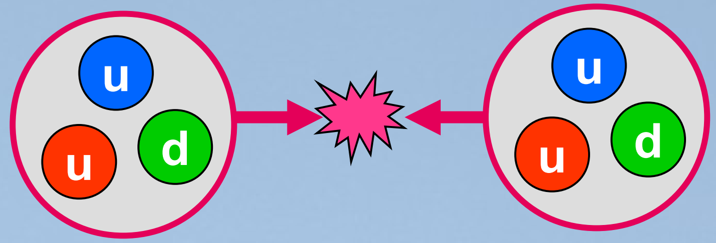
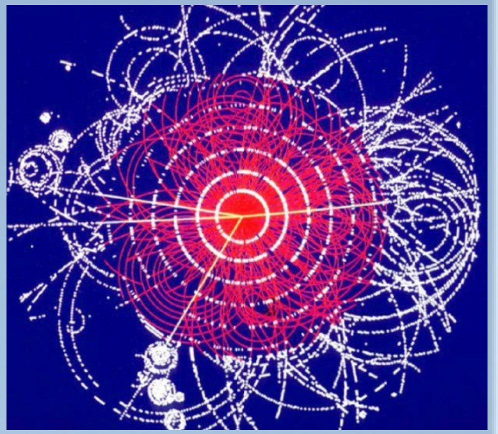


- e+e- collision is a simple interaction.
- The initial states is well defined.
- Easy to reconstrcut the final states.
- This full reconstruction is powerful and essential for e^+e^- colliders.

Hadron collider and Lepton Collider

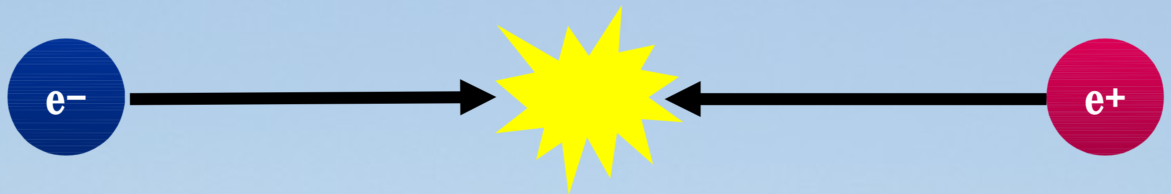
Hadron Collider

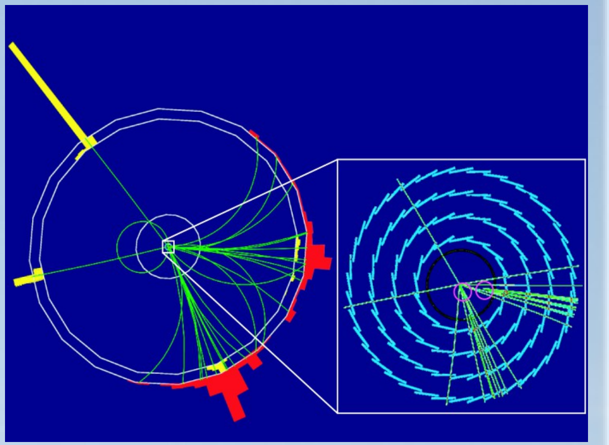




- Collision between composite particles (protons).
- Initial state is not defined.
- Extremely high energy, high event rate, large noise.

Lepton Colliders





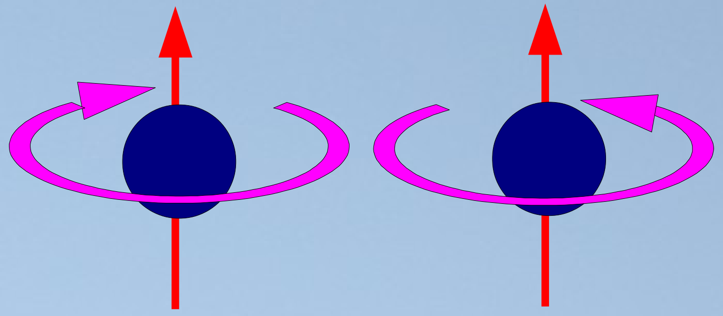
- Collision between elementary particles (leptons).
- The initial state is well defined.
- Full reconstruction of events.

Well defined initial states

- Electron and position are spin ½ 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.

$$l_L \equiv \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \quad I_W = \frac{1}{2}, \quad Y_W = -1$$

$$e_R \quad I_W = 0, \quad Y_W = -2$$

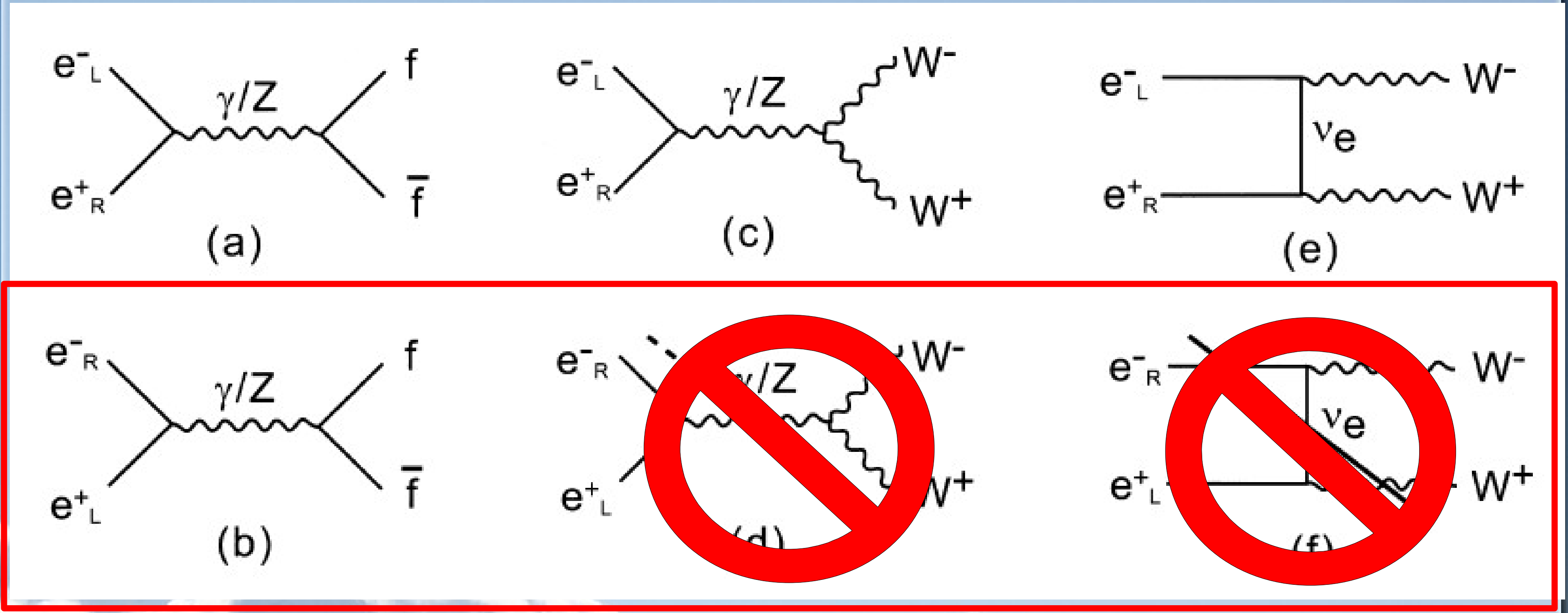


- Ideal well defined initial states means that the beam contains only one spin state.
- Practicaly, the beam should be polarized.

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

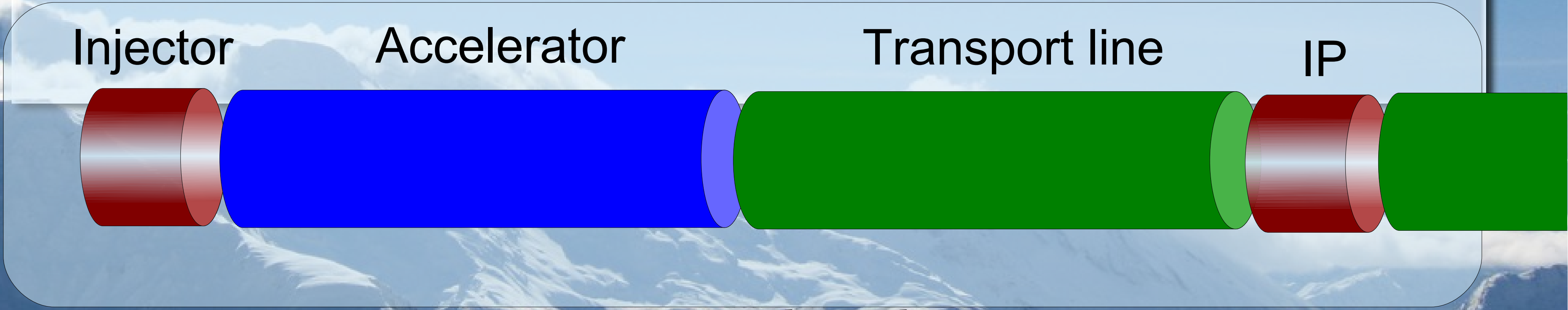
Suppress Background

By righthanded polarzed beam (e^-_R)



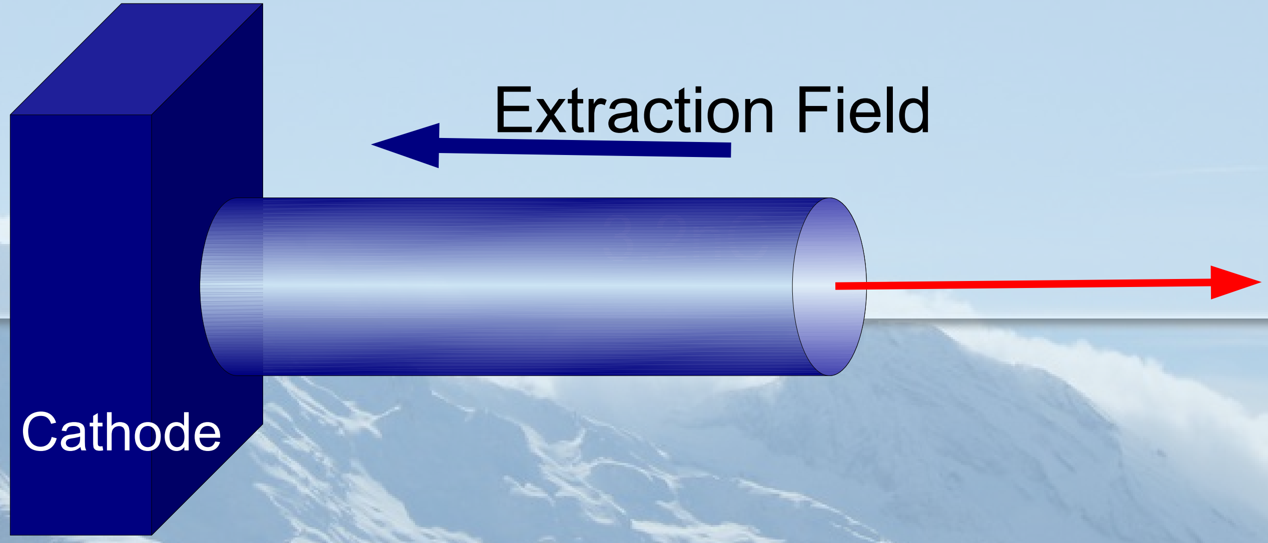
Injector

- 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



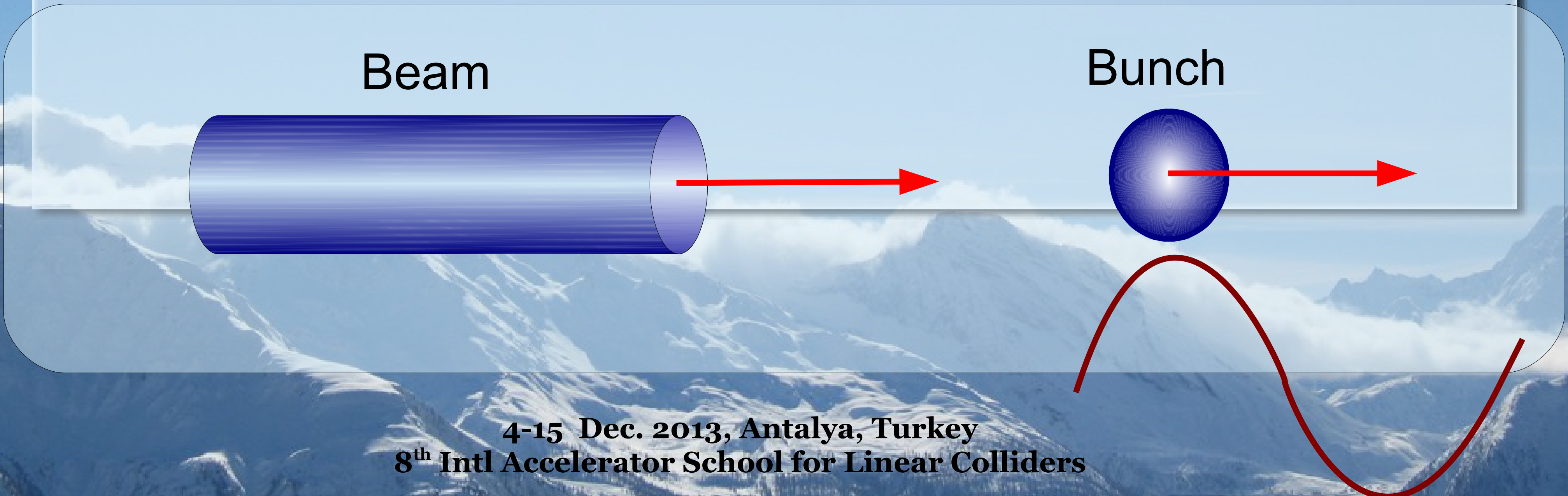
Electron Gun

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



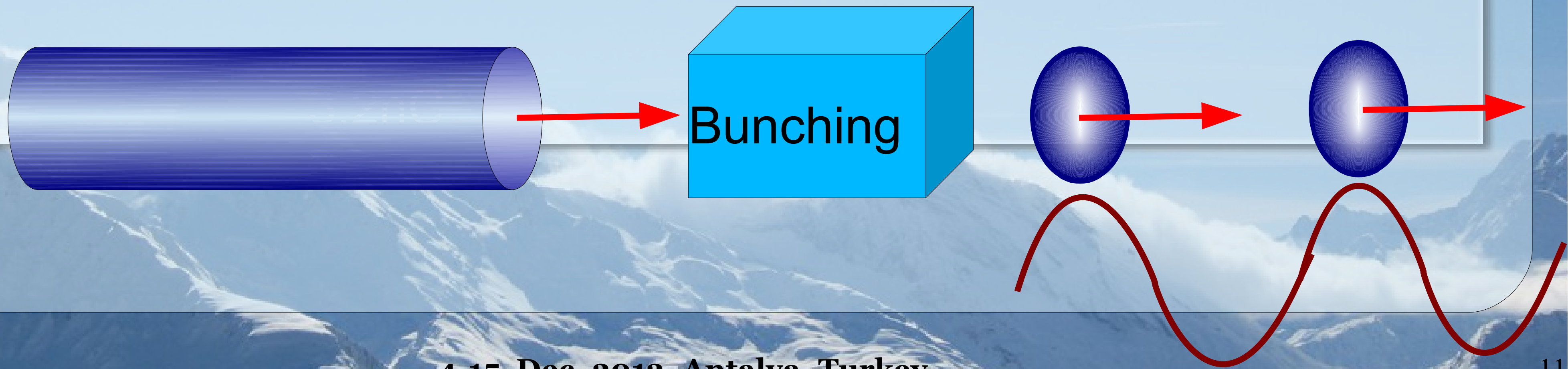
Bunching (1)

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

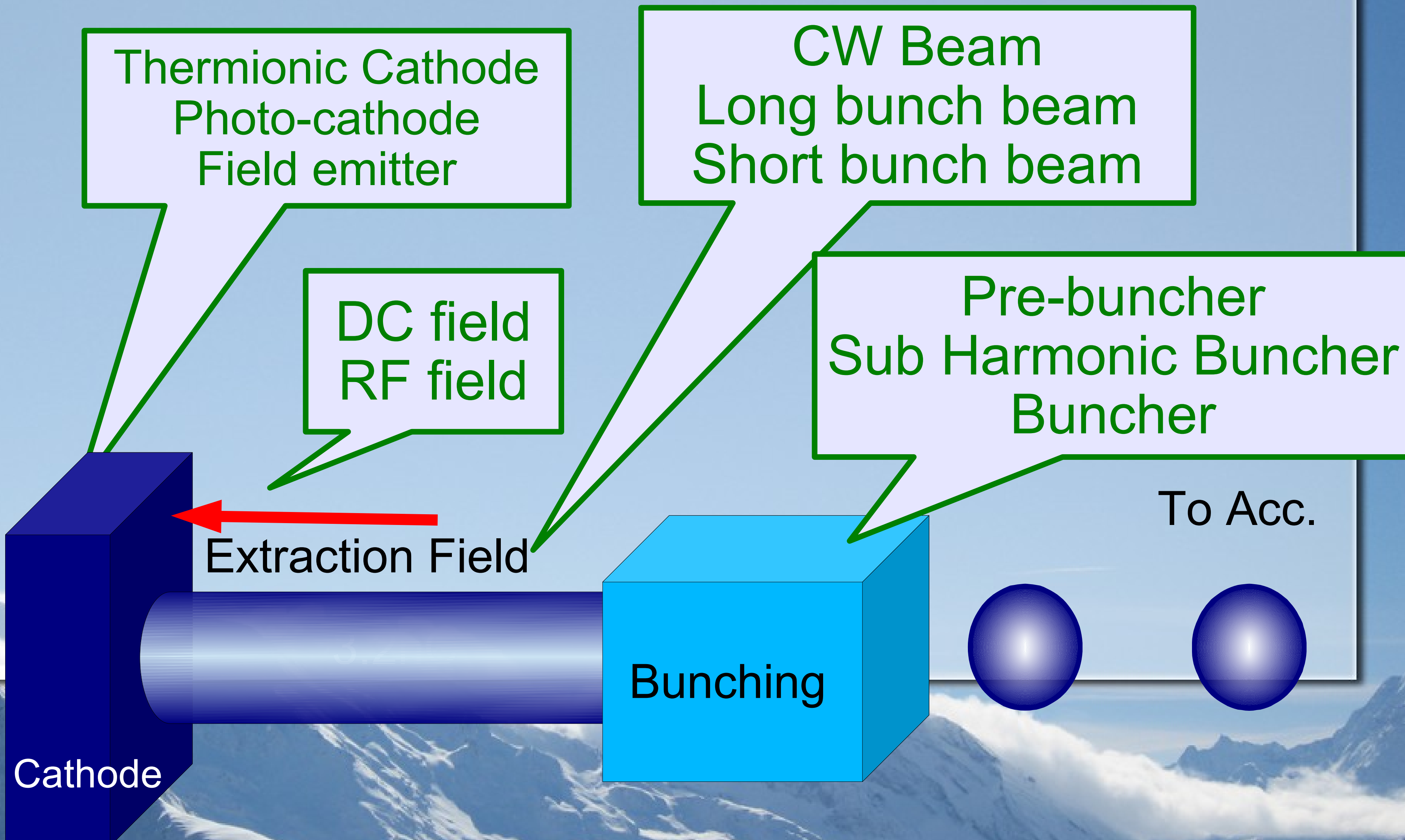


Bunching (2)

- 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



Injector Concepts



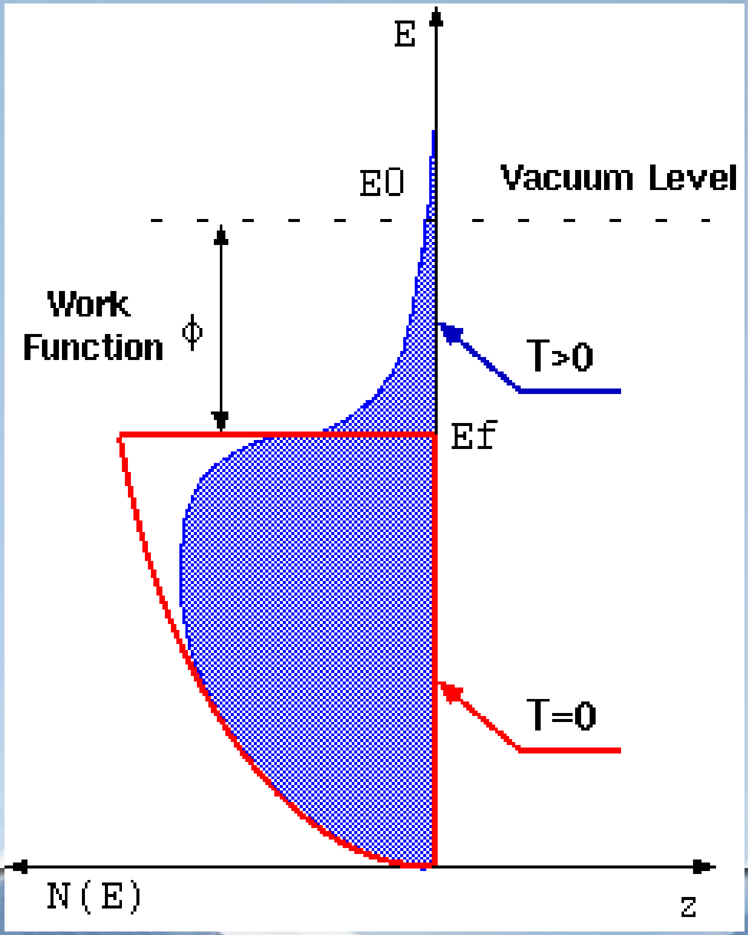
Electron Emission

Fundamental Process

- Thermal electron emission : Electron emission from the heated material (typically 1000 - 3000K).
- Field emission: Emission from the high field gradient surface.
- Photo-electron emission: Emission by photo-electron effect.
- Secondary electron emission: Emission induced by electron absorption.

Electronic States

- Electrons in a metal are confined in a well potential and distributed according to Fermi-Dirac Distribution.
- T=0: Electrons occupy the energy states up to Fermi-level (Fermi energy, E_f).
- T>0: Electron distribution extends to higher energy state due to the thermal energy.



Electronic States (2)

Electron density in a metal is product of state density D(ε) and distribution function f(ε),

$$n(\epsilon)=D(\epsilon)f(\epsilon) \qquad (1-1)$$

State density in phase space (x, v_x) – ($x+dx$, v_x+dv_x).... is

$$D(\epsilon)=\frac{2\mathrm{m}^2}{h^3}dx\,dy\,dz\,dv_x\,dv_y\,dv_z \qquad (1-2)$$

Distribution function f(ε) is given by Fermi-Dirac function

$$f(\epsilon)=\frac{1}{\exp\left(\frac{\epsilon-\mu}{kT}\right)+1} \qquad (1-3)$$

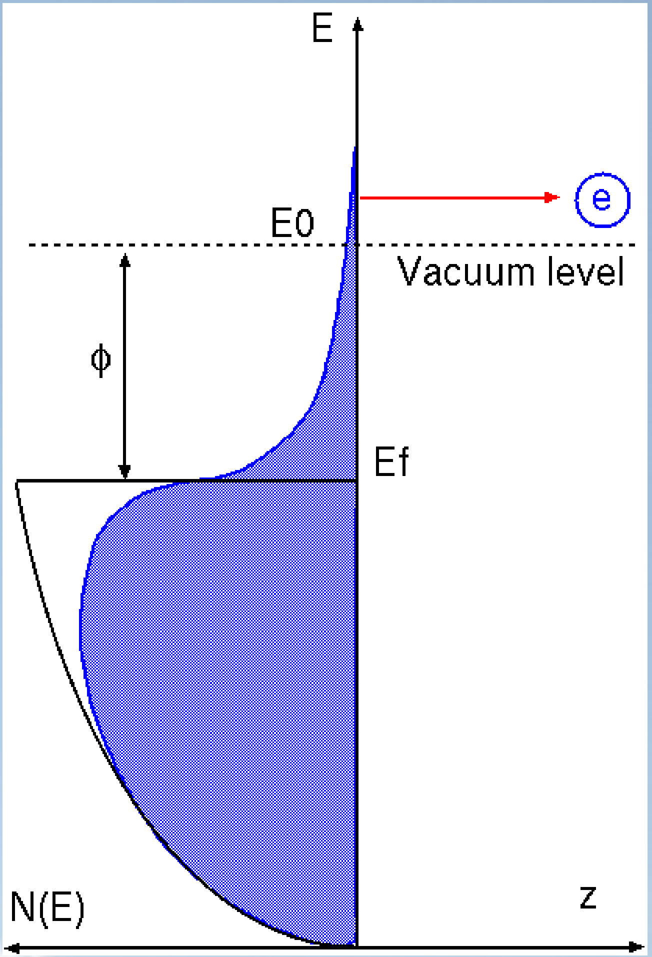
Number of electron with energy ε<E is

$$N(\epsilon)=\int_0^E f(\epsilon)D(\epsilon)d\epsilon \qquad (1-4)$$

Thermal Electron Emission

- If the temperature is sufficiently 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)

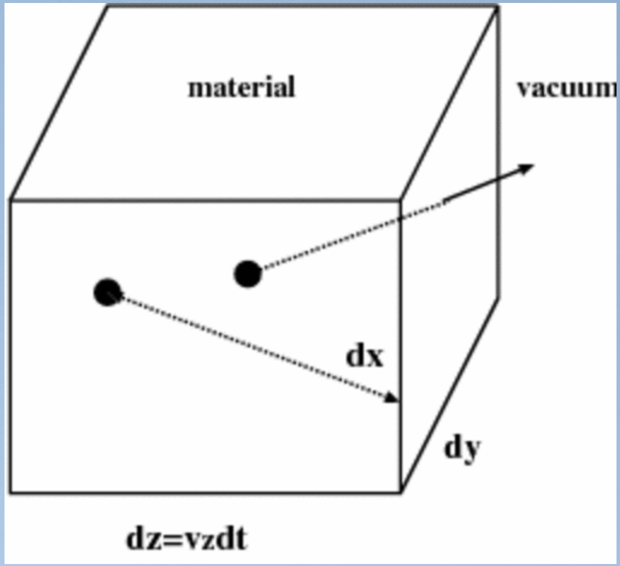
Number of emitted electron:

In depth (z-direction)

$$z \leq v_z \Delta t \qquad (1-5)$$

Kinetic energy for z-direction must be more than vacuum potential energy, μ+Φ

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



Number of electron emitted from the cathode is give by

$$N = \int dx \int dy \int_0^{v_z \Delta t} dz \int_{-\infty}^{+\infty} dv_x \int_{-\infty}^{+\infty} dv_y \int_{v_{vac}}^{+\infty} dv_z\, f(\epsilon) D(\epsilon) \quad (1-7)$$

Emission Density (2)

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

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

From this equation, emission density per unit time is obtained

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

Emission Density (4)

Because ε-μ≫kT, f(ε) is approximated as

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

The density is simplified as

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

Replacing the energy with the velocity,

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

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

Emission Density (5)

Integral for v_x and v_y can be performed as

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

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

$$\sigma=\frac{4\pi m k^2 T^2}{h^3}\exp\left(-\frac{\phi}{kT}\right) \qquad (1-15)$$

Electric current density J is given by

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

Richardson-Dushman Equation

$$J = AT^2 e^{-\frac{\phi}{kT}} \qquad (1-17)$$

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

A : thermionic emission constant

T: Temperature (K)

k : Boltzmann constant ; 1.38E-23 (J/K)

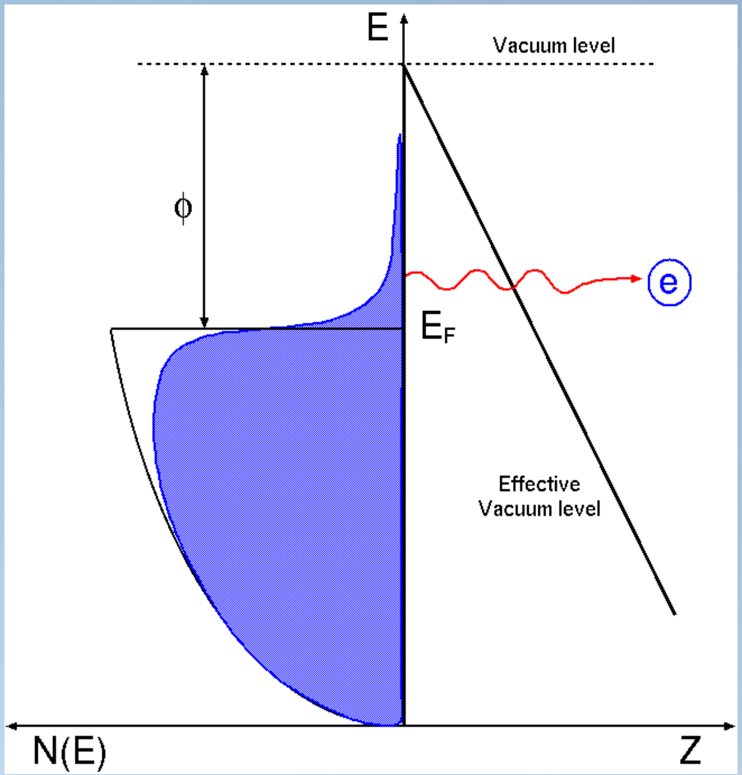
e : electronic charge

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 field is applied.
  - Large surface field makes the potential barrier very thin.
  - The tunnel current becomes significant with 1E+8 V/m.

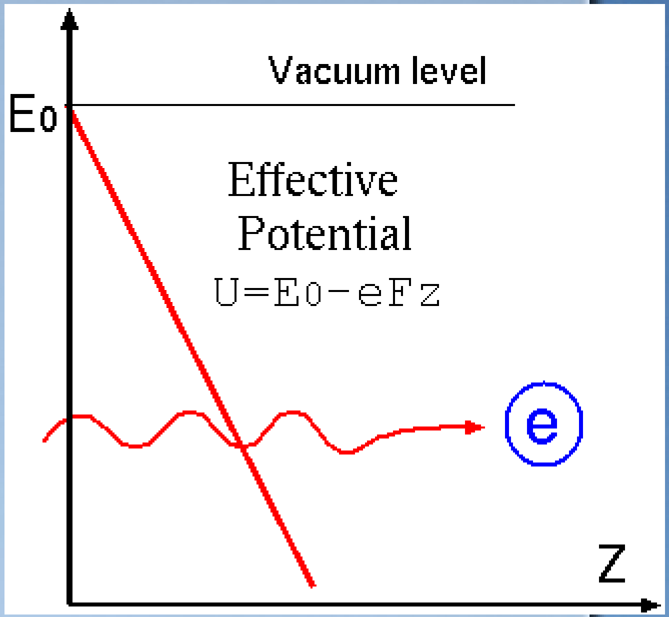


Field Emission (2)

$$J = e\int_0^{\infty} n(\epsilon_z)\, P(\epsilon_z)\, d\epsilon_z \qquad (1-18)$$

Electron density

Tunneling probability



Tunneling Probability by WKB method

$$P(\epsilon_z, F) = \exp\left[-\int_0^{w}\sqrt{\frac{8\mathrm{m}(2\pi)^2}{h^2}\{U(z)-\epsilon_z\}}\,dz\right]$$

$$= \exp\left[\frac{-8\pi\sqrt{2\mathrm{m}}}{3\mathrm{heF}}(E_0-\epsilon_z)^{3/2}\right] \qquad (1-19)$$

$$U(z) = E_0 - eFz$$

$$w = \frac{E_0-\varepsilon_z}{eF}$$

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

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

$$=\frac{4\pi em}{h^3}\exp\left(\frac{-8\pi\sqrt{2m}}{3heF}\phi^{3/2}\right)\int_0^\infty d\acute{\epsilon}\,\acute{\epsilon}\exp\left[-4\pi\frac{\sqrt{2m}}{heF}\phi^{1/2}\acute{\epsilon}\right] \qquad (1-22)$$

where $\varepsilon'=\varepsilon_z-\mu$.

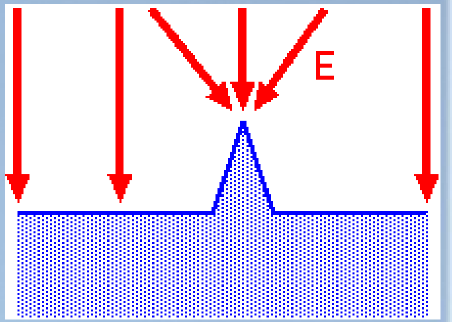
$$J=\frac{e^3F^2}{8\pi\phi}\exp\left(-\frac{8\pi\sqrt{2m}}{3heF}\phi^{3/2}\right) \qquad (1-23)$$

(Fowler-Nordheim formula)

Fowler-Nordheim Plot

Fowler-Nordheim formula with field enhancement factor κ

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



κ: local field enhancement by surface condition,

Taking $\ln(J/F^2)$ and plotting as a function of 1/F,

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

The gradient gives information on the surface condition, κ.

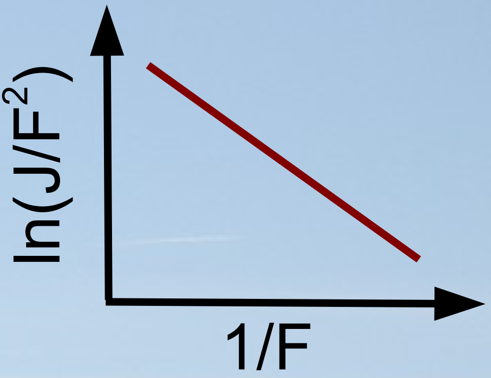
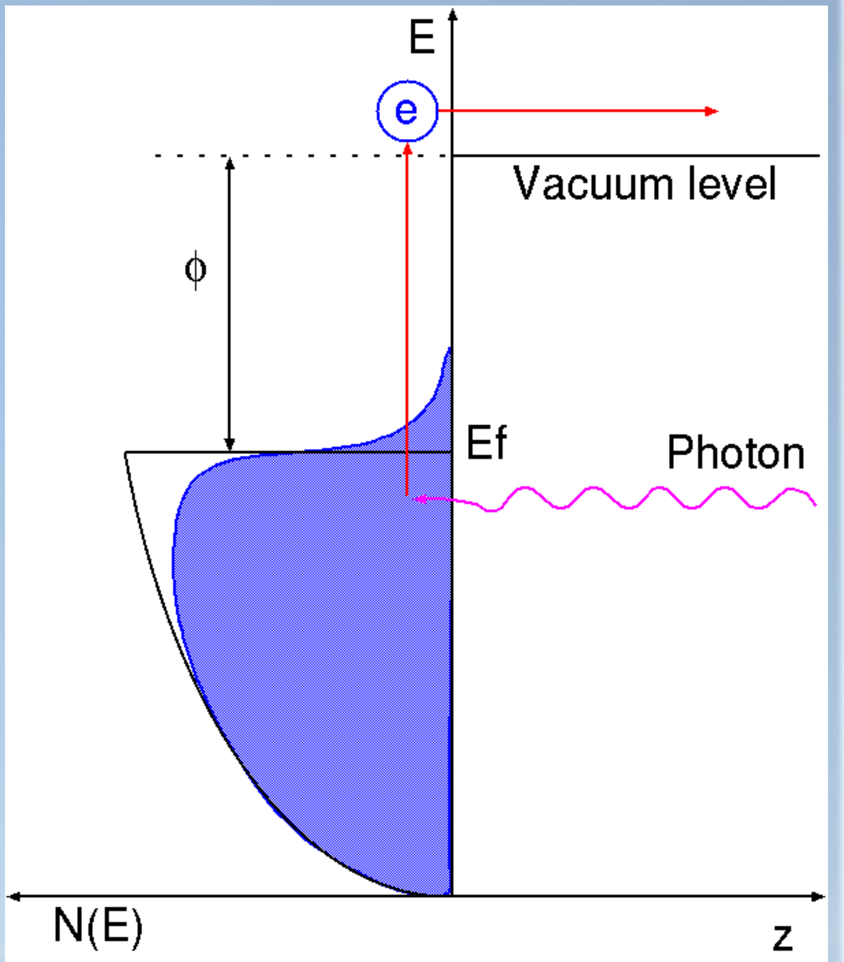


Photo-electron Emission

- Electron emission by photo-electron 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,

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



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 $y=(\varepsilon_z+h\nu-E_0)/kT$ and $\delta=h(\nu-\nu_0)/kT$,

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

Emission Density (2)

$$f(\delta)=\int_0^\infty dy\ln\left[1+e^{\delta-y}\right] \qquad (1-30)$$

(a) $\delta=h(\nu-\nu_0)/kT<0$ (ph. energy is less than f):

$$f(\delta)=\sum_{n=1}^{\infty}(-1)^{n-1}\frac{e^{n\delta}}{n}\int_0^\infty dy\, e^{-ny}$$

$$=\sum_{n=1}^{\infty}(-1)^{n-1}\frac{e^{n\delta}}{n^2} \qquad (1-31)$$

since

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

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

Emission Density (3)

(b) $\delta = h(\nu - \nu_0)/kT > 0$ (ph. energy is more than f),

$$f(\delta) = \left(\int_0^\delta dy + \int_\delta^\infty dy \right) \left[\ln(1 + e^{\delta - y}) \right] \qquad (1-34)$$

(b-1) first integral, $w = \delta - y$

$$\int_0^\delta dy \ln(1 + e^{\delta - y}) = \int_0^\delta dw \ln(1 + e^{w})$$

$$= \int_0^\delta dw \left\{ w + \ln(1 + e^{-w}) \right\}$$

$$= \left[\frac{w^2}{2} \right]_0^\delta + \sum_{n=1}^{\infty} (-1)^n \frac{1}{n^2} [e^{-nw}]_0^\delta$$

$$= \frac{\delta^2}{2} + \frac{\pi^2}{12} + \sum_{n=1}^{\infty} (-1)^n \frac{e^{-n\delta}}{n^2} \qquad (1-35)$$

Emission Density (4)

(b-2) second integral, w=y-δ

$$\int_{\delta}^{\infty} dy \ln(1+e^{\delta-y}) = \int_0^{\infty} dw \ln(1+e^{-w})$$

$$= \left[w \ln(1+e^{-w}) \right]_0^{\infty} + \int_0^{\infty} dw \frac{w}{1+e^{w}} \qquad (1-36)$$

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(δ)

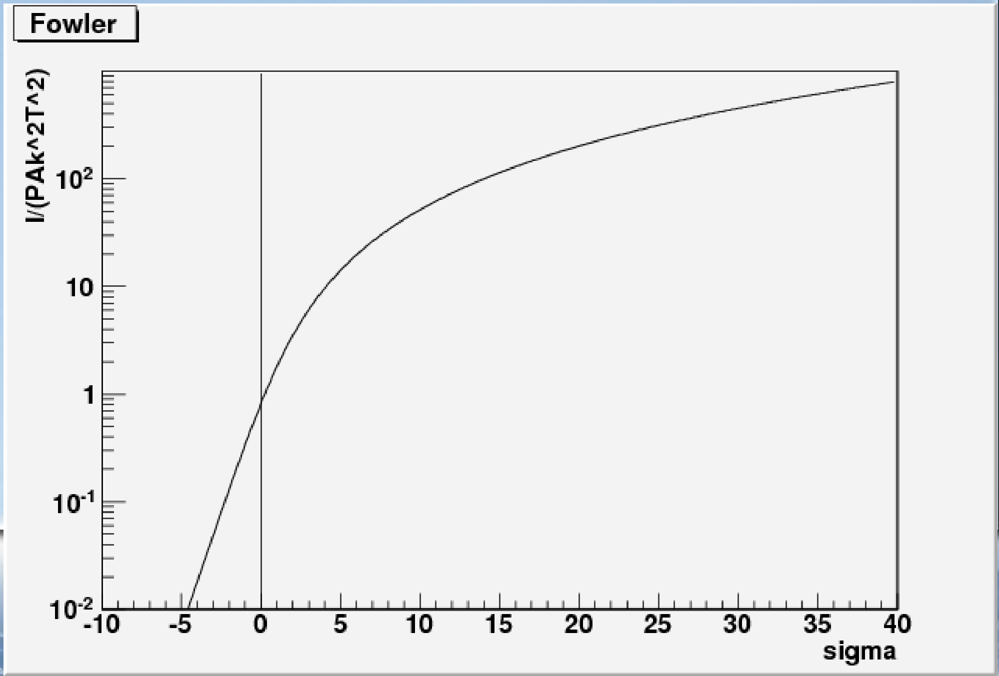
$$f(\delta) = \frac{\delta^2}{2} + \frac{\pi^2}{6} + \sum_{n=1}^{\infty} (-1)^n \frac{e^{-n\delta}}{n^2} \qquad (1-38)$$

Fowler Equation

$$J = AT^2 P \begin{cases} \sum_{n=1}^{\infty} (-1)^{n-1} \frac{e^{n\delta}}{n^2} & \delta < 0 \\ \frac{\delta^2}{2} + \frac{\pi^2}{12} + \sum_{n=1}^{\infty} (-1)^n \frac{e^{-n\delta}}{n^2} & \delta > 0 \end{cases} \qquad (1-39)$$

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

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



Quantum Efficiency

Quantum Efficiency, η, is practically used to qualify the photo-electron emission

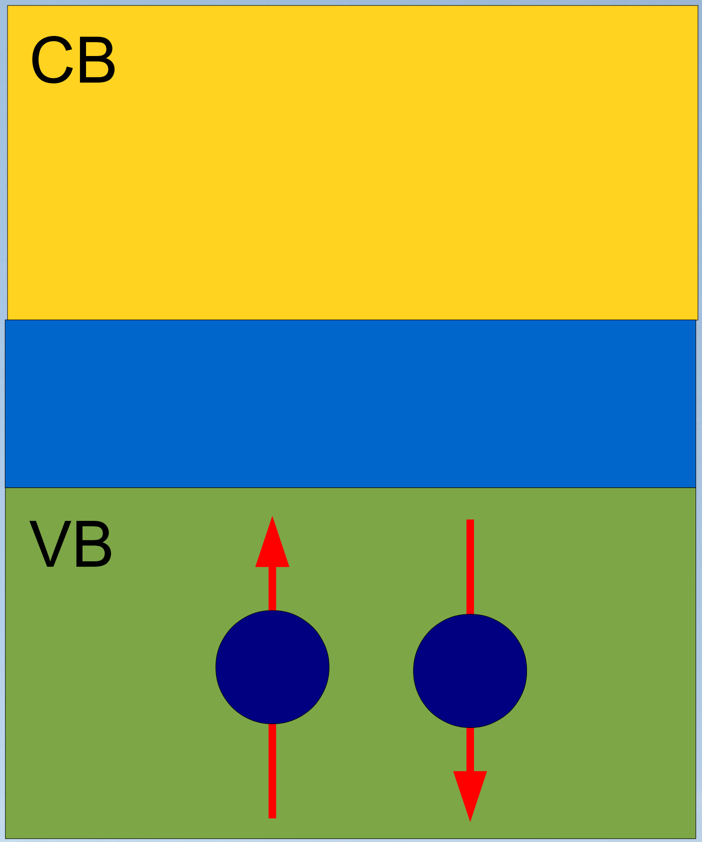
$$\eta = \frac{number\ of\ photoelectrons}{number\ of\ photons} \qquad (1-40)$$

With practical units,

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

Polarized electron

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



Excitation

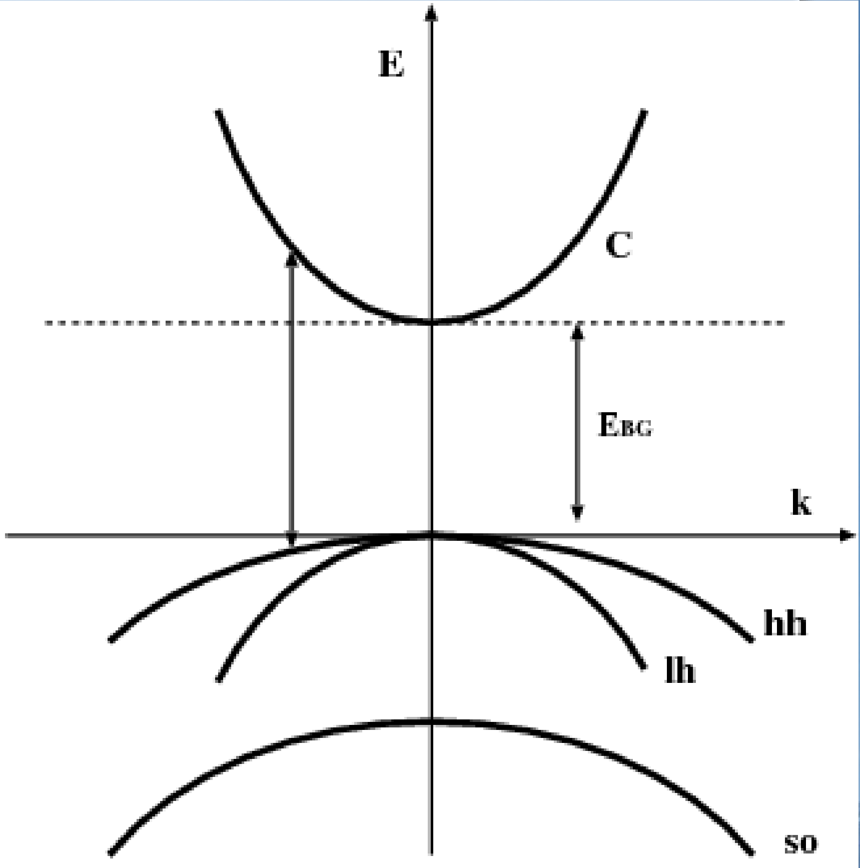
- Transition probability ~ Fermi's golden rule

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

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

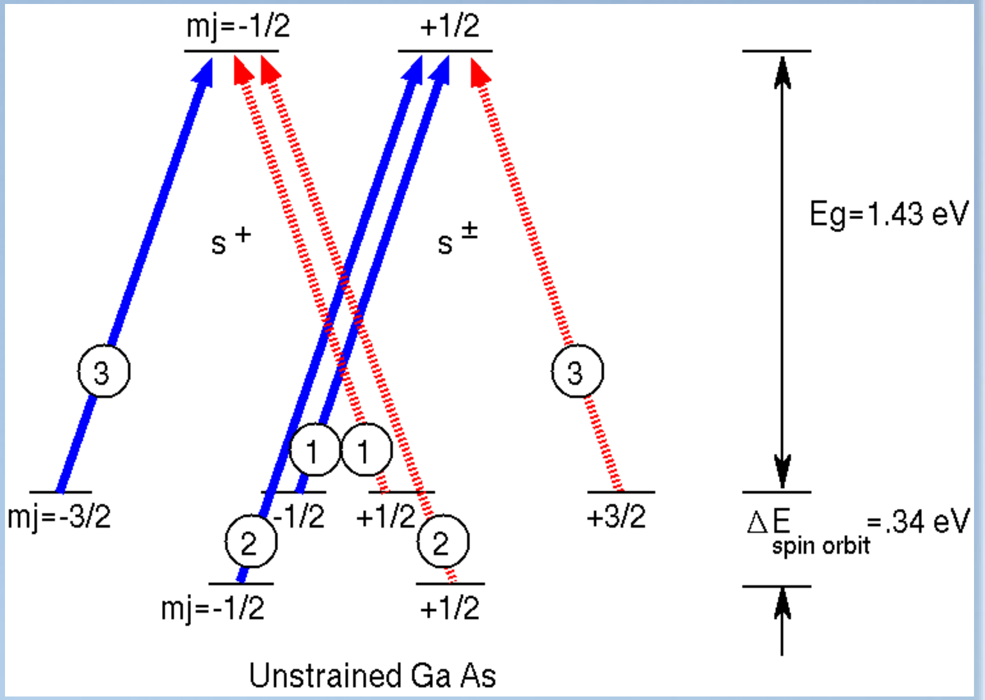
Matrix Element of GaAs

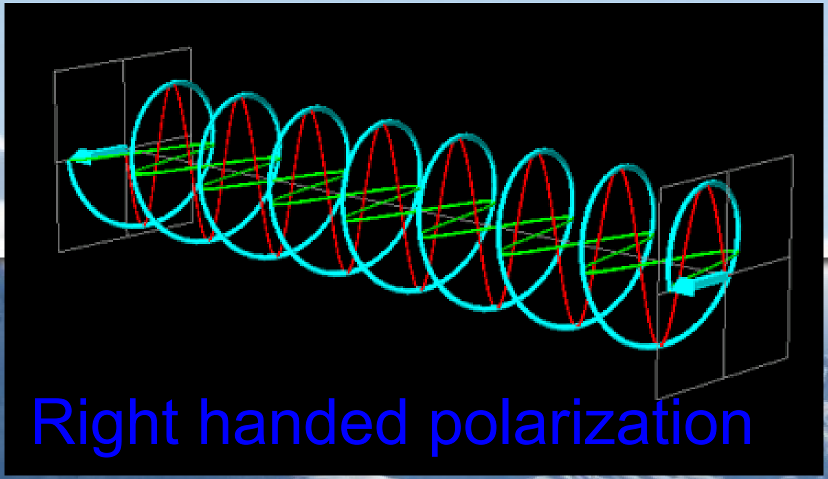
- Band gap of GaAs is Γ point (k=0).
  - VB:
    - J=|3/2,±3/2> (heavy hole)
    - J=|3/2, ±1/2> (light hole).
  - CB:
    - J=|1/2,±1/2>
- Matrix Element of transition (Clebsh-Gordon coef.)
  - Heavy hole: $\sqrt{3}/2$
  - Light hole: 1/2

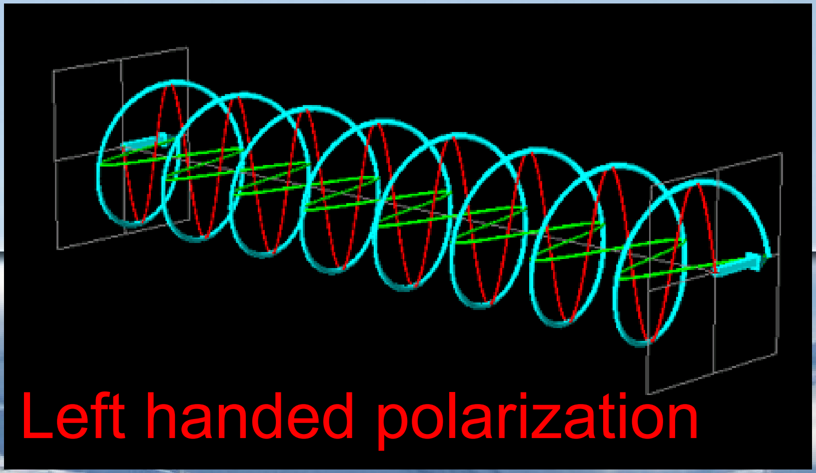


Polarization

- Energy and helicity limitation, only two of six transitions are possible.
- Number of excited electron are polarized by 3:1 matrix amplitude.

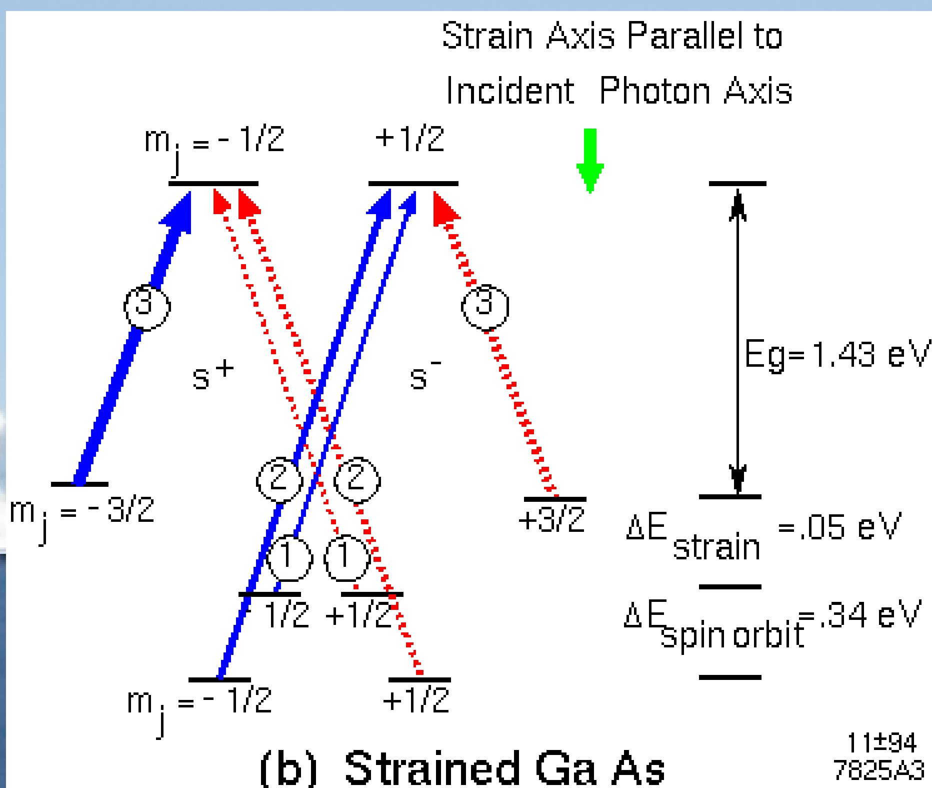


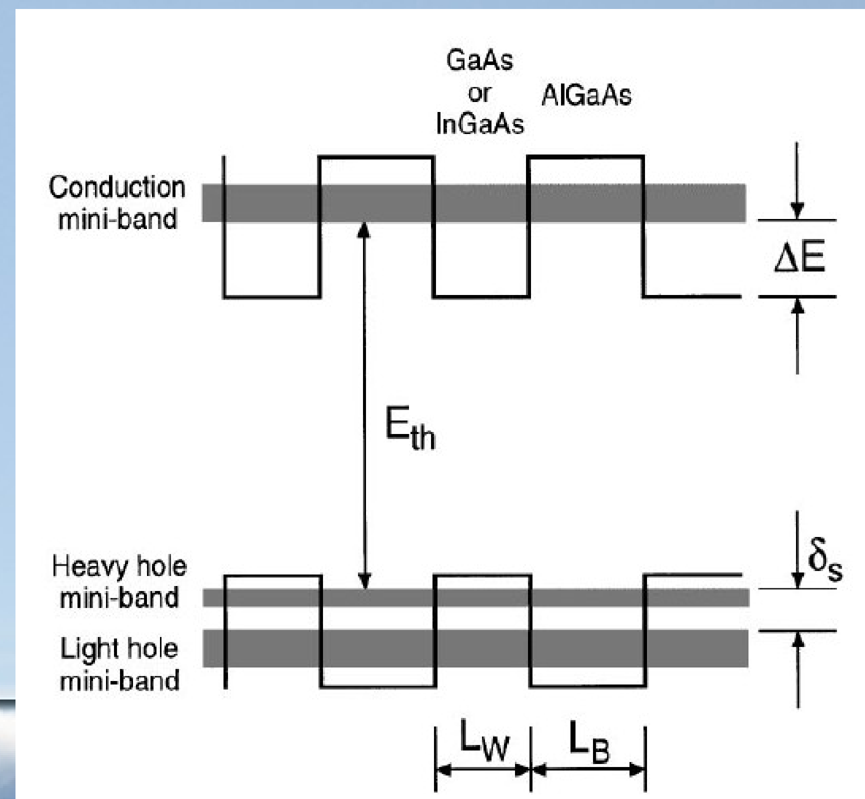




Polarization Enhancement

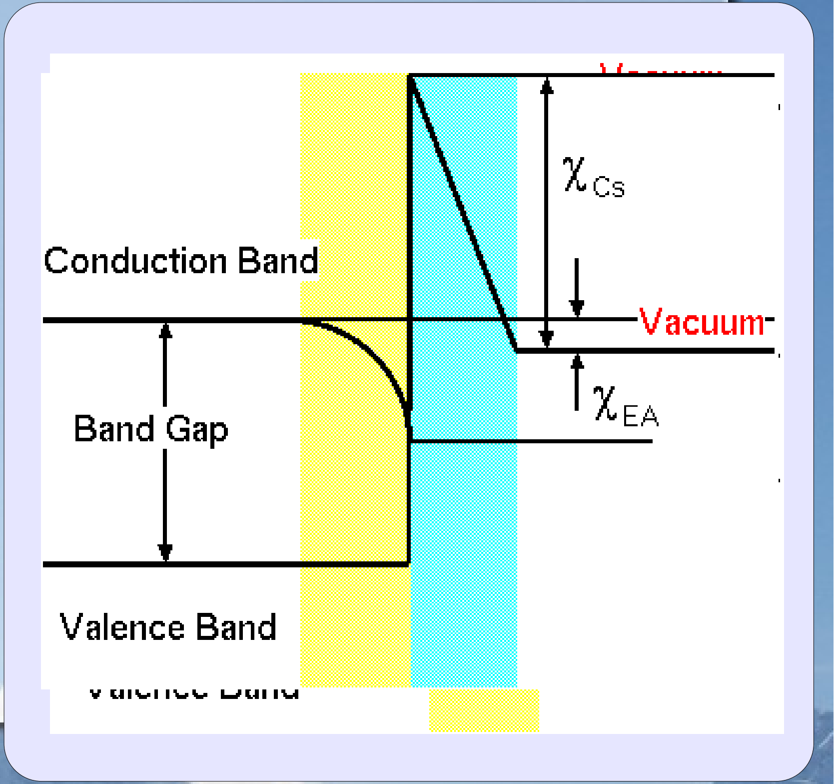
- Further enhancement by breaking the degeneration.
- It is achieved by GaAs/GaAsP Strained Super-lattice Crystal.





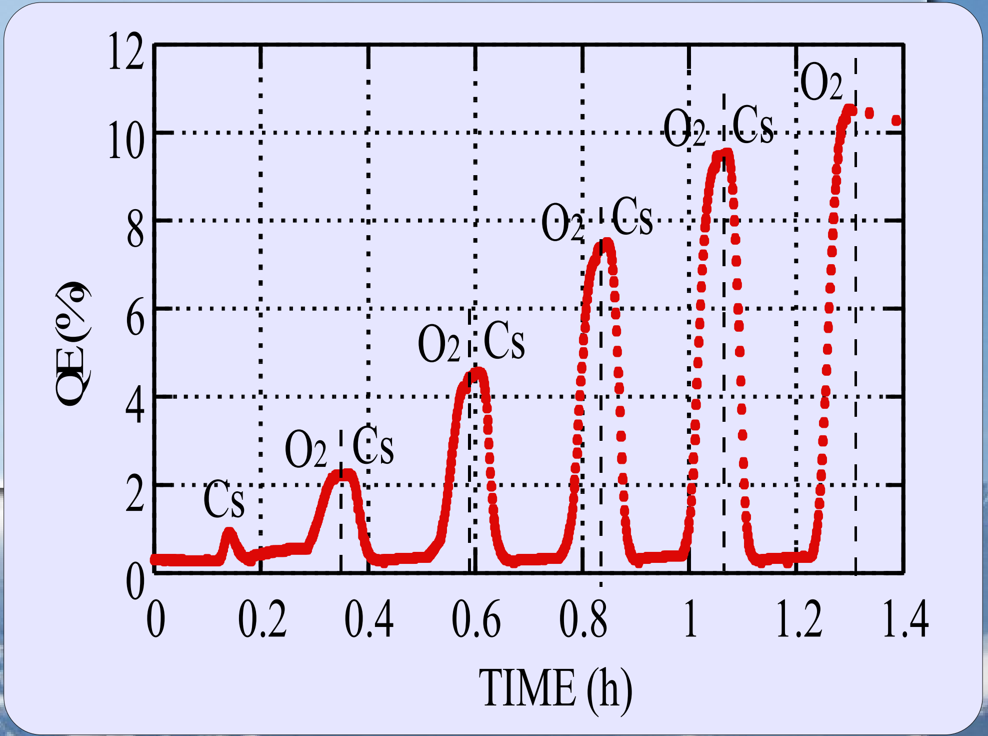
NEA surface (1)

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



NEA surface (2)

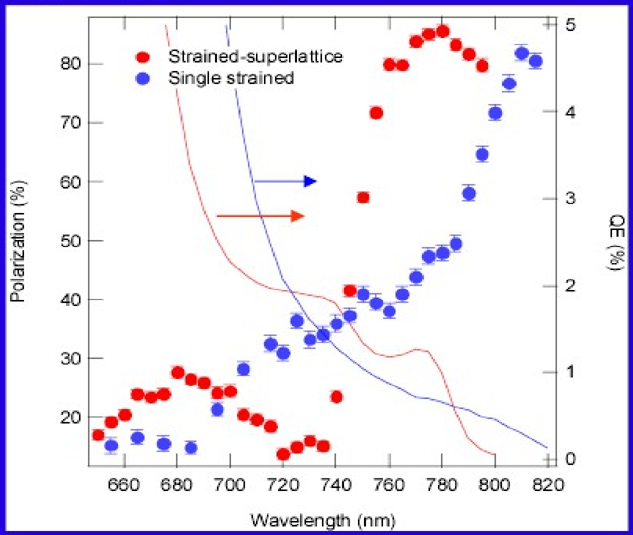
- NEA surface is made by evaporation of Cs and O_2 /NF_3 on cleaned GaAs.
- GaAs: chemical etching by H_2S0_4 and treatment by HCl-Isopropanol solution followed by heat cleaning.
- Alternating deposition of Cs and O_2.
- The process should be made in extremely low vacuum pressure, <5.0E-9Pa.



Polarized Electron (3)

Performance of GaAs/GaAsP superlattice

SLAC



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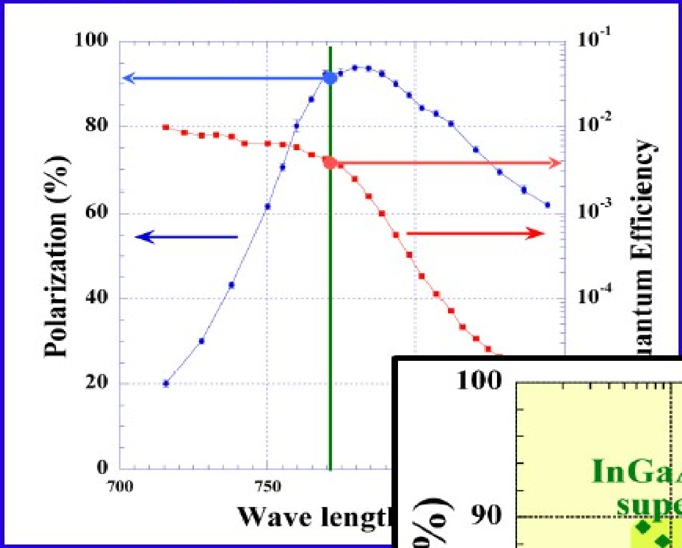

T. Nishitani

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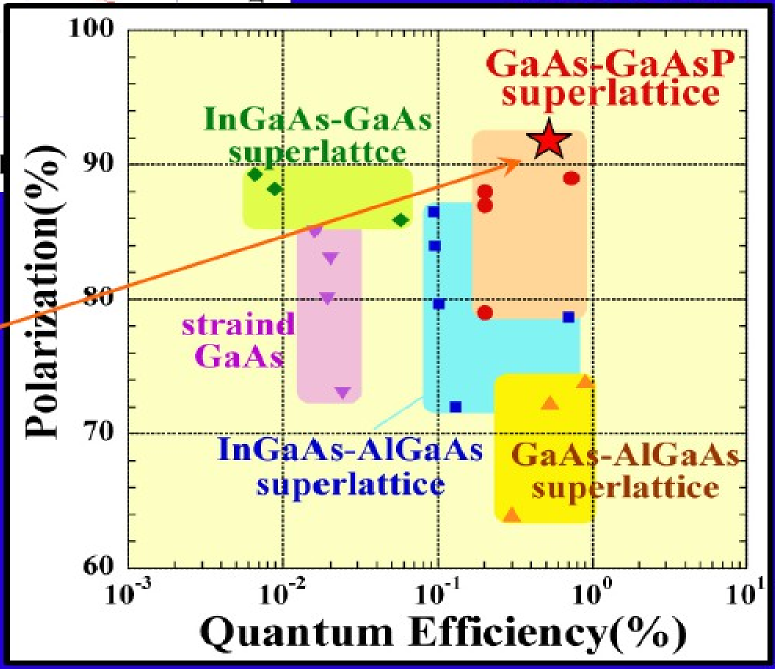


GaAs-GaAsP superlattice shows the best performance !

@778nm

Polarization ~ 90%

Q.E. ~ 0.5%

Related Physics Process

Roll of the field

- Electrons in cathode is tightly bond by the potential.
- The external field on the cathode surface is important not only to lead the beam, but also to extract the beam from the cathode.
- Surface field modifies 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)

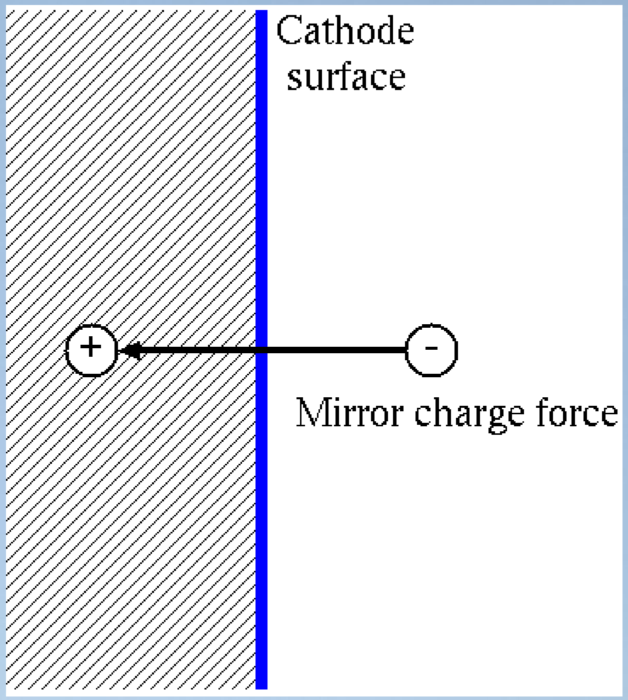
Schottky Effect (1)

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

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



Schottky Effect (2)

Mirror charge potential and external field give

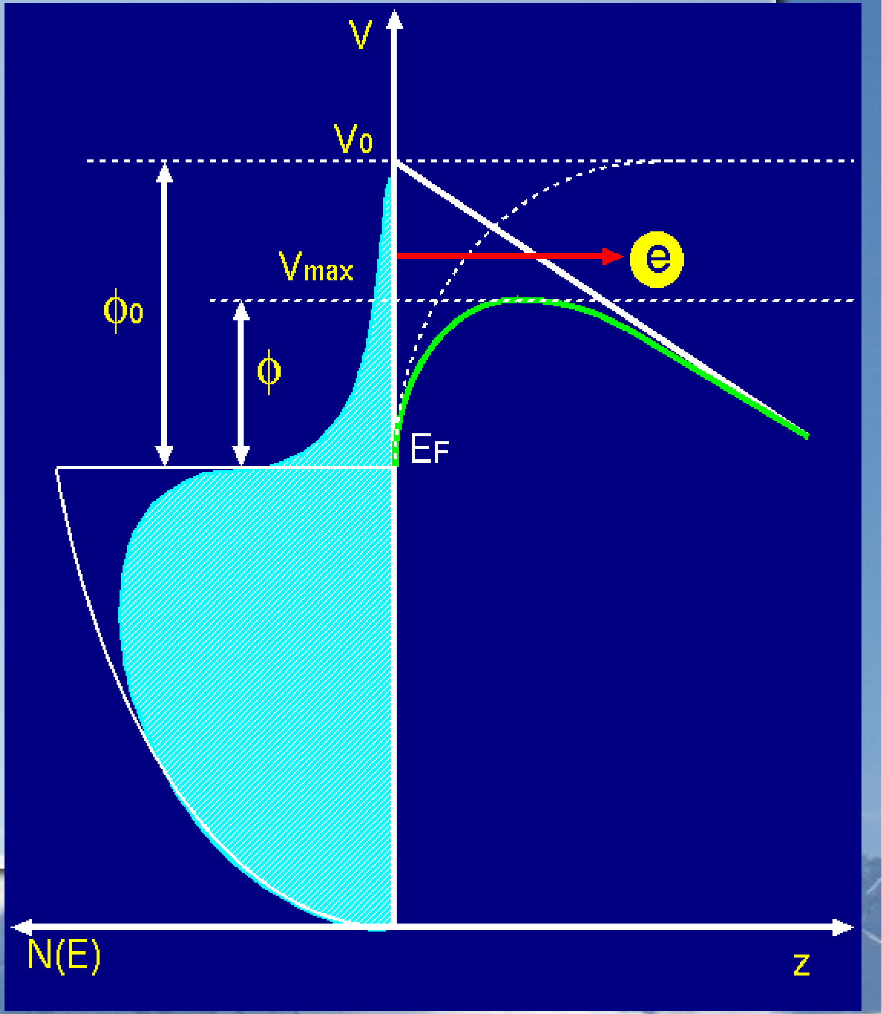
$$V(z) = \phi_0 - \frac{e^2}{16\pi\epsilon z} - eEz \qquad (2-3)$$

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

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

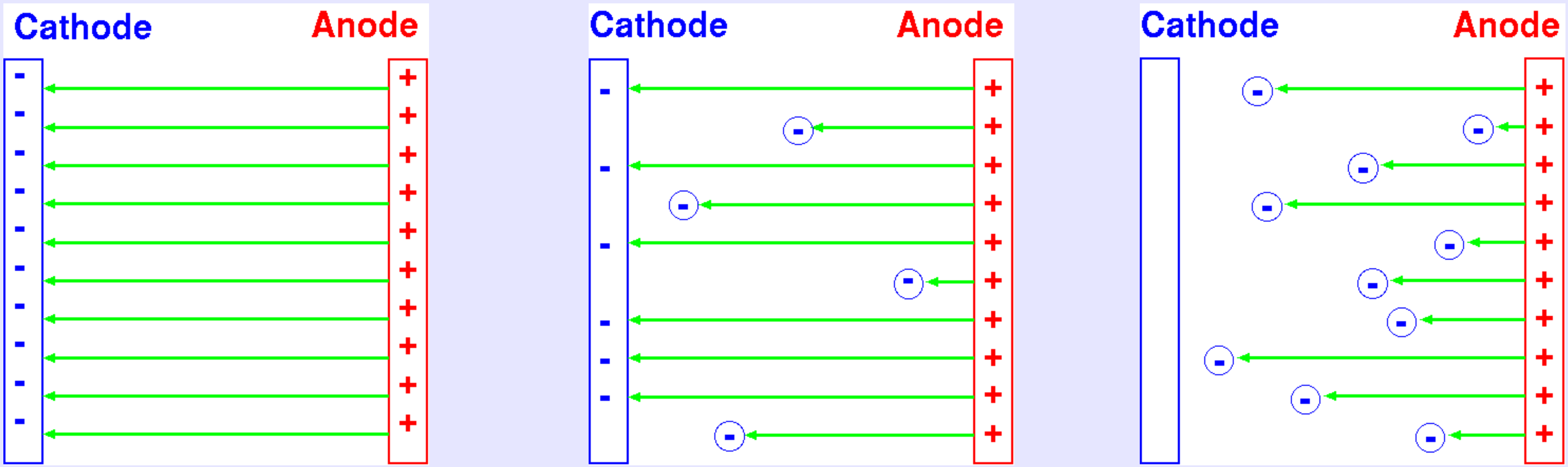
Effective work function

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



Space Charge Limit

- Electron terminates the electric flux (Gauss's law).
- Electric field is weakened by the space charge.
- When all flux is terminated by the charge, the field at the cathode surface is disappeared .



Space Charge Limit (2)

Poisson equation is

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

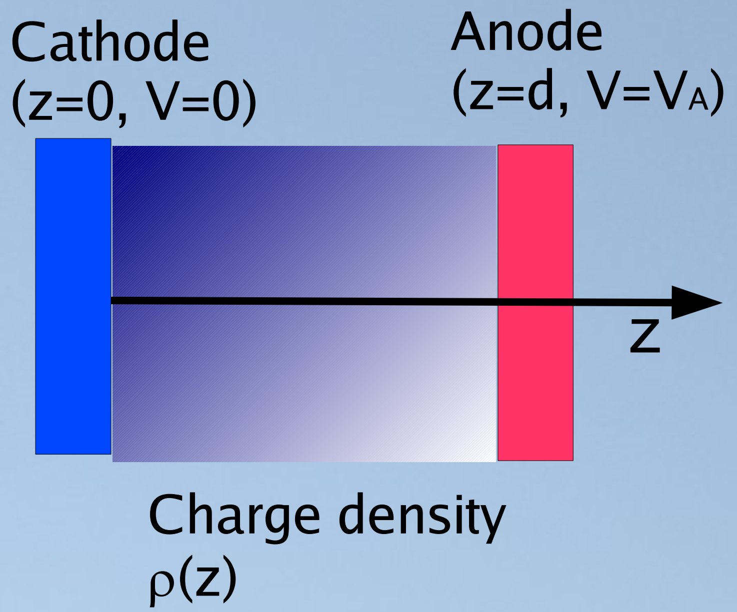
The current density J is given by the charge density ρ and velocity v,

$$J = -\rho(z)\, v(z) \qquad (2-8)$$

According energy conservation,

$$\frac{1}{2} m\, v(z)^2 = eV(z) \qquad (2-9)$$

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



SC Limited Current (2)

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*

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

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

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) , ρ(z) are expressed as a function of z

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

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

$$\rho(z) = -\frac{4\epsilon_0}{9}\frac{V_A}{d^{4/3}}z^{-2/3} \qquad (2-17)$$

Child-Langmuir Law

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

$$I = 2.33\times10^{-6}\frac{S\,V^{3/2}}{d^2} = PV^{3/2}(A) \qquad (2-18)$$

V **and** ***d*** **: voltage and distance between two electrodes.**

S **: cathode area**

P **: perveance defined as;**

$$P = 2.33\times10^{-6}\frac{S}{d^2}\left(A\,V^{-3/2}\right) \qquad (2-19)$$

DC Gun design (2D SC Limited Flow)

2D case solution for SC limited flow;

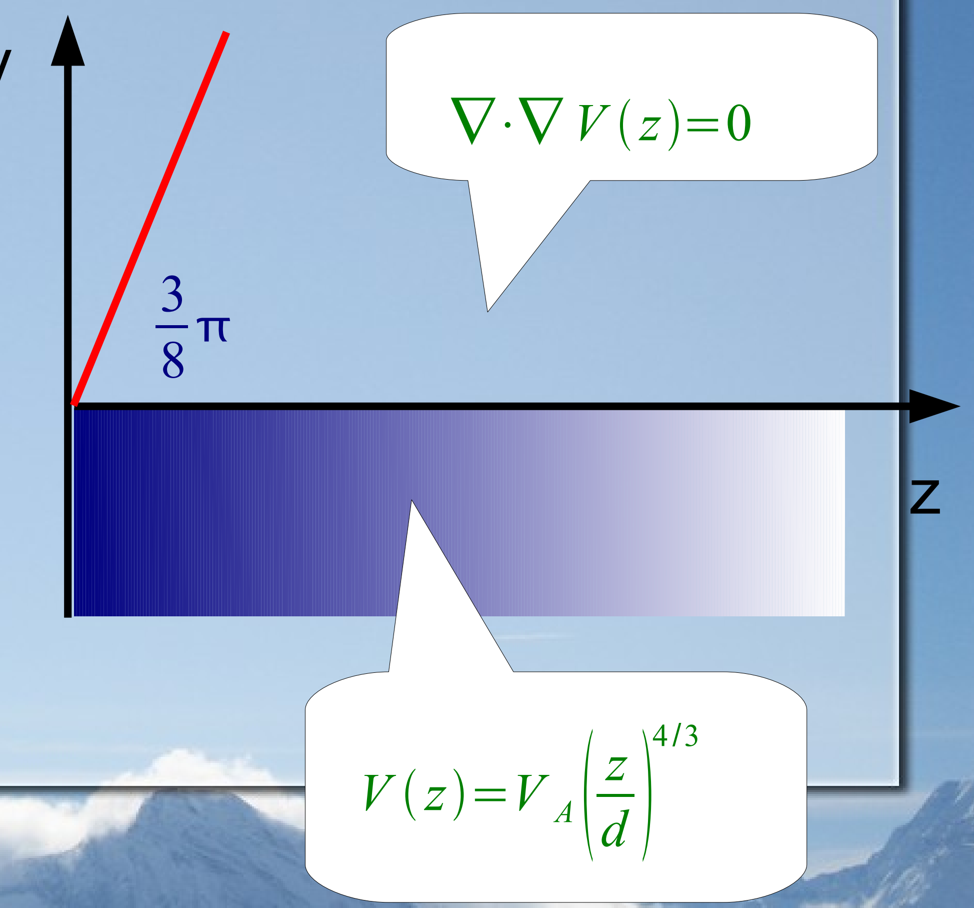
$$V(z,y)=V_A\frac{\Re\left[(z+iy)^{4/3}\right]}{d^{4/3}}$$

$$=V_A(z^2+y^2)^{2/3}\cos\frac{4}{3}\theta \quad (2-22)$$

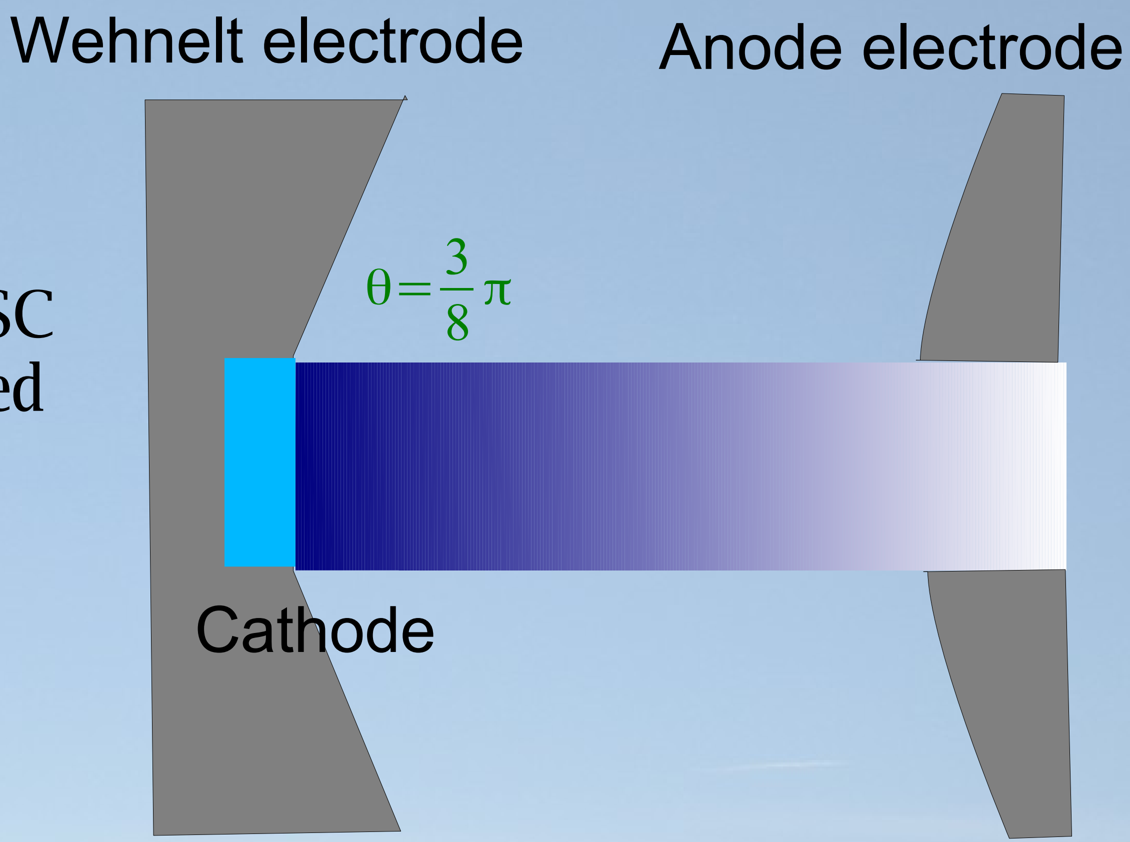
V=0 equi-potential line:

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

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



DC Gun design : Real geometry



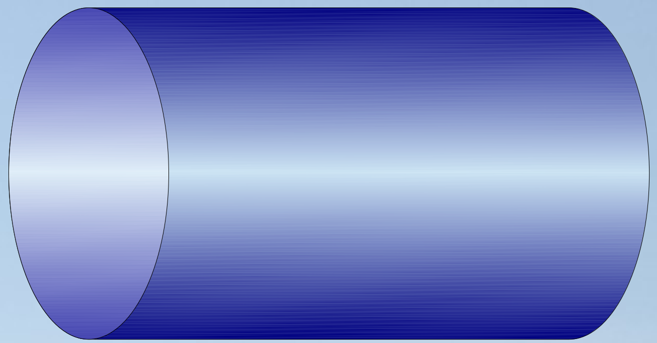
- By setting Wehnelt and anode electrodes to reproduce the potential, SC limited current is extracted from the cahode.
- This is Pierce type gun;
    - Conventional type,
    - DC bias voltage,
    - Thermionic cathode,
    - Continous beam.

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 flux 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

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

The magnetic flux is given as

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

The Lorentz force to electron is

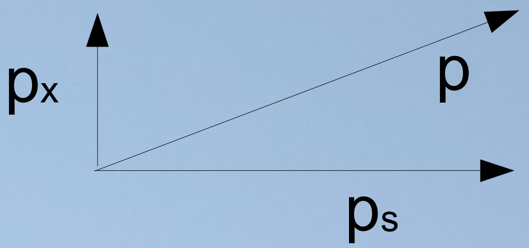
$$\boldsymbol{F} = e\boldsymbol{E} + e\beta c\boldsymbol{B} = \frac{Ne^2 r}{2\pi a^2 \epsilon_0}(1-\beta^2)\vec{e}_r$$

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

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

Beam Emittance

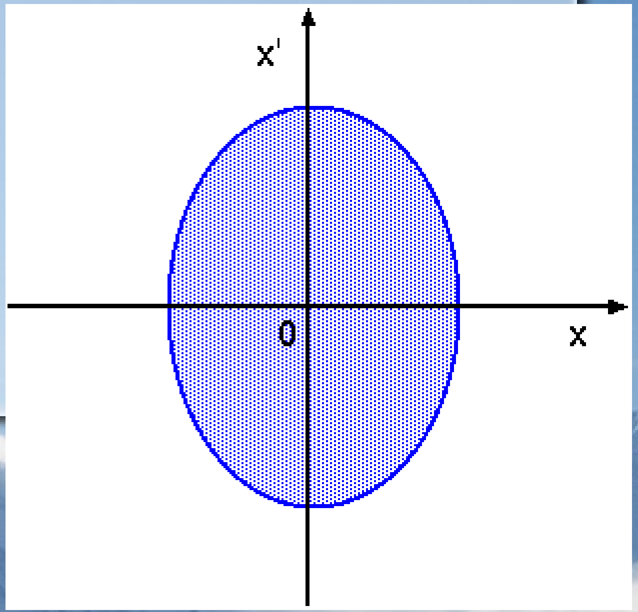
Emittance is defined as area in the phase space where particles occupy. The phase space is defined x and x'=dx/ds



$$\acute{x} = \frac{dx}{ds} = \frac{v_x}{v_s} = \frac{p_x}{p_s} \sim \frac{p_x}{p} \qquad (2-28)$$

In general, RMS emittance is given as

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

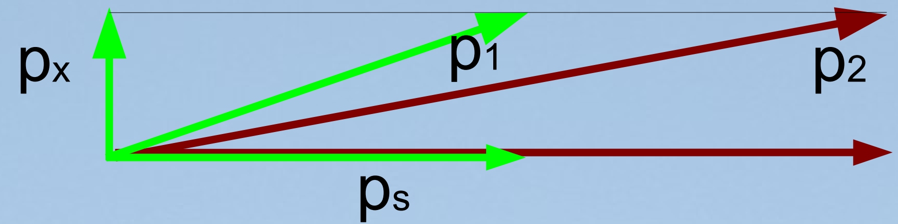


If there is no correlation between x and x',

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

Normalized emittance

In acceleration, transverse momentum p_x is conserved, but p is scaled as



$$p_s = \gamma \beta mc \qquad (2-31)$$

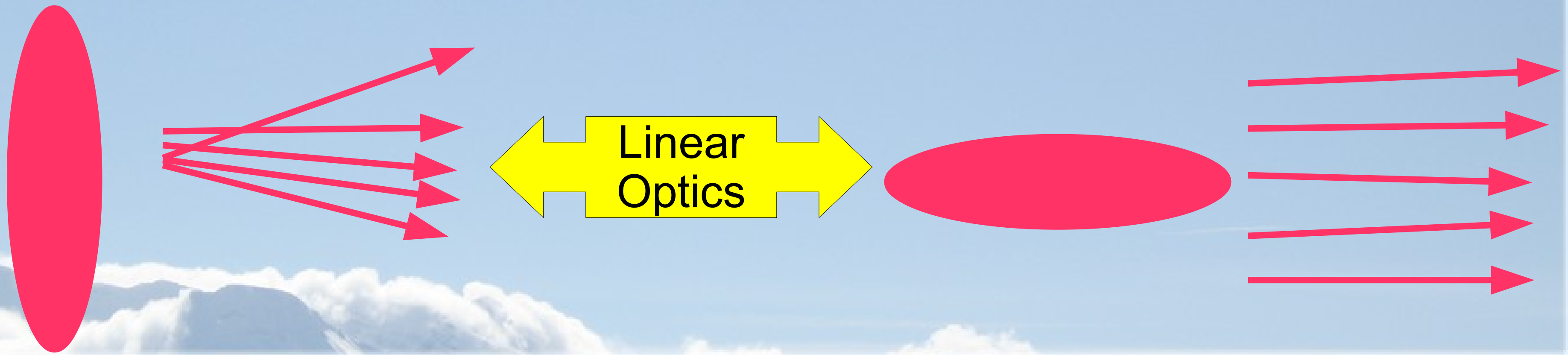
The emittance is inversely scaled. To avoid the energy dependence ($\gamma\beta$) on the emittance, the normalized emittance is defined

$$\epsilon_{nx} = \gamma \beta \epsilon_x$$

$$= \gamma \beta \frac{R}{2} \sqrt{\left\langle \left(\frac{p_x}{\gamma \beta m c} \right)^2 \right\rangle} = \frac{R}{2\mathrm{mc}} \sqrt{\langle p_x{}^2 \rangle} \qquad (2-32)$$

What is the 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.



What is the fundamental limit on the emittance?

- Everbody 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

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

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

$$E_t=\frac{4\pi m}{h^3}\int_{\mu+\phi}^{\infty}d\epsilon_z\int_0^{\infty}d\epsilon_t\,\epsilon_t\exp\left(-\frac{\epsilon_z+\epsilon_t-\mu}{kT}\right)$$
$$=\frac{4\pi m}{h^3}k^3T^3\exp\left(-\frac{\phi}{kT}\right) \qquad (2-34)$$

The average transverse energy per electron is

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

Emittance of Beam from Thermionic Cathode (2)

Thermal energy is,

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

The transverse emittance is

$$\varepsilon_x = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle} = \frac{1}{\gamma \beta m c} \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle} \qquad (2-37)$$

Substituting the thermal energy $\frac{\langle p_x^2 \rangle}{2\mathrm{m}} = \langle \epsilon_x \rangle = \frac{kT}{2}$, 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

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

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

The momentum is

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

Emittance is

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

Emittance of Beam from Photo-cathode (3)

Acounting thermal energy, the transverse energy becomes

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

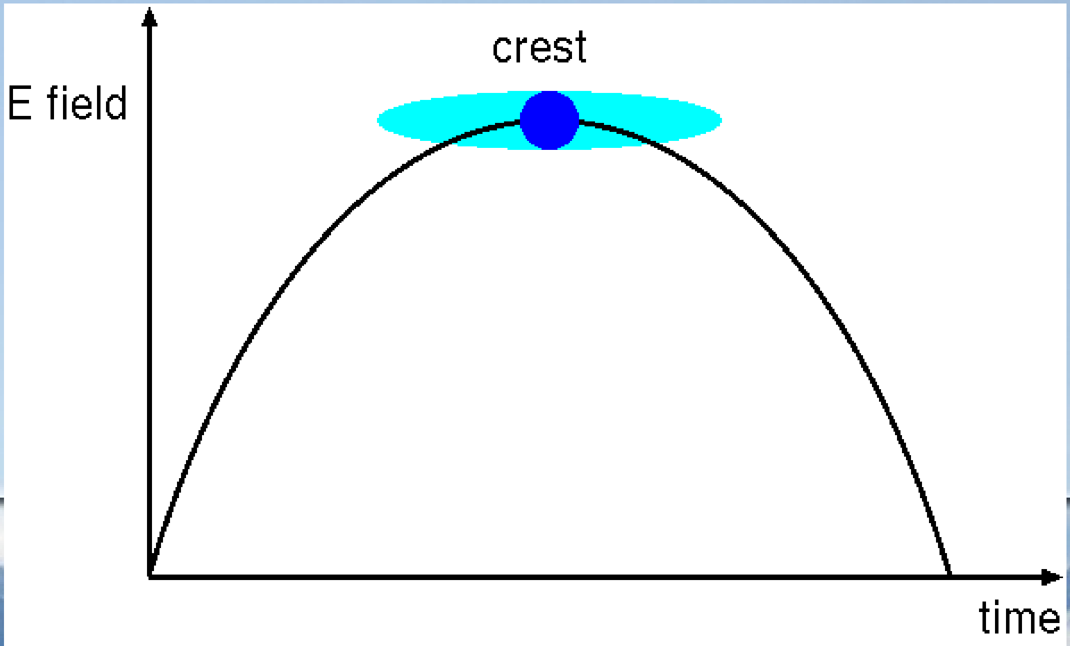
The transverse emittance is

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

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

Bunch Compression (1)

- In any RF accelerators, the beam should be concentrated in a short period of longitudinal space for small energy spread;
  - $E=E_0\cos(\omega t-ks)$, $k\delta_s \ll 1$ for efficient 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 ($\beta < 1$).

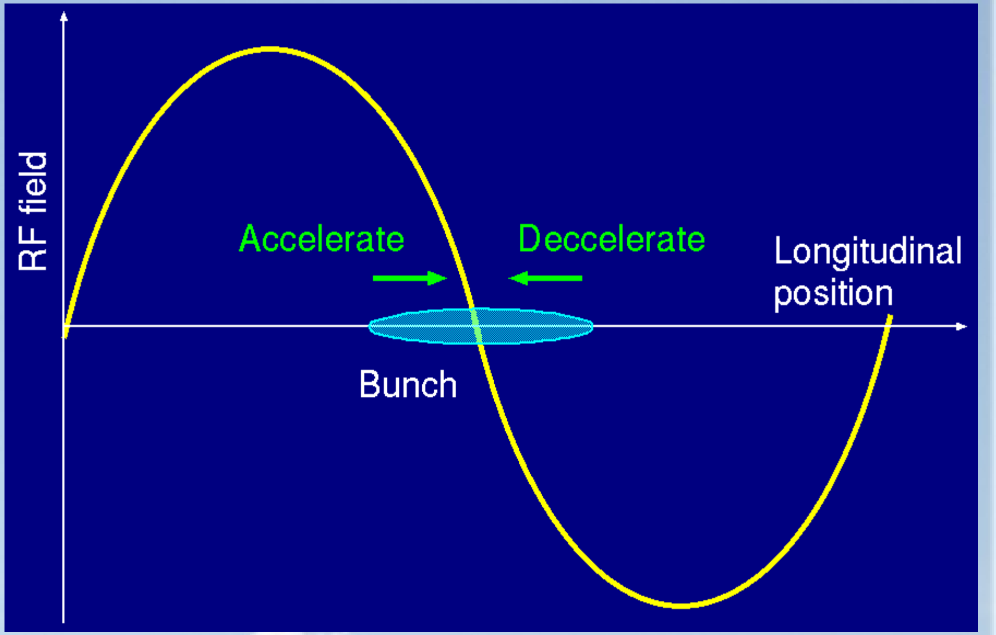
Velocity Bunching (2)

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

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

Velocity Bunching (3)

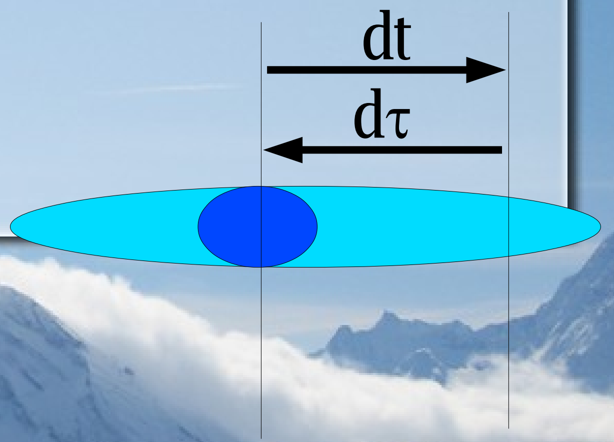
$$\tau = \frac{L}{c\beta} \qquad (2-57)$$

► In drift space L, Time delay ($d\tau$) with the energy modulation (dE) is

$$d\tau = -\frac{L}{c\gamma^2\beta^3}\frac{dE}{E} \sim -\frac{L}{c\gamma^2\beta^3}\frac{eV_0\omega}{E}dt \qquad (2-58)$$

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

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



Magnetic Bunching (1)

- 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

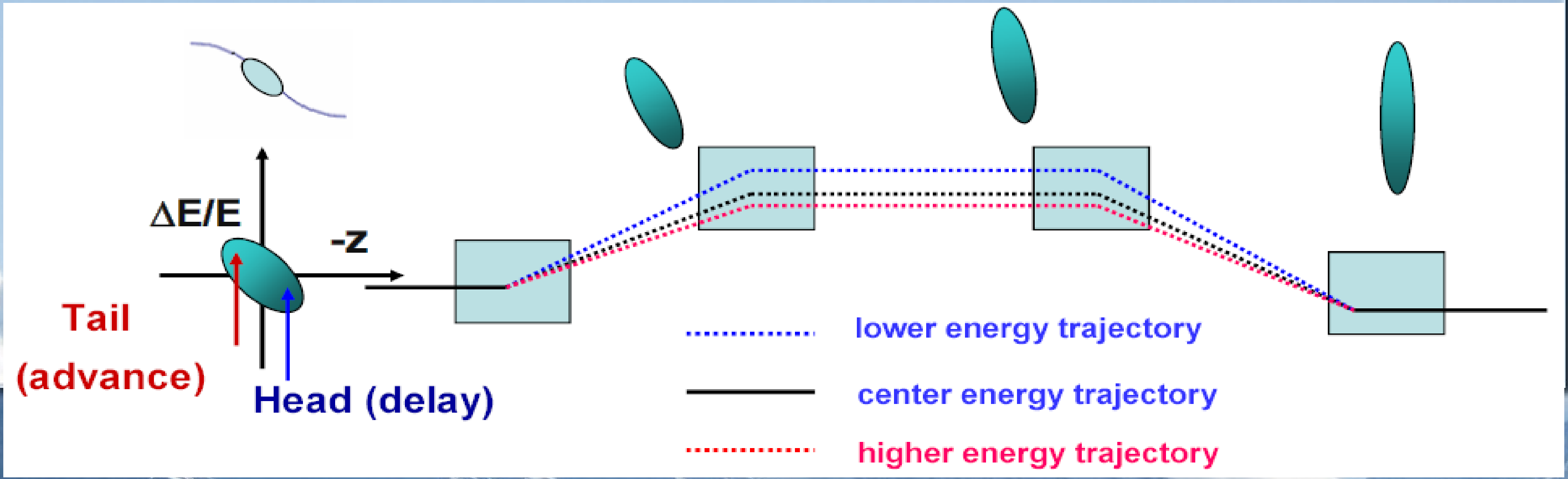
$$\Delta z = \eta_l \frac{\Delta P}{P} \qquad (2-59)$$

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

- It works well for any energy particle.

Magnetic Bunching (2)

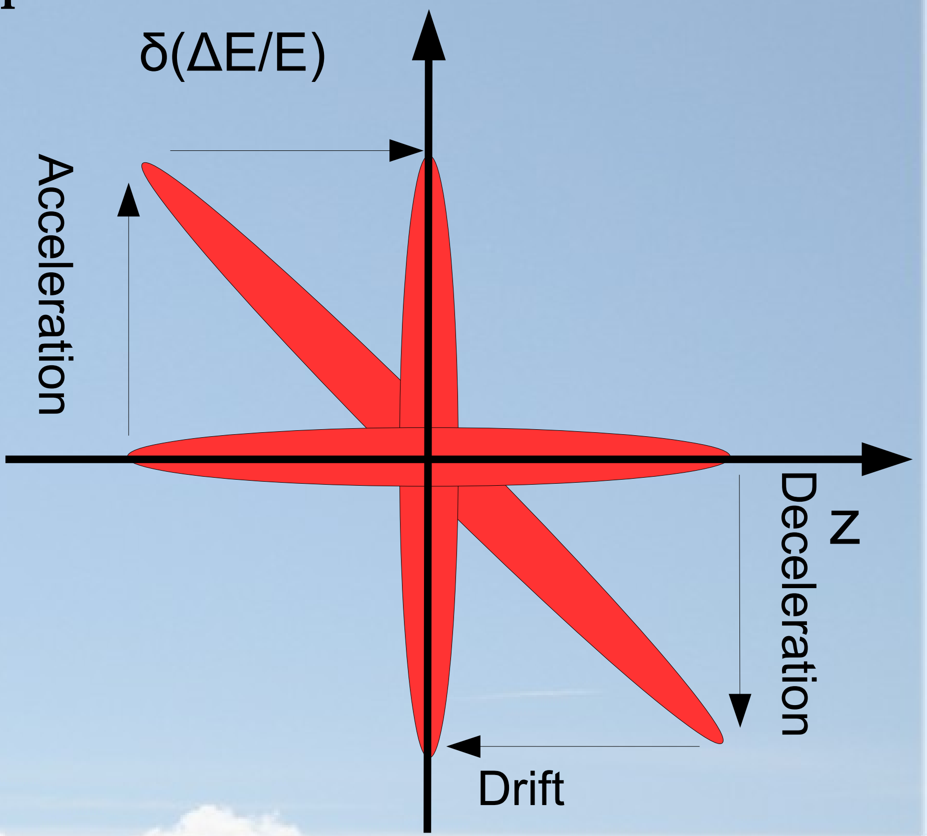
- Energy Modulation : RF cavity.
- Dispersive section : different path for different energy.
- Bunch head (tail) travels longer (shorter) path and bunch length becomes shorter.



By E.S. Kim

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 (2)

R-matrices

Drift space:

$$\begin{bmatrix} z(s) \\ \delta(s) \end{bmatrix} = \begin{bmatrix} 1 & R_{56} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} z(0) \\ \delta(0) \end{bmatrix} \qquad (2-60)$$

$$R_{56} = -\frac{L}{\gamma^2 \beta^2} \qquad (2-61)$$

Dispersive section:

$$\begin{bmatrix} z(s) \\ \delta(s) \end{bmatrix} = \begin{bmatrix} 1 & R_{56} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} z(0) \\ \delta(0) \end{bmatrix} \qquad (2-62)$$

$$R_{56} = \eta_l = \int ds \frac{\eta}{\rho} \qquad (2-63)$$

RF Energy modulation

$$\begin{bmatrix} z(s) \\ \delta(s) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} z(0) \\ \delta(0) \end{bmatrix} \qquad (2-64)$$

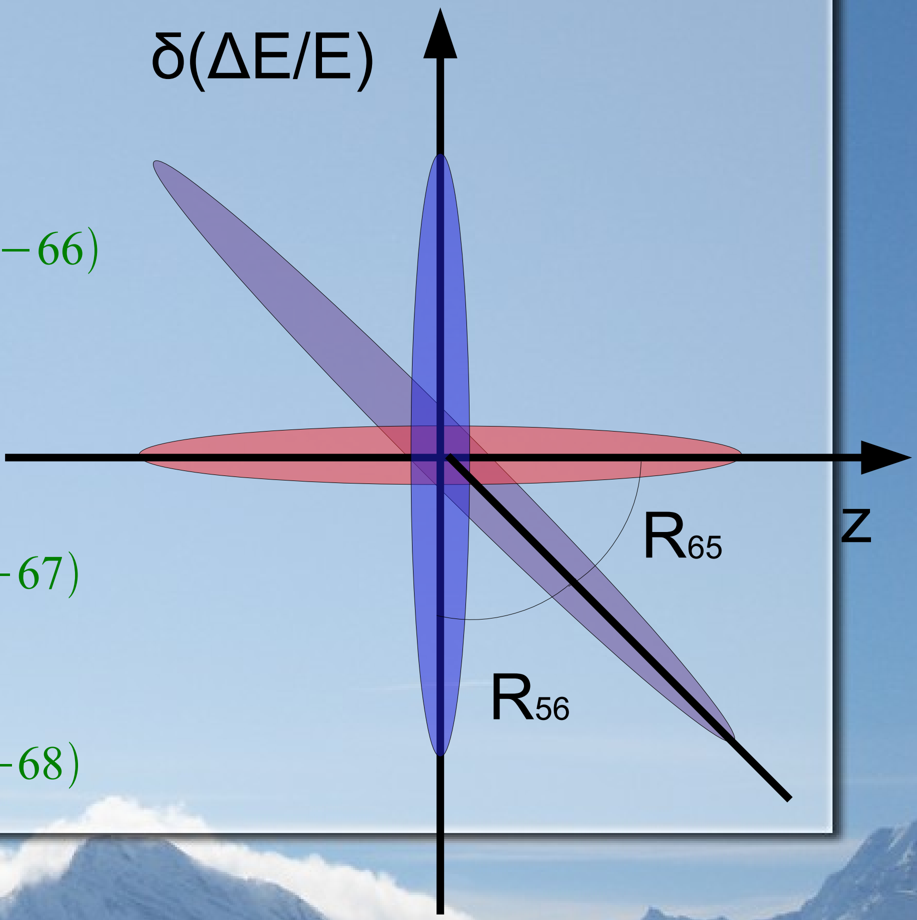
$$R_{65} = \frac{1}{z} \frac{\Delta E}{E} \sim \pm \frac{eV_0}{E} \frac{\omega}{\beta c} \qquad (2-65)$$

Common formalism (3)

Total Transfer Matrix of BC section.

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

$$= \begin{bmatrix} 1 + R_{56} R_{65} & R_{56} \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} z(s_0) \\ \delta(s_0) \end{bmatrix} \qquad (2-66)$$



Bunching condition : $1+R_{56}R_{65}=0$

Velocity bunching:

$$1 + R_{56} R_{65} = 1 - \frac{L}{\gamma^2 \beta^2} \frac{eV_0}{E} \frac{\omega}{\beta c} = 0 \qquad (2-67)$$

Magnetic bunching:

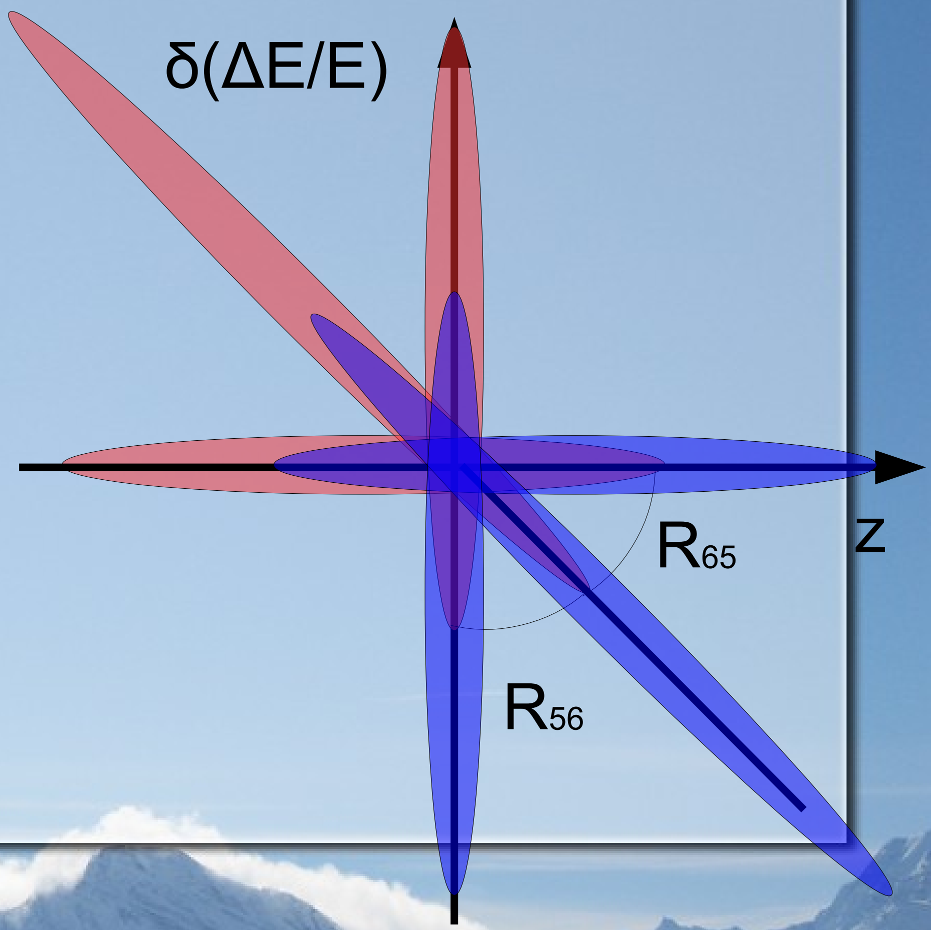
$$1 + R_{56} R_{65} = 1 + \eta_l \frac{eV_0}{E} \frac{\omega}{\beta c} = 0 \qquad (2-68)$$

Common formalism (4)

- When the bunching condition is satisfied,

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

- The position $z(s_2)$ does not depends on $z(s_0)$.
- This is a good mechanism to stabilize the bunch position.



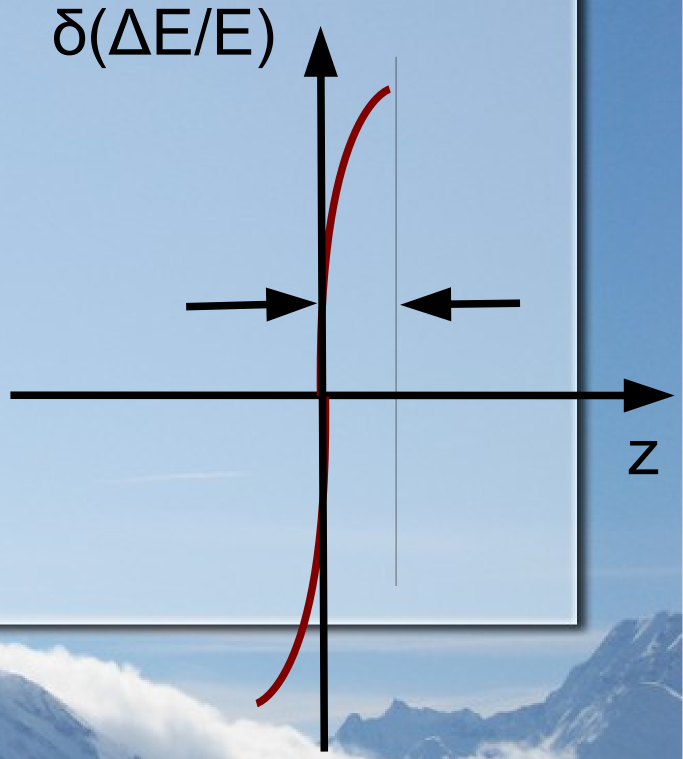
Common formalism (5)

Final bunch length after an optimized BC section ($1+R_{56}R_{65}=0$) is determined by the initial energy spread;

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

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

$$z_{nl} = \frac{L}{\gamma^2\beta^2}\frac{dE_{nl}}{E}$$



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

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

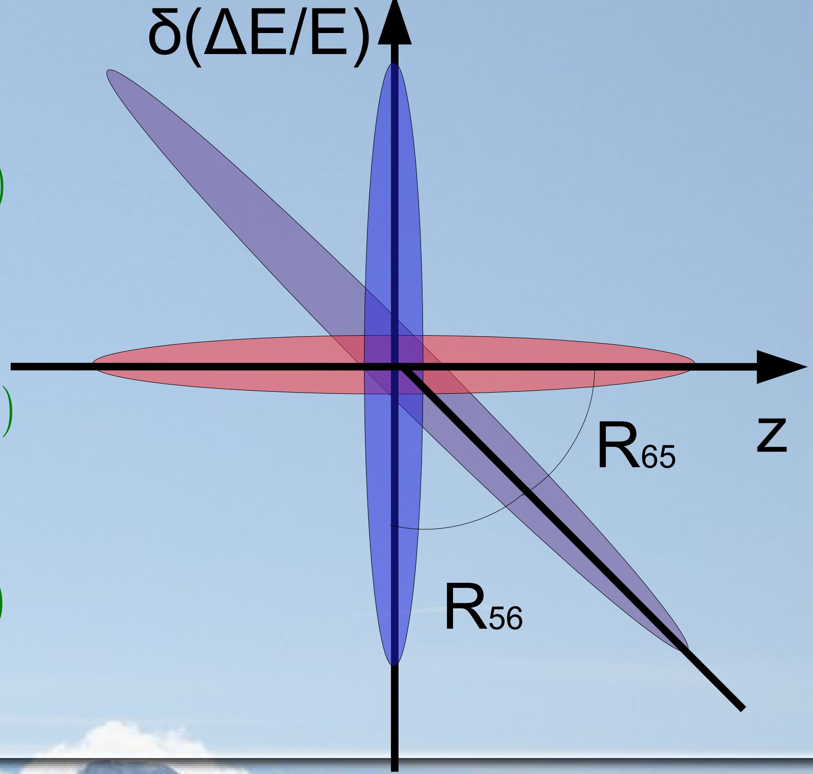
$$= \begin{bmatrix} 1 & R_{56} \\ R_{65} & 1 + R_{56} R_{65} \end{bmatrix} \begin{bmatrix} z(s_0) \\ \delta(s_0) \end{bmatrix} \qquad (2-71)$$

Matching condition for energy compression is

$$1 + R_{56} R_{65} = 0 \qquad (2-72)$$

The final energy spread is

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



Electron Gun

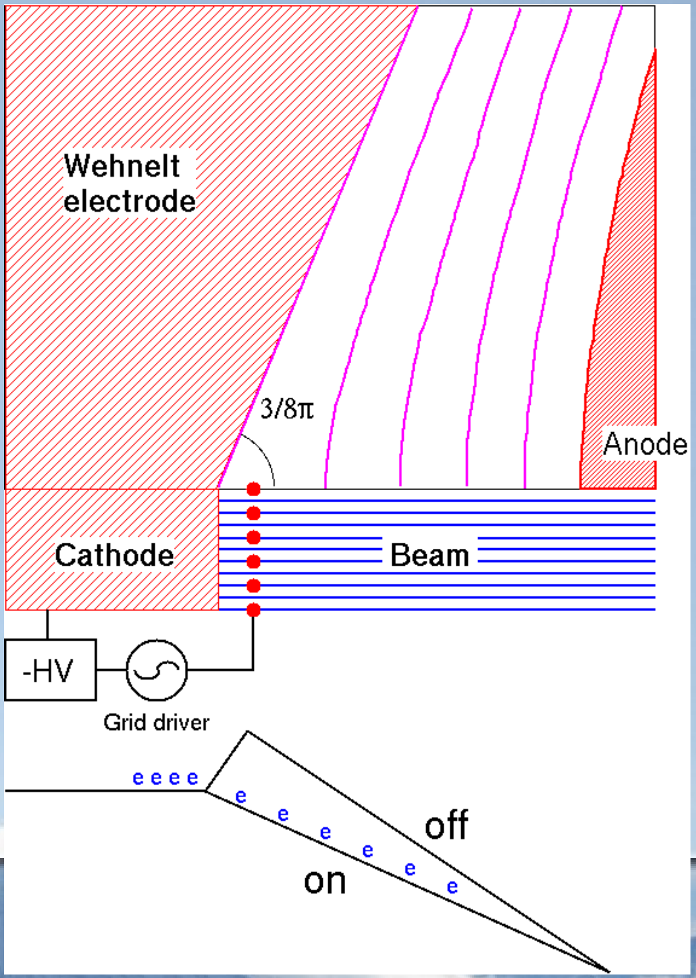
Electron Gun

	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

Thermionic DC gun

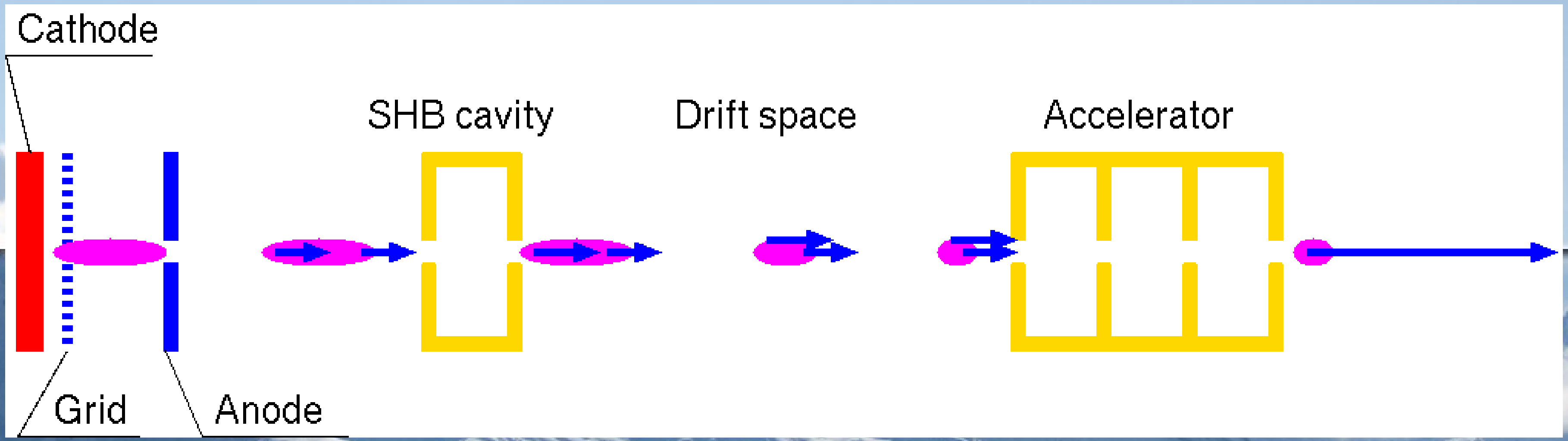
- Thermionic cathode with DC bias.
- It is a conventional gun widely used.
- Continous beam or
- Bunched beam by grid switching, but the bunch length is down to ~1ns.
- Energy at the gun exit is

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



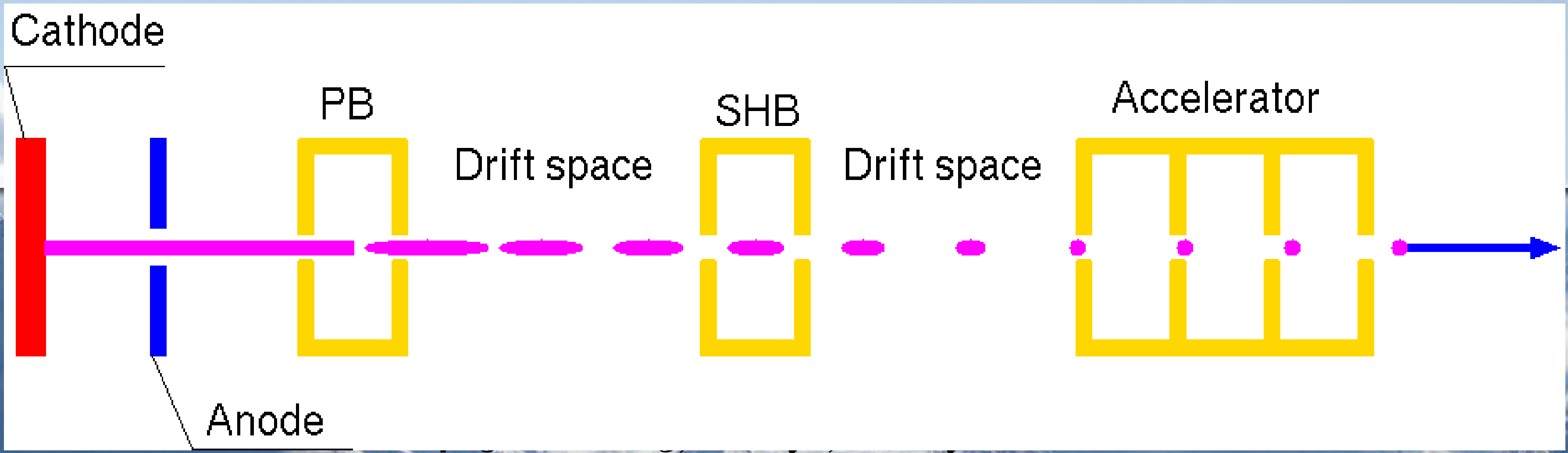
Thermionic Gun:
A typical configuration (1)

- 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 configuration (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

- $\varphi/T_e<2.0$ is practically used as thermionic cathode.
- Impregnated type BaO cathode is widely used for conventional accelerator.
- CeB_6 and LaB_6 have advantage for high-brightness beam generation.

Material	ϕ (ev)	T_e (K)	ϕ/T_e(x1E+3)
W	4.5	2860	1.57
Ta	4.1	2680	1.53
Mo	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 field.
- Beam energy at the gun exit is determined by the bias voltage ,

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

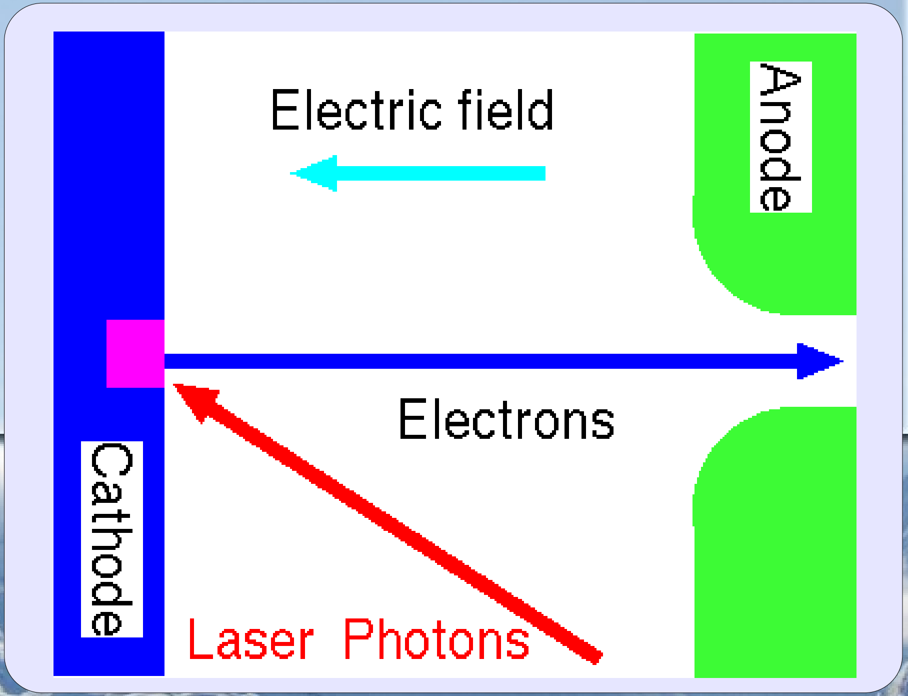


Photo-Cathode DC Gun (2)

- Because the velocity at the gun exit is slow, the first cavity is "low β 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.

$$L_{cell} = \frac{\Delta \phi}{2 \pi f} \beta c \qquad (3-2)$$

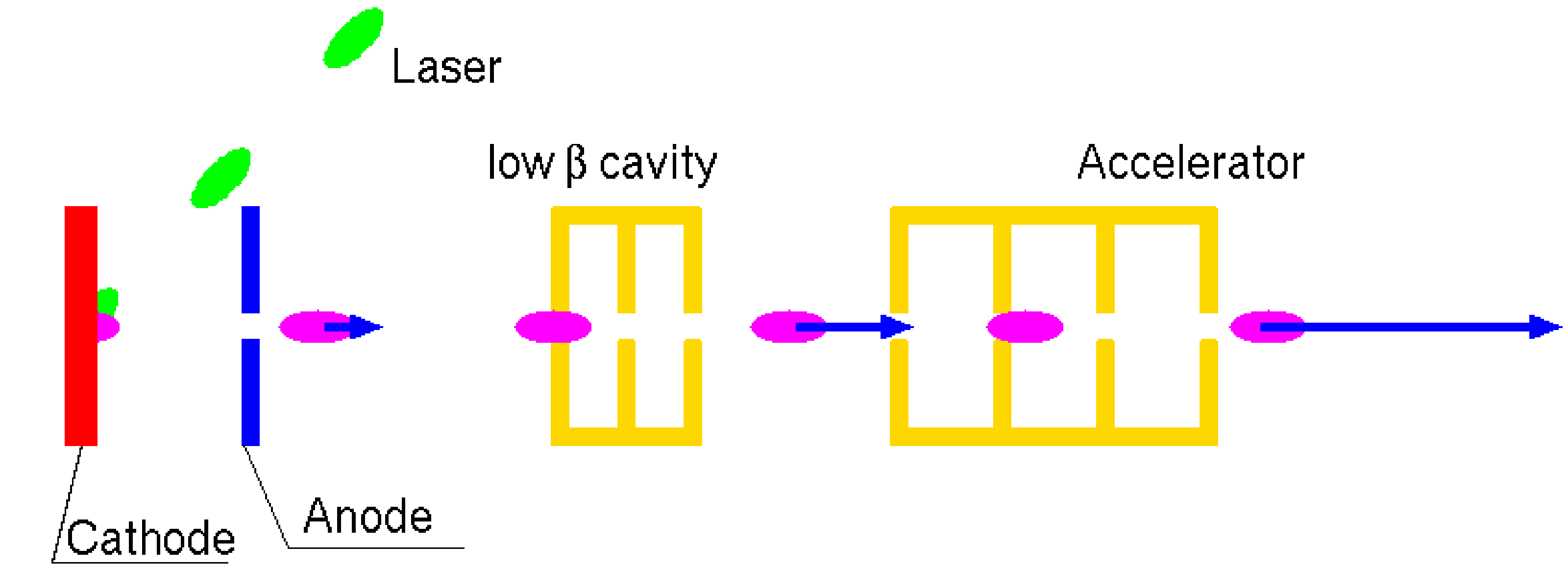
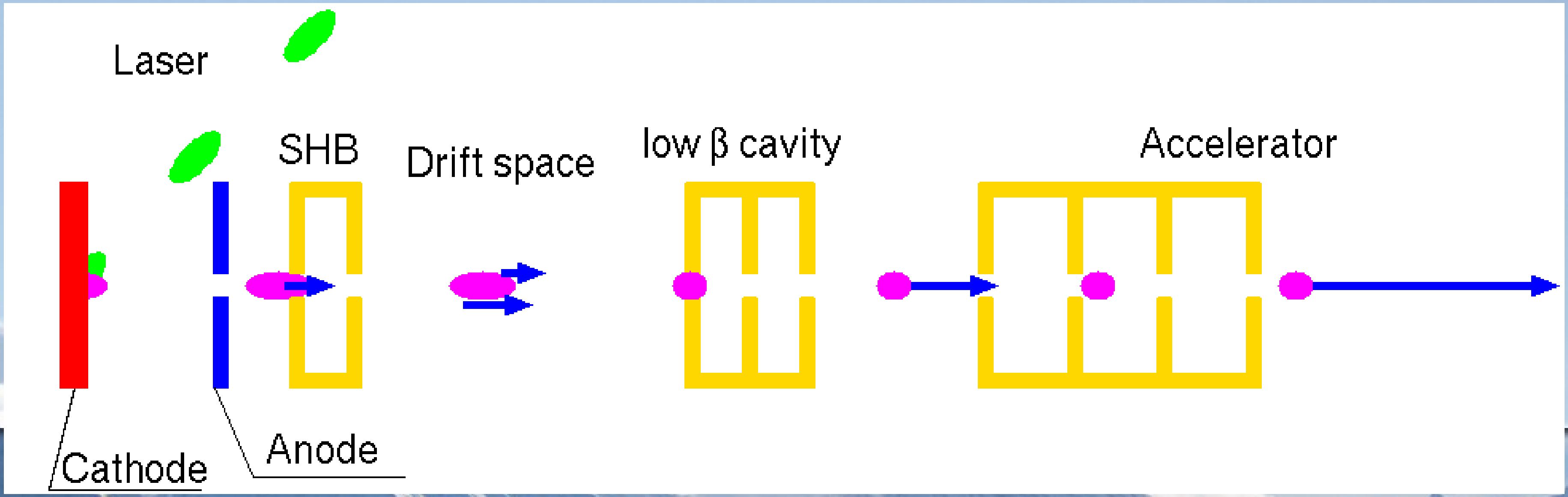


Photo-Cathode DC Gun (3)

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

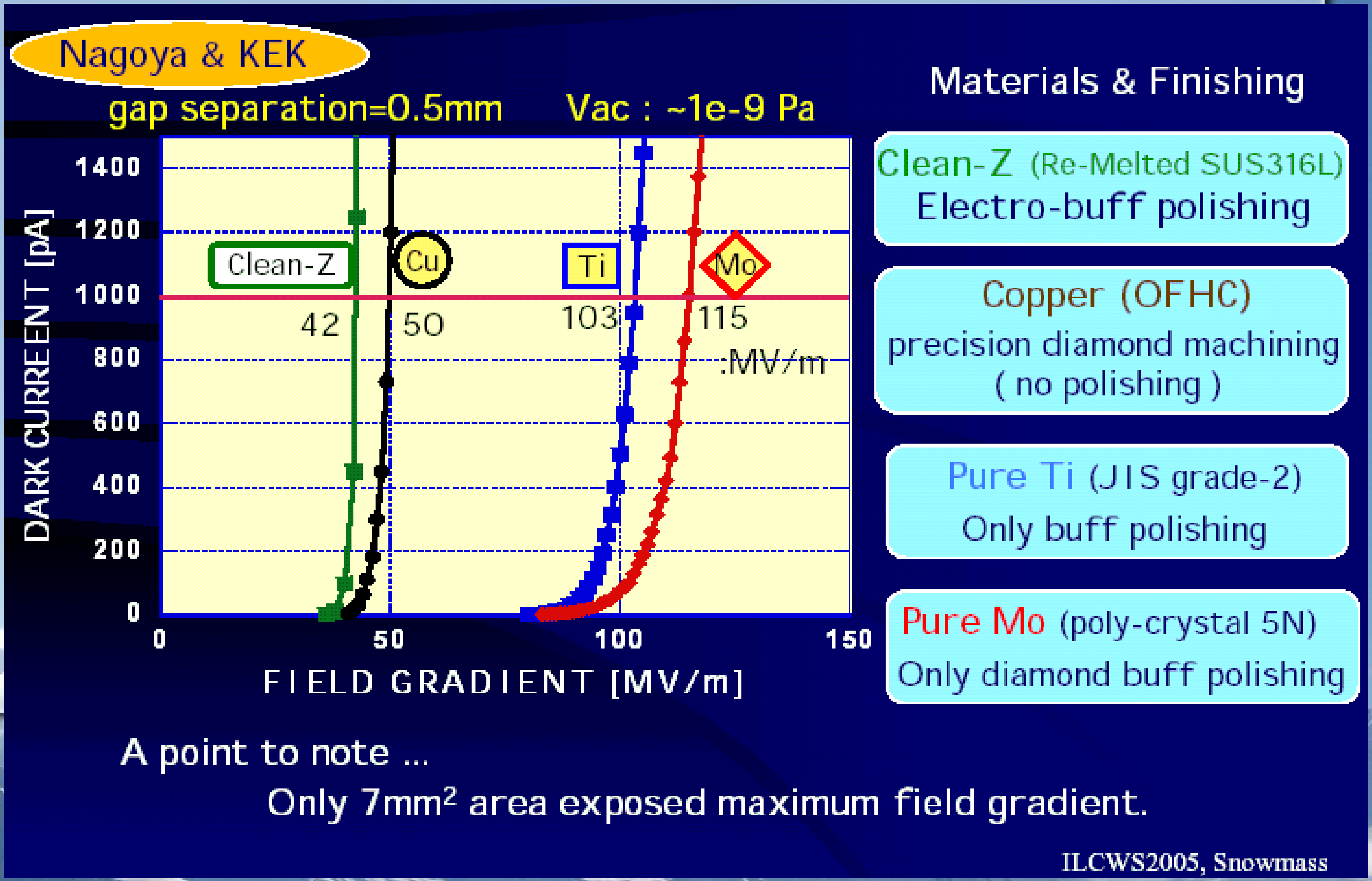


HV Operation (1)

- 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.

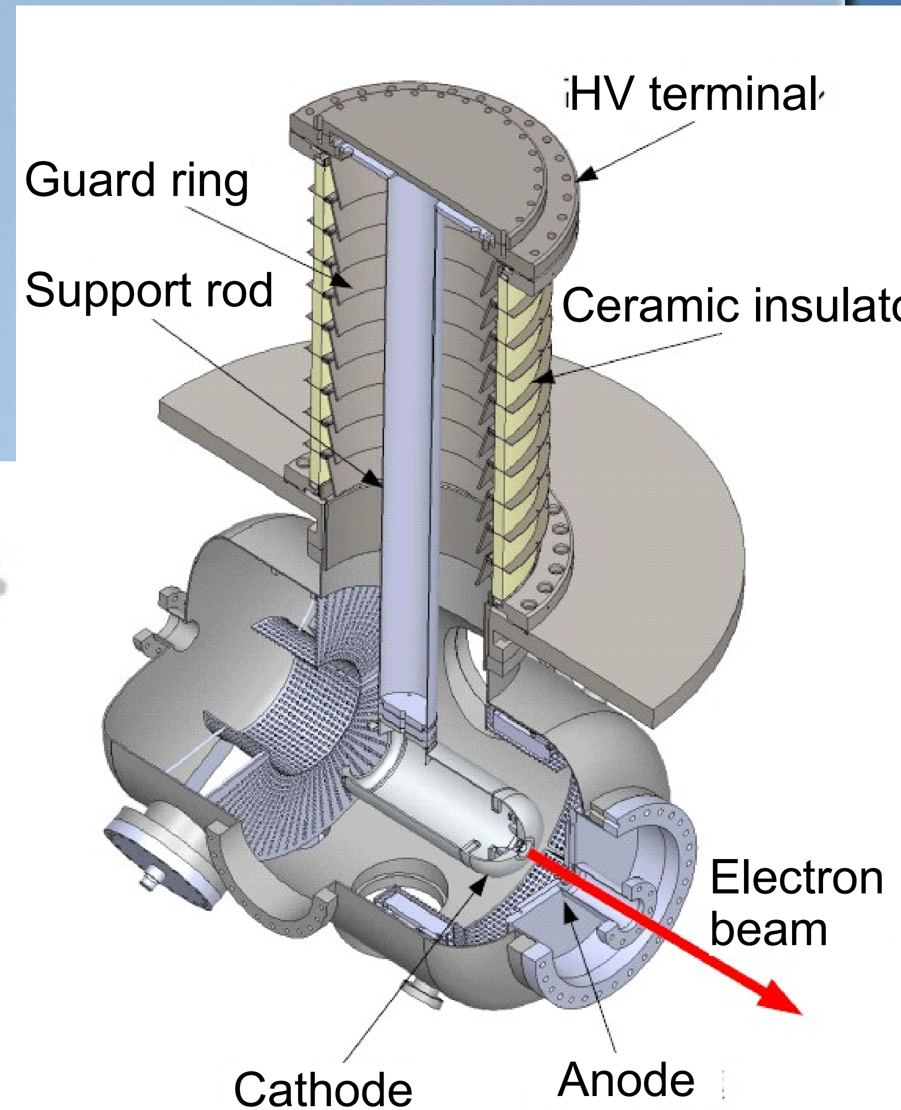
HV Operation (2)

M. Yamamoto on behalf of F. Furuta



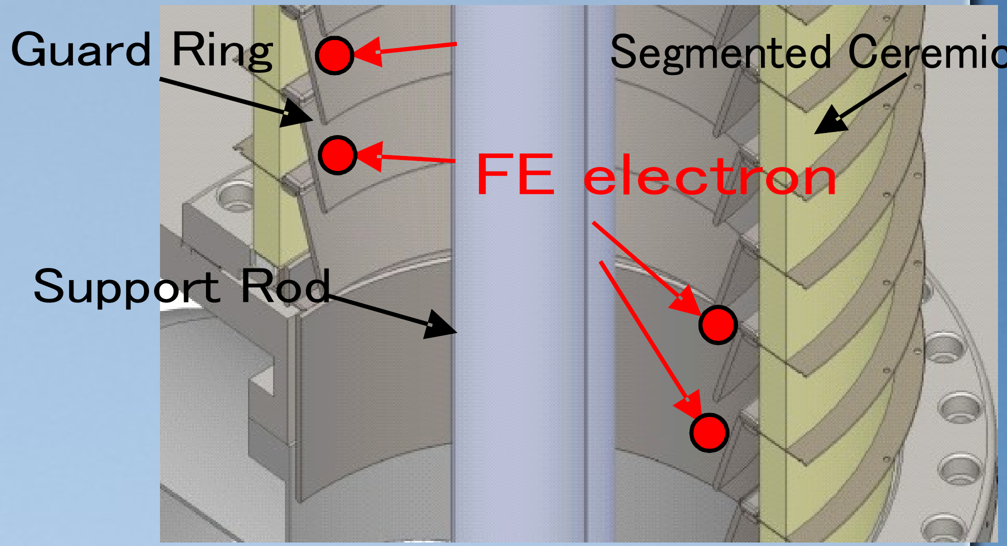
HV Operation (3)

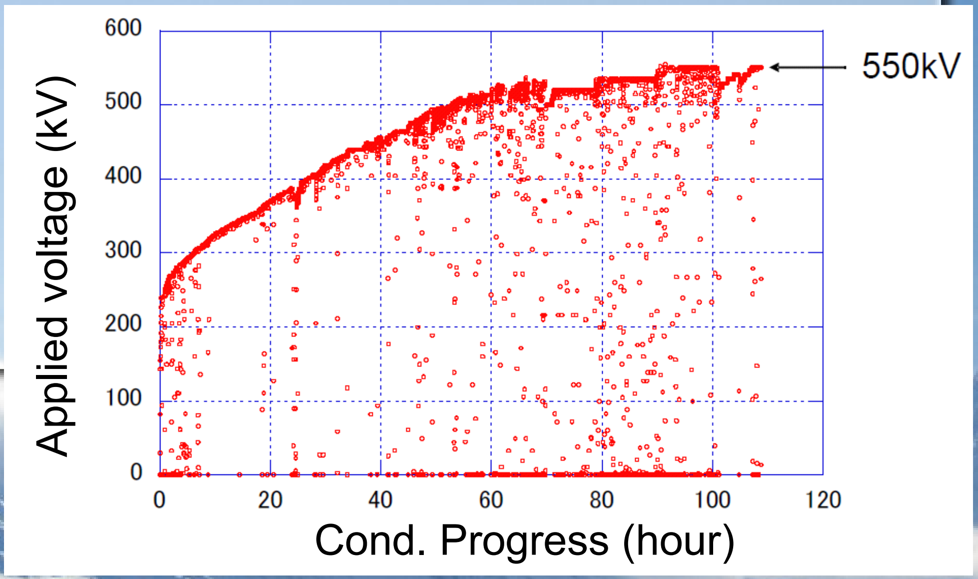
- Future light source based on ERL employs PC-DC gun.
- For extremely low emittance, HV operation is essential.



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.

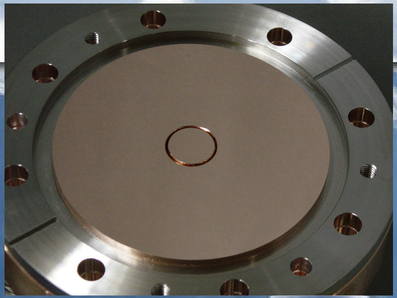


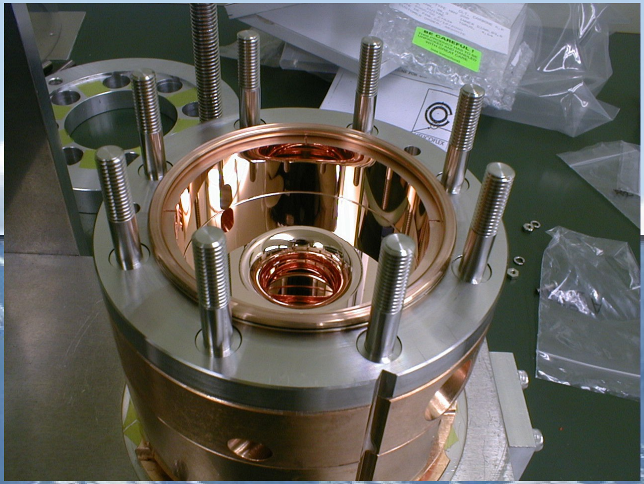


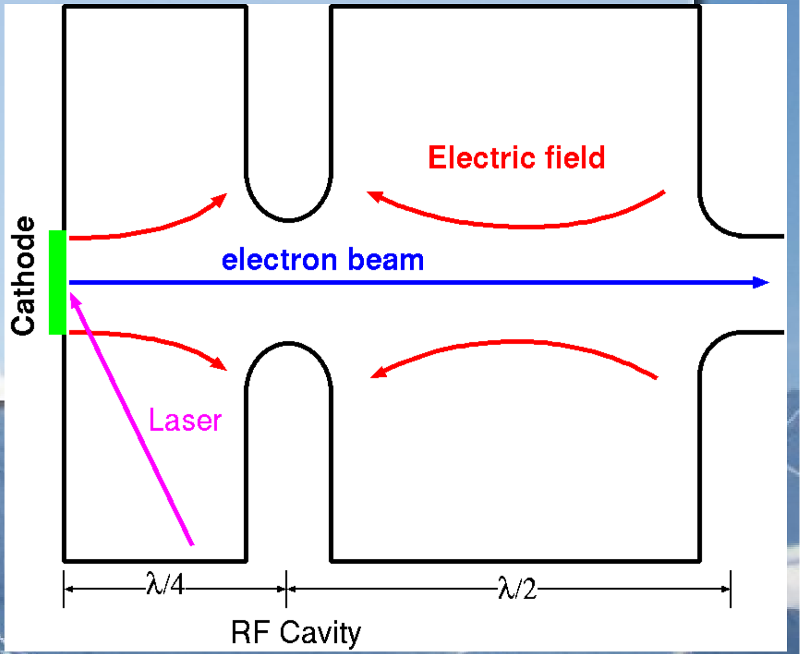
R. Nagai, RSI(81)033304(2010)

RF Gun (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

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

P: RF input power,
R:shunt impedance

Photo-cathode

- Quantum efficiency, η and temporal response are important property of Photo-cathode.
  - Quantum efficiency determines required laser pulse energy.
  - Temporal response should be even fast to form a short electron bunch, several 10s ps.
- Metal cathode (Cu, Mg) has low η and fast response.
  - η is typically $10^{-4}\sim10^{-5}$, response is fast in fs.
- Alkali cathode (CsTe, CsKSb) high η and medium response.
  - η is typically $10^{-1}\sim10^{-2}$, response is in sub ps.
- NEA GaAs cathode has high η and slow response.
  - η is typically $10^{-1}\sim10^{-2}$, response is 10s ps

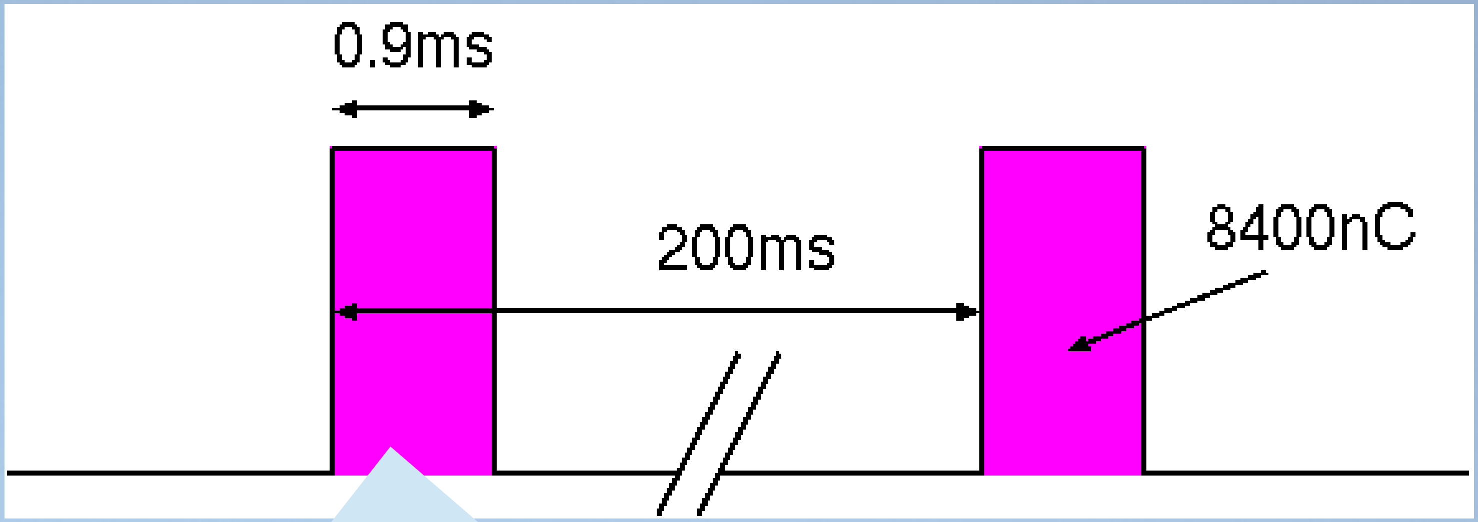
Electron source for Linear Colliders

ILC Requirements

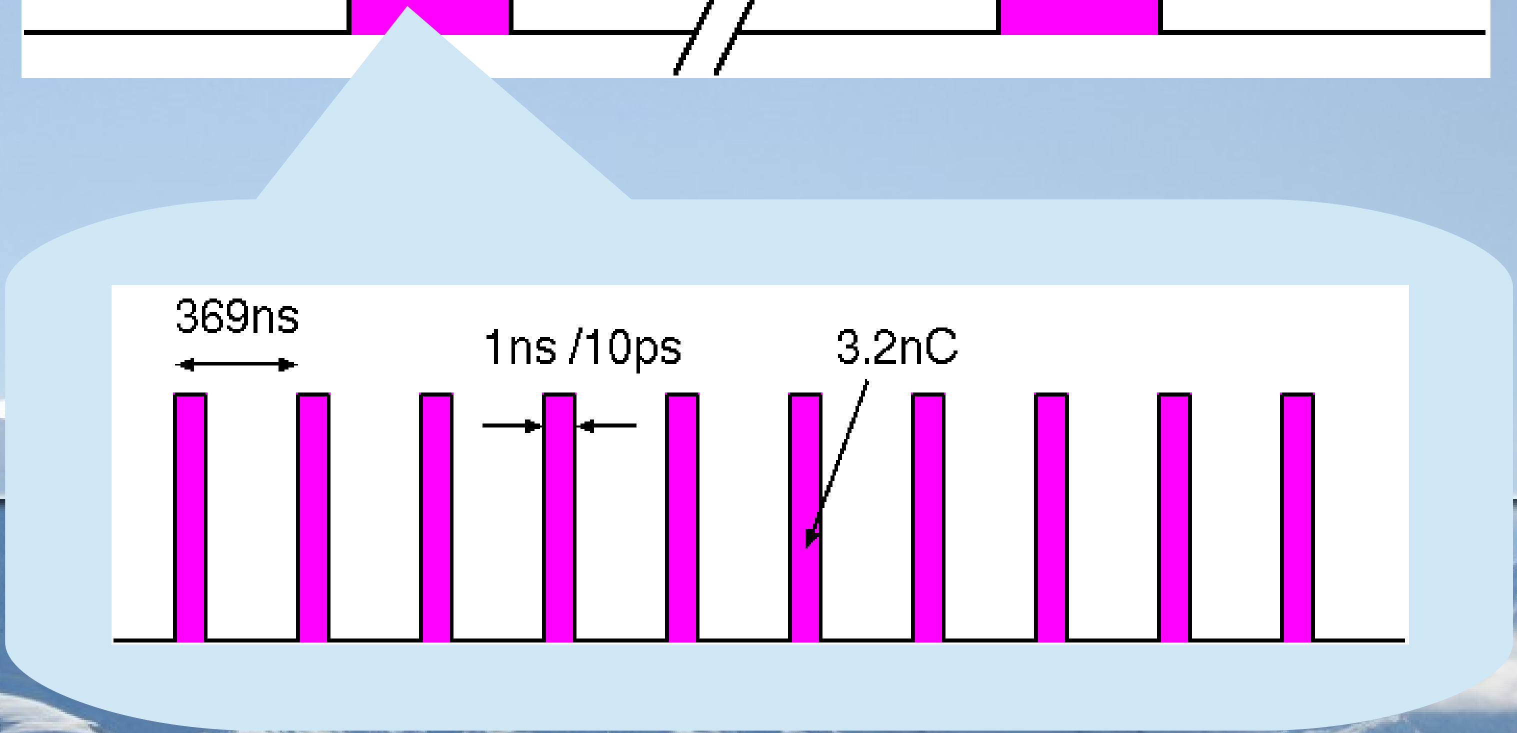
Parameters	
Pulse length	0.9ms
Pulse repetition f_{rep}	5Hz
# of bunches in a pulse n_b	2625 (1310)
Bunch separation	369(670)ns
# of electrons in a bunch N	$2x10^{10}$
Micro bunch length at source	1ns
Peak current	3.2A
Electron Polarization	80%

ILC Pulse Structure

Macro Pulse

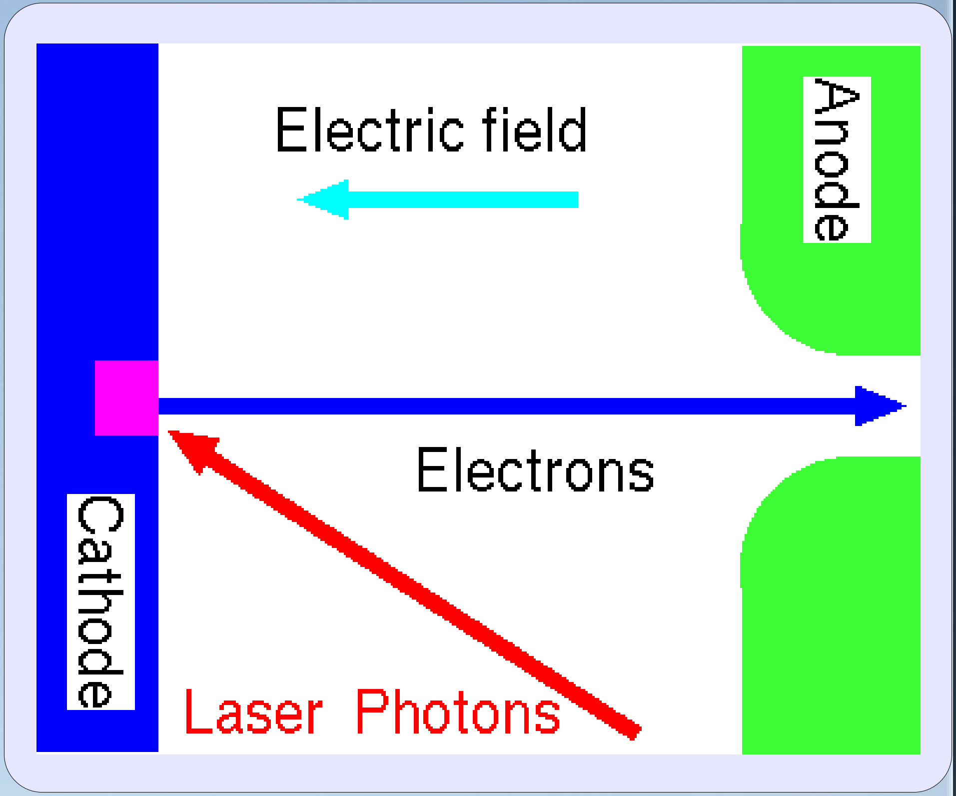


Micro Pulse



Basic Concept

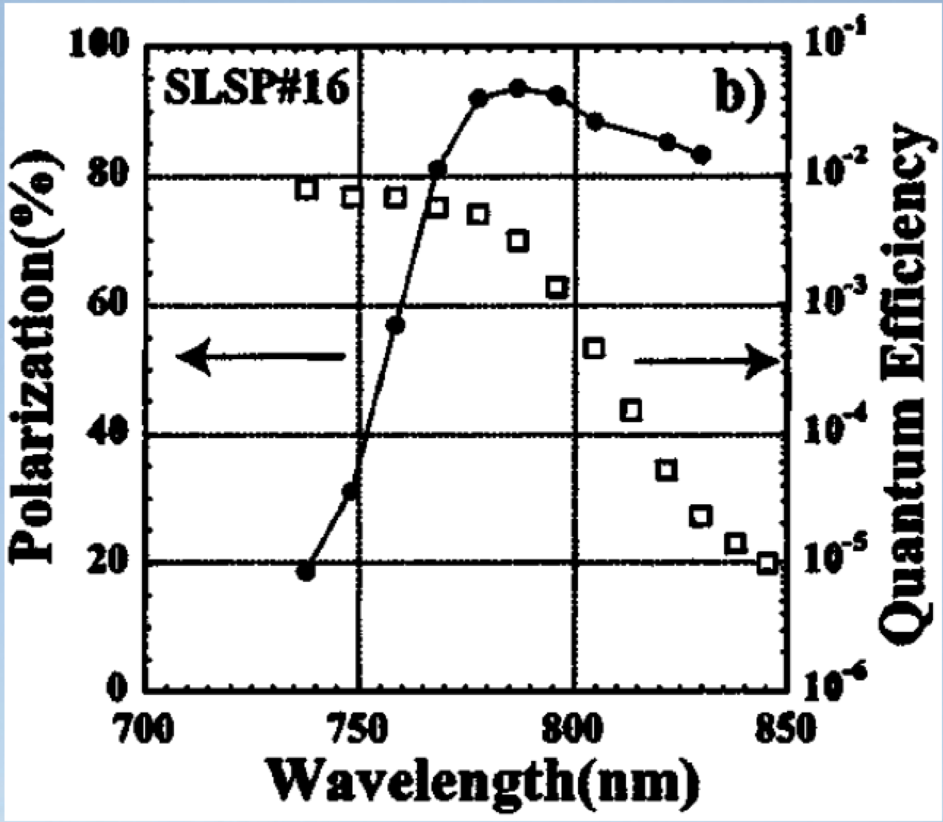
- NEA GaAS cathode with circularly polarized laser is the only solution for polarized electrons.
- Beam extraction by a static electric field (DC photo-cathode gun) because RF gun is not compatible with GaAs cathode.



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)

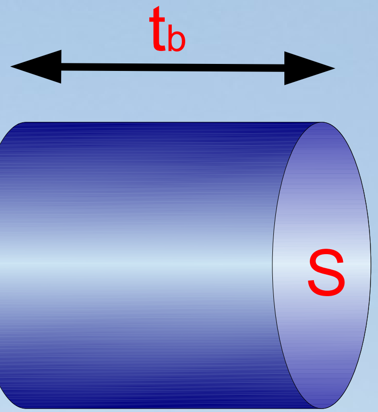
Bunch extraction
Bunch shape

- 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.

$$J[A/m^2]=2.33\times10^{-6}\frac{V^{3/2}}{d^2}$$

$$I[A]=JS$$

$$t_b=\frac{Q}{I}$$



Injector Design

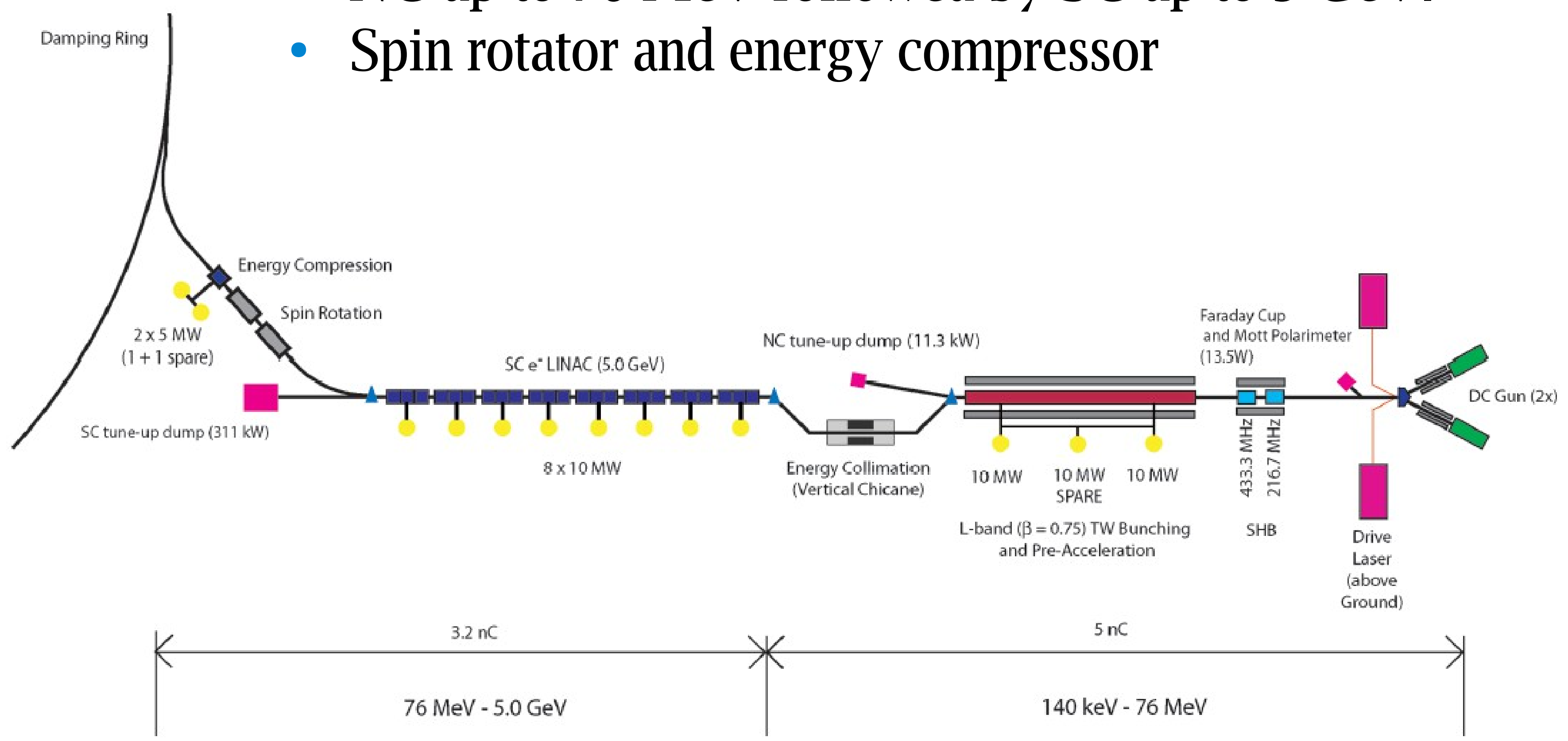
- If the bunch length at gun t_b is adequate for RF acceleration, any bunching section is not needed.
- Otherwise, we need a bunching section.
- RF period for the bunching should be long enough comparing to t_b for linear modulation.
- RF frequency for the bunching should be harmonics of bunch repetition,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

$$T_{bunching} \gg t_b$$

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

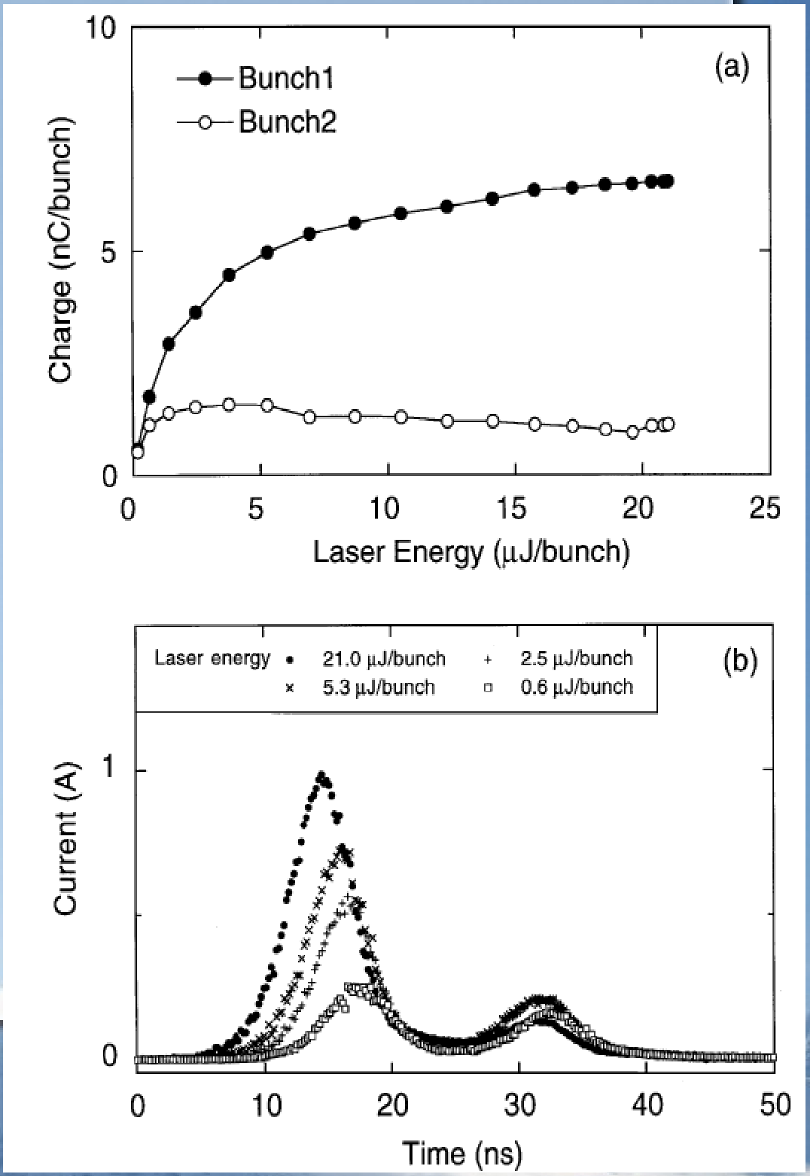
ILC Electron Source

- DC photo cathode gun with GaAs cathode.
- Two identical guns are for redundancy.
- Buncher for short bunch length.
- NC up to 76 MeV followed by SC up to 5 GeV.
- Spin rotator and energy compressor



Surface Charge Limit (1)

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

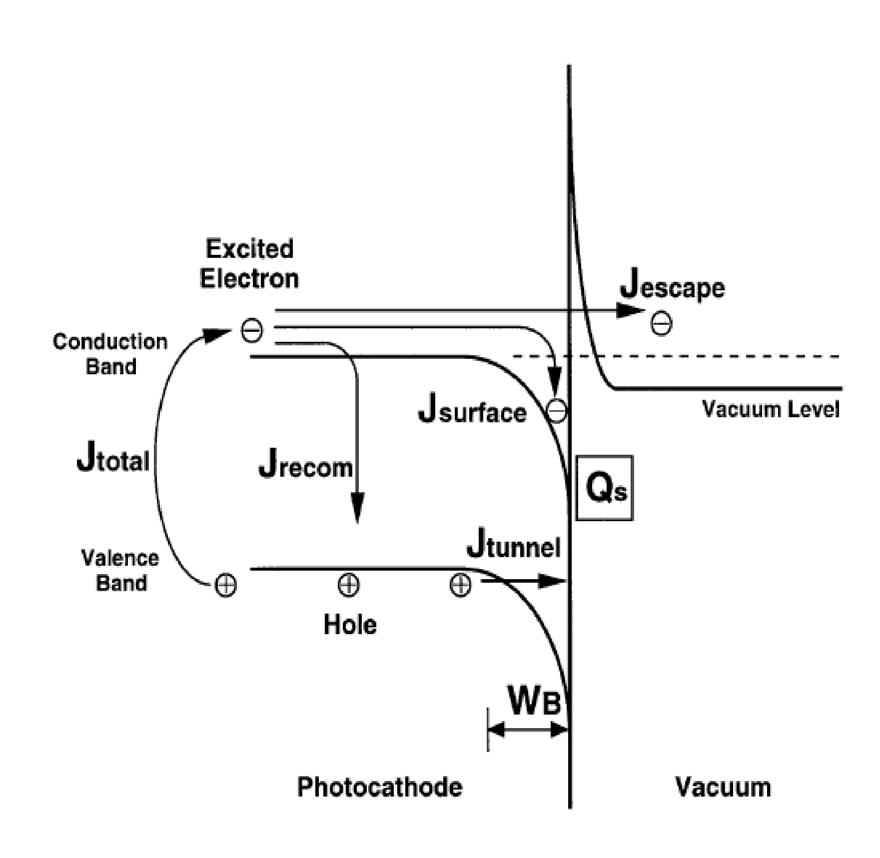


K. Togawa, NIM A 414 (1998) 431-445

GaAs with a Be-dope 5E+18cm3

Surface Charge Limit (2)

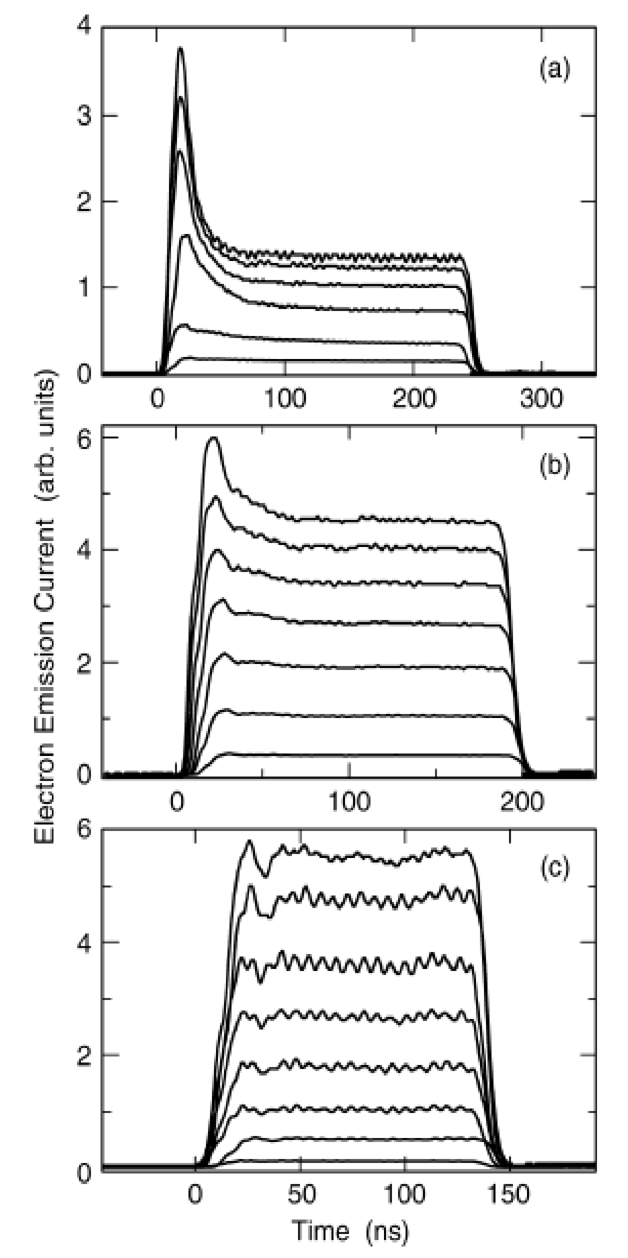
- The surface charge limit is caused by Photo-voltage effects;
- Some electrons, $J_{surface}$ is captured at BBR(Band Bending Region).
- By the captured electrons, the effective vacuum level is increased.
- Photo-voltage effects decrease size of EA and limit the current.



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/cm^2 is achieved. It is more than the requirement of ILC gun.

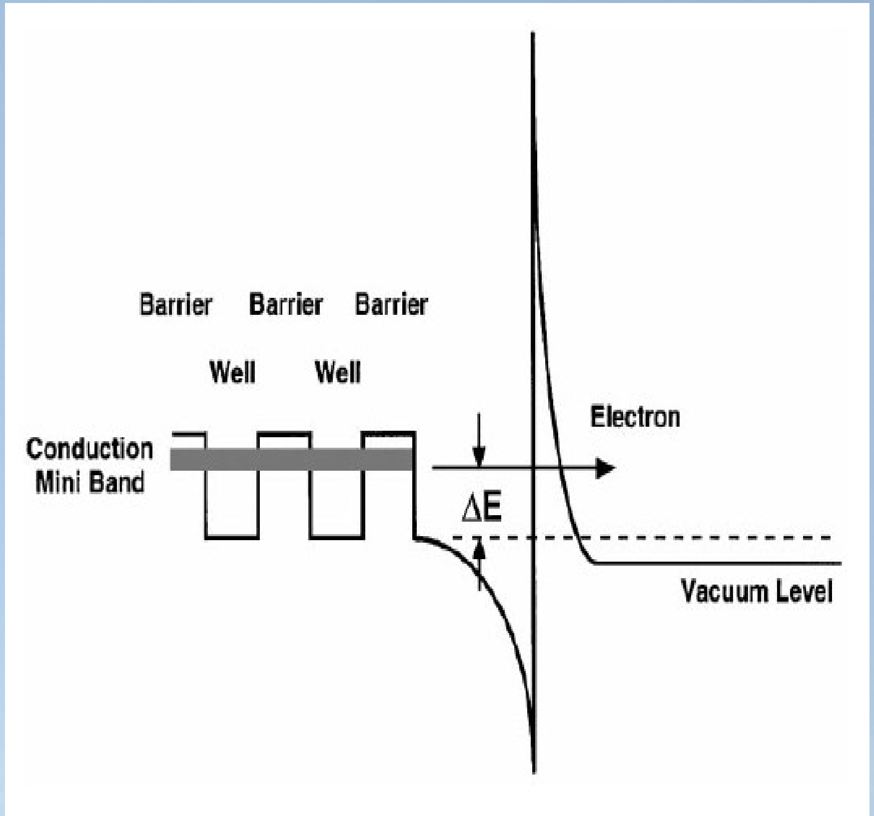


(a) sample 1b(Na=0.5),
(b) sample 2a(Na=1.0), and
(c) sample 3(Na=2.0). The laser intensity is 1 to 150 W/cm2.

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

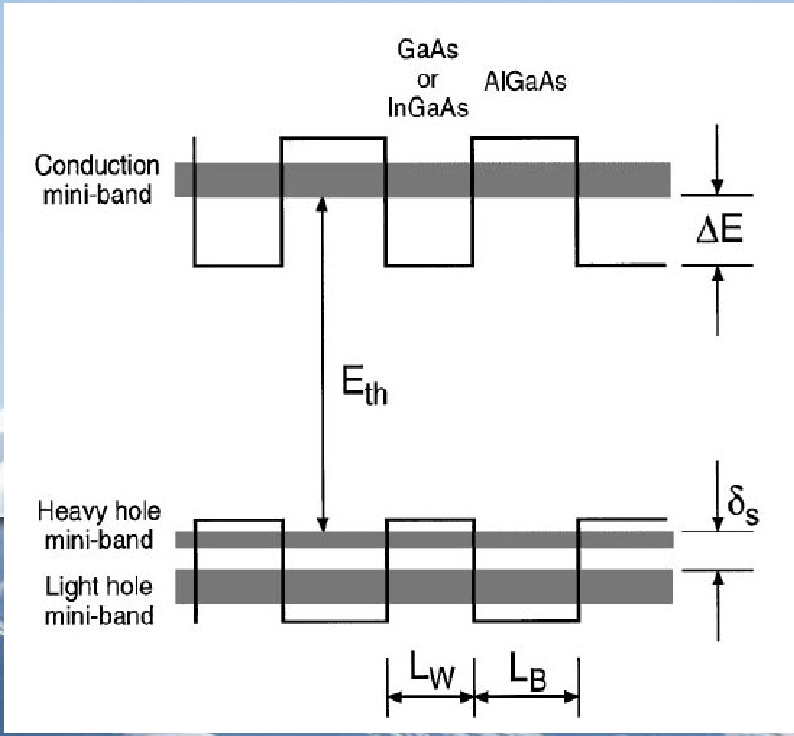
Surface Charge Limit (4)

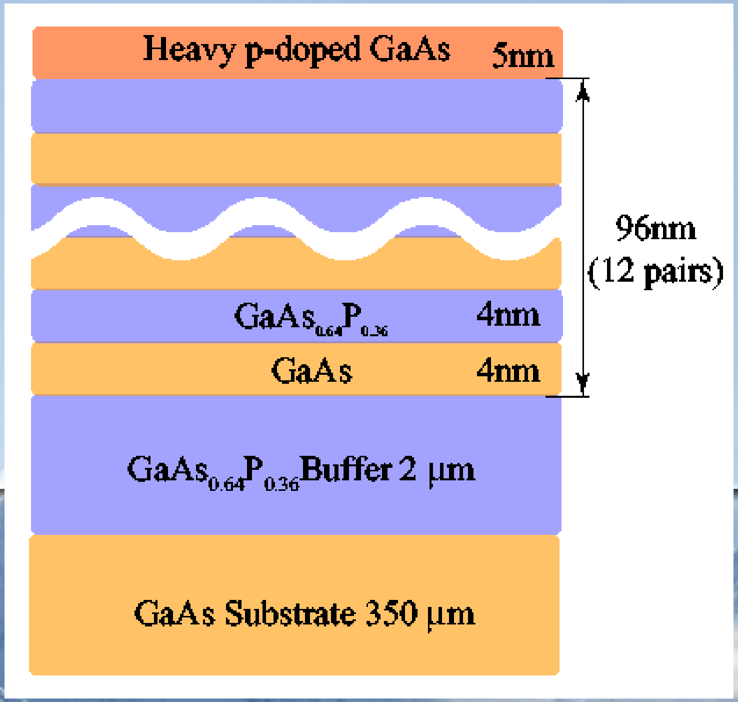
- Super-lattice Cathode has an advantage against SCL.
- J_{escape} is proportional to the size of NEA.
- The effective size of NEA in Super-lattice cathode is larger than that of bulk-GaAs.
- The escape probability, $J_{esacape}/J_{total}$ is larger for Super-lattice cathode. SCL current should be higher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



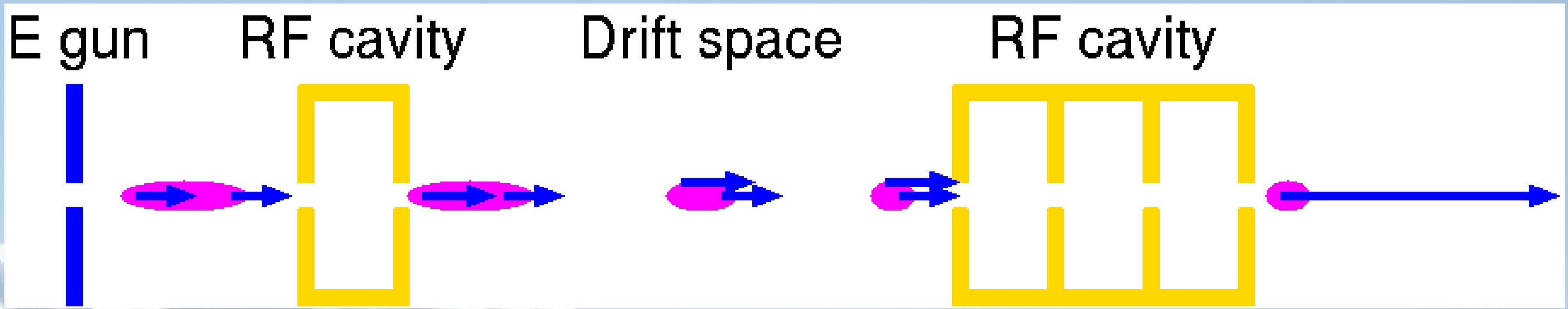


Bunching(1)

- 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 significantly 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.