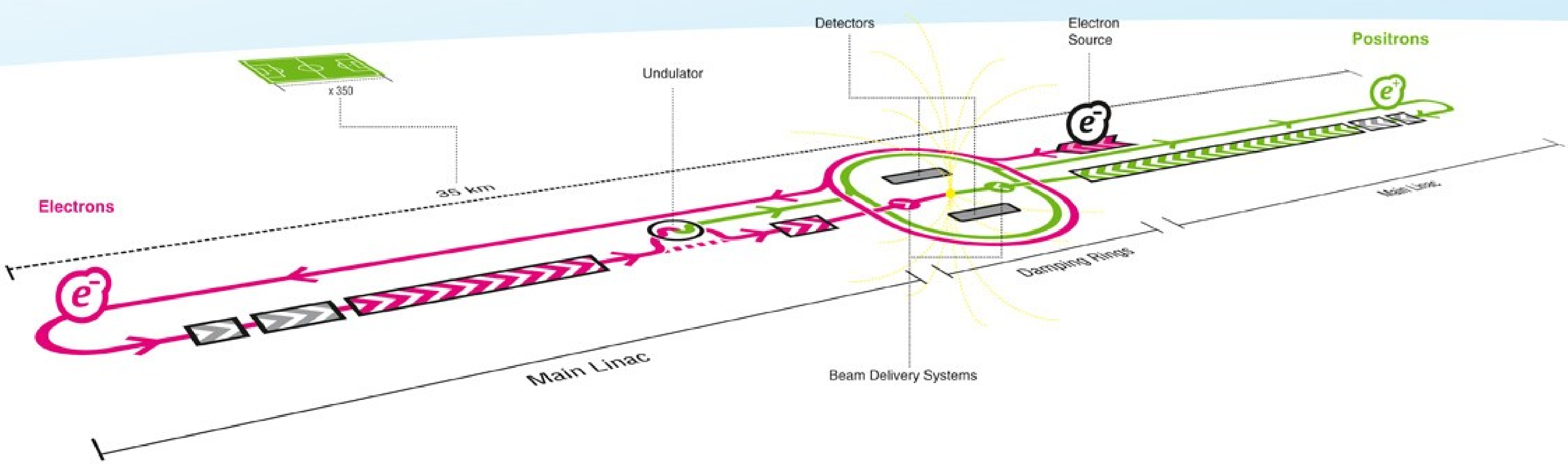
Electron source for Linear Colliders

KURIKI Masao (Hiroshima/KEK)



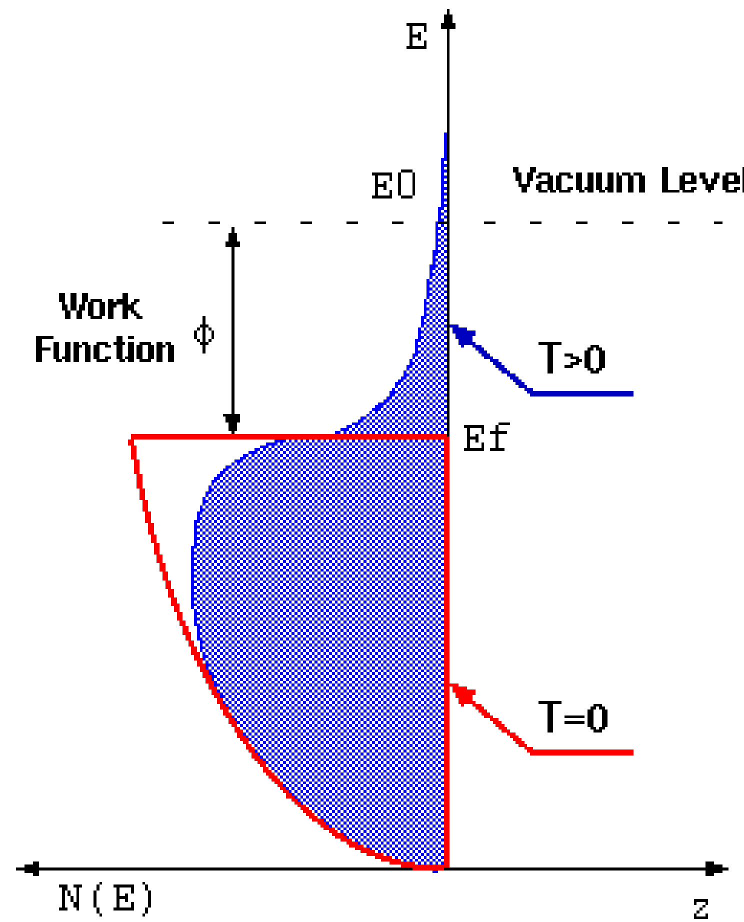
Contents

Electron Emission (1)

- 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.

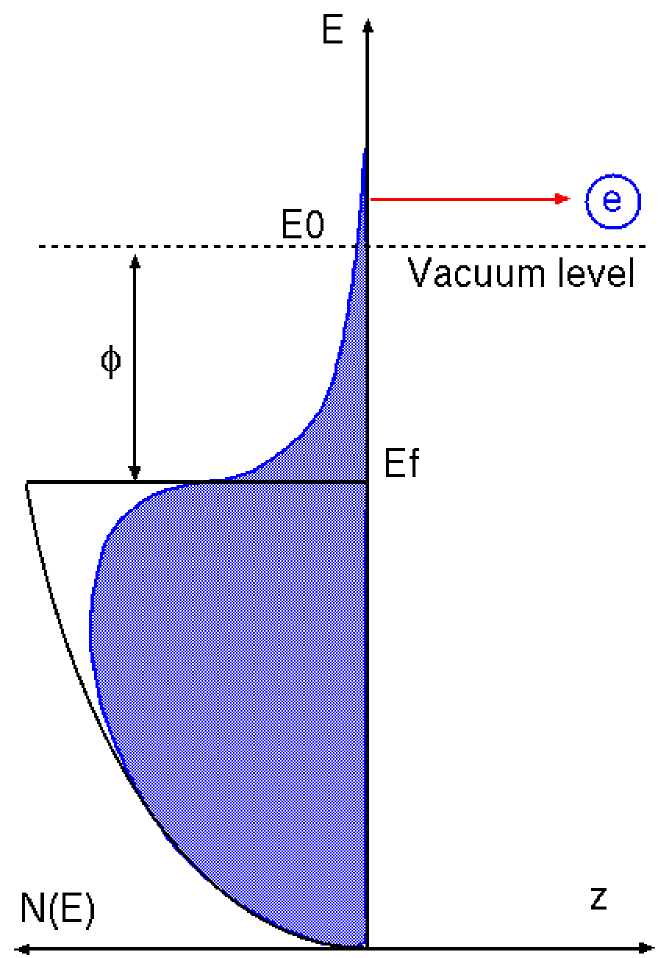
Fermi-Dirac Distribution

- 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.



Thermal Electron Emission

- If the temperature is sufficiently high, so that the electrons are distributed up to the vacuum level (E_0), 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.



Richardson-Dushman Equation

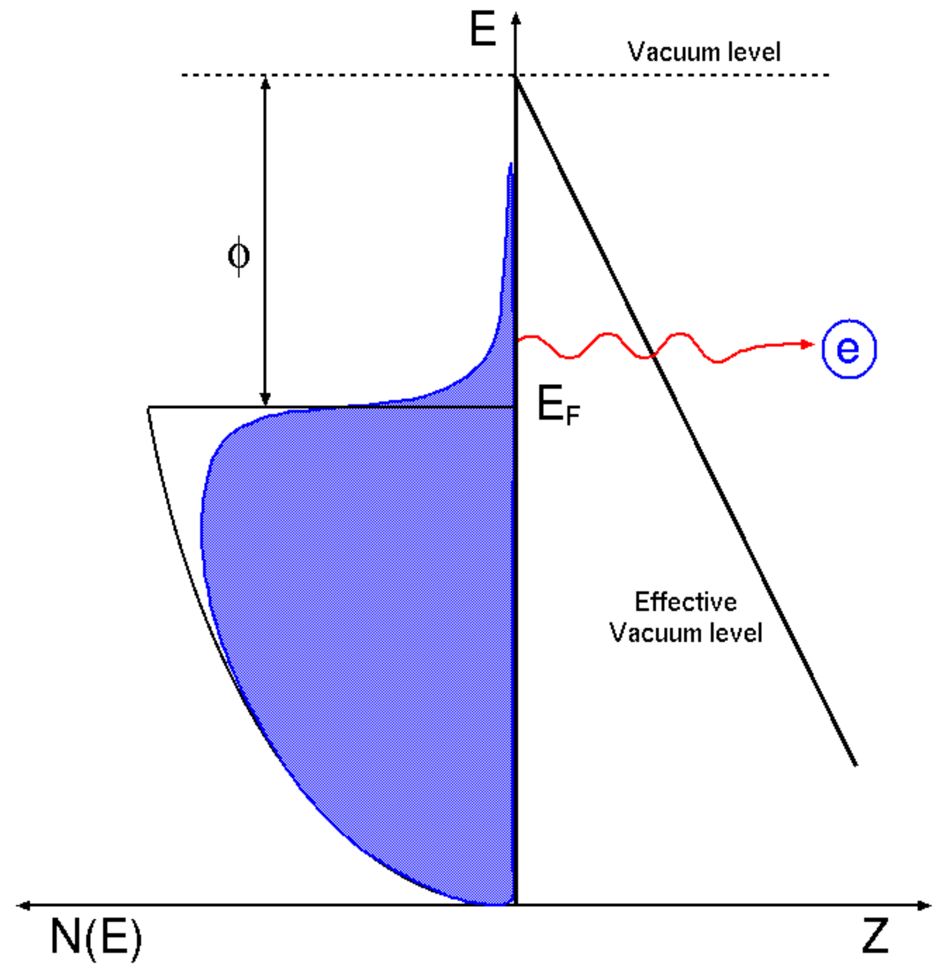
$$J = AT^2 e^{-\frac{\phi}{kT}}$$

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

- *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

- With large surface field, the potential barrier to the outside becomes very thin.
- When the field is more than 1E+8 V/m, the tunnel current becomes significant.
- Because of the emission at the cold temperature, it is called sometimes as cold emission.



Fowler-Nordheim Formula

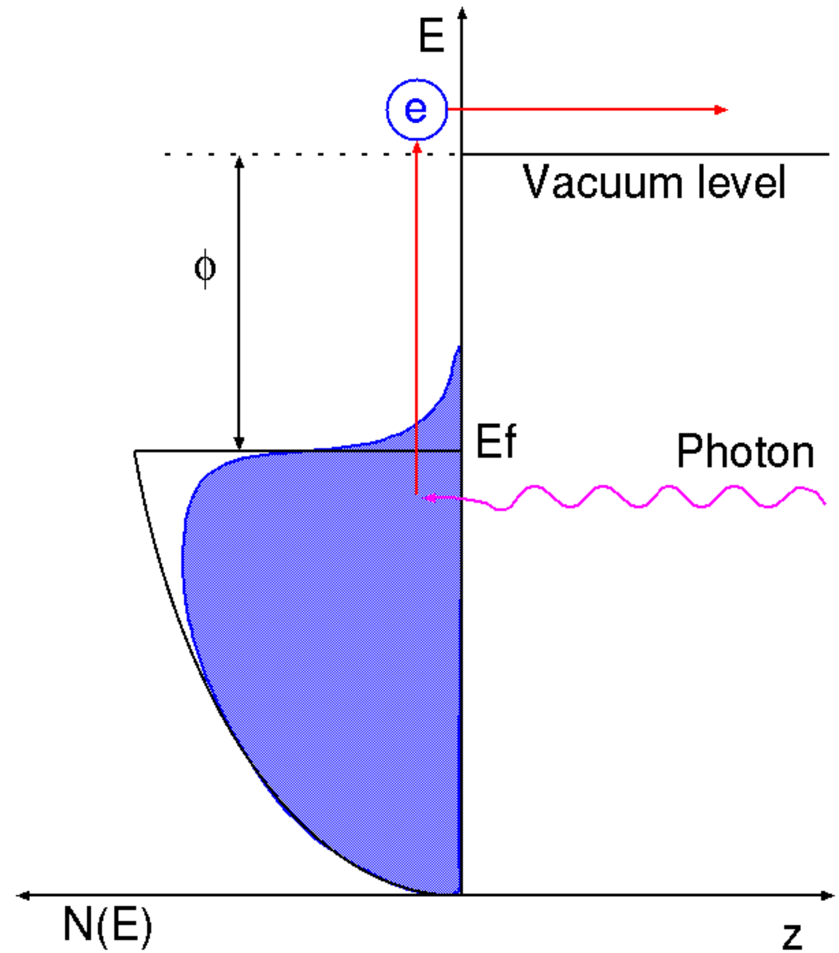
- The emission current is expressed by Fowler-Nordheim formula with *F*, surface field;

$$J = \frac{e^3 F^2}{8 h \pi \phi} \exp\left(\frac{4\sqrt{2m}}{3 h e F} \phi^{3/2}\right)$$

- The vacuum potential is assumed to be $E_0 - Fz$.
- The tunnel current was estimated with WKB approximation.

Photo-electron Emission

- Photons excite electrons into higher energy states.
- If the states are higher than the vacuum level, the excited electrons are extracted as the photo-electrons; Photo-electron effect.
- Photo-emission condition : $h\nu \geq \phi$



Fowler Equation

$$J = AT^2 \int_0^{\omega_0} \frac{\log(1+\omega)}{\omega} d\omega$$

$$A = \frac{2\pi e m}{h^3} Pk^2 \qquad \omega_0 = e^{\frac{E_f - E_z}{kT}}$$

- *P* shows the transition probability, E_z is the kinetic energy of electrons in z direction.
- Practically, Quantum Efficiency, η, is defined as

$$\eta = \frac{number\ of\ photo\ electrons}{number\ of\ photons}$$

with practical units

$$\eta[\%] = 124 \frac{J[nA]}{P[\mu W]\lambda[nm]}$$

Shottky Effect

- Potential near the surface is modified by the mirror charge potential and surface field

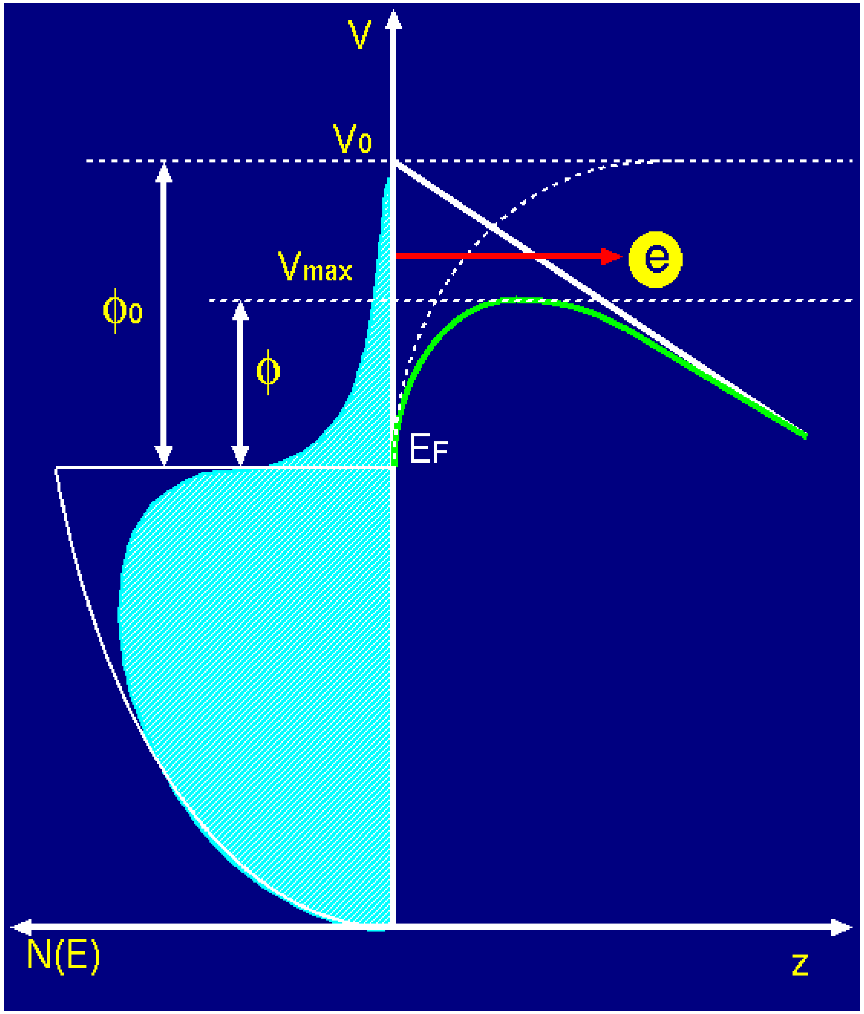
$$V(z) = V_0 - \frac{e^2}{16\pi\epsilon z} - eEz$$

- Crest of the potential curve is

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

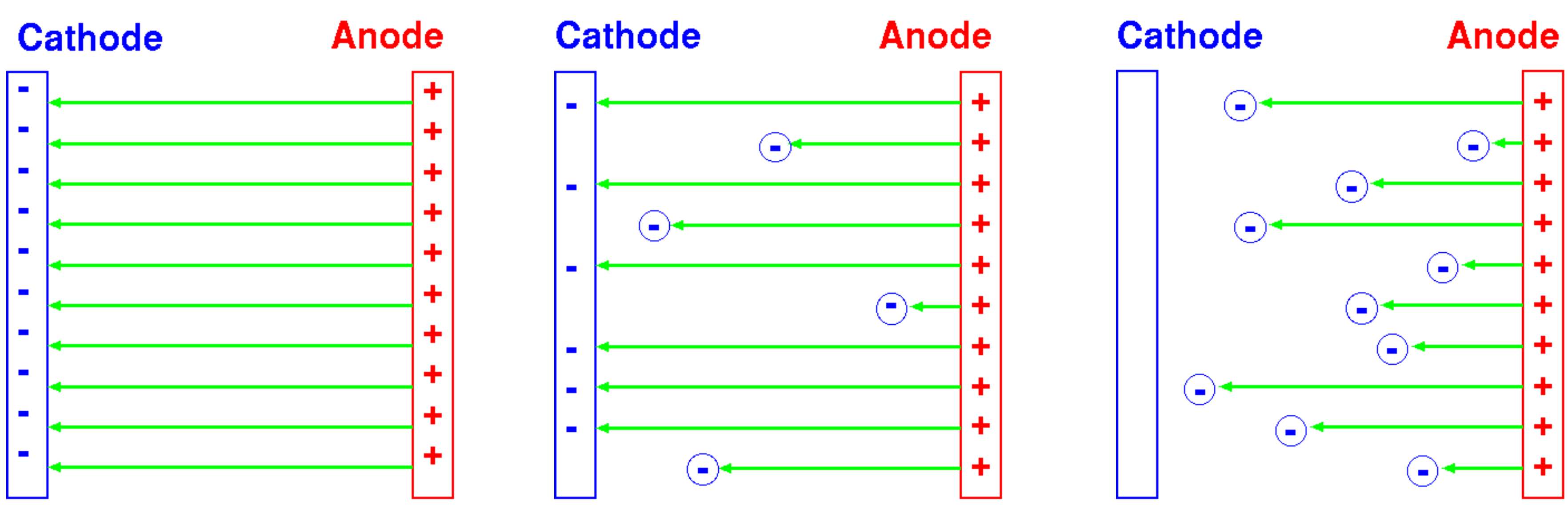
- The effective work function is

$$\phi(E) = \phi_0 - e\sqrt{\frac{eE}{4\pi\epsilon}}$$



Space Charge Limit

- Electron terminate the electric flux (remember Gauss's law).
- Electric field is weakened by the space charge.
- At some limit, the field at the cathode surface is disappeared and no electrons extracted further; the space charge limit.



Child-Langmuir Law

- In the space charge limit, the dynamics of the electron cluster decides the electron current, rather than the emission from the cathode.
- In diode geometry - two electrodes and one dimension - the current is;

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

  - *V* and *d* : voltage and distance between two electrodes.
  - *S* : area size
  - *P* : perveance defined as; $P = 2.33 \times 10^{-6} \frac{S}{d^2} (A V^{-3/2})$

Actual Emission Current

- When the surface field is not sufficiently high, the actual current is determined by the space charge limit.
- When the surface field is sufficiently high, the actual current is determined by that from the cathode.
- Then, the actual emission current form a cathode is

$$I_E = min(I_C, I_{SC})$$

  - **I_C: Emission current of the fundamental process (thermal emission, etc.)**
  - **I_{SC}:Space charge limit**

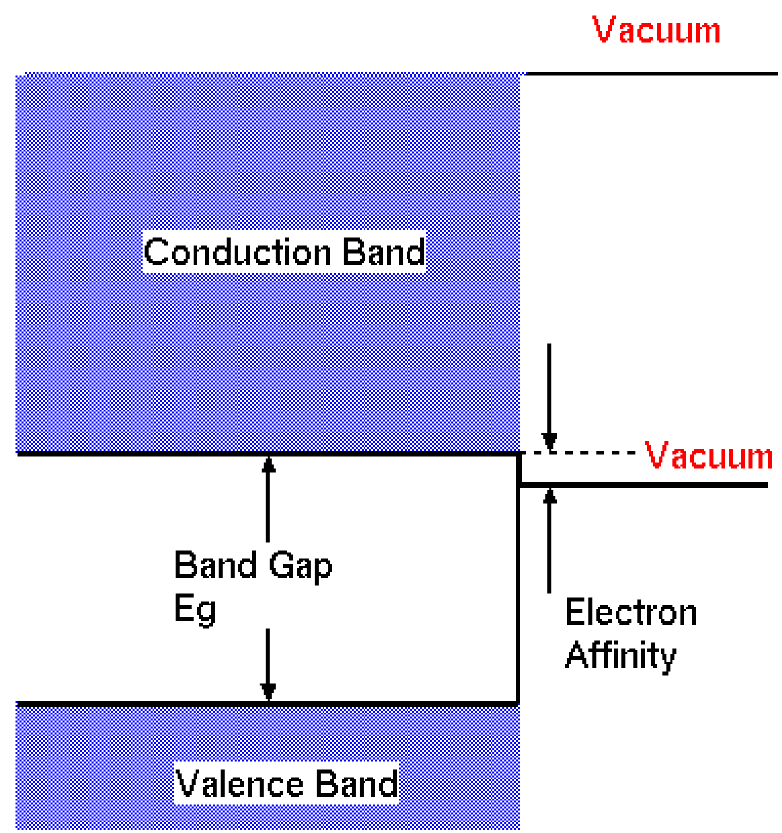
Polarized Electron (1)

- Polarized Electron generation: 3 step model
  1. Excitation
  2. Transportation
  3. Emission

Polarization is made by the first step as consequence of selective excitation from the valence band to conduction band.

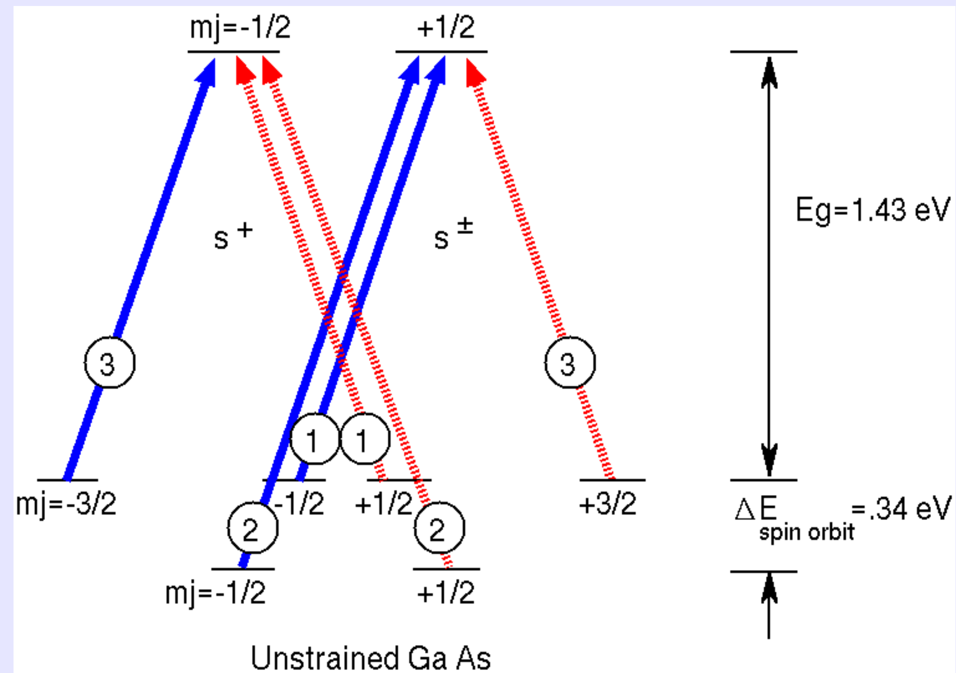
Excited electron can be transported because of the forbidden band, band gap.

Step 3 is realized artificial treatment (NEA surface).



Polarized Electron (2)

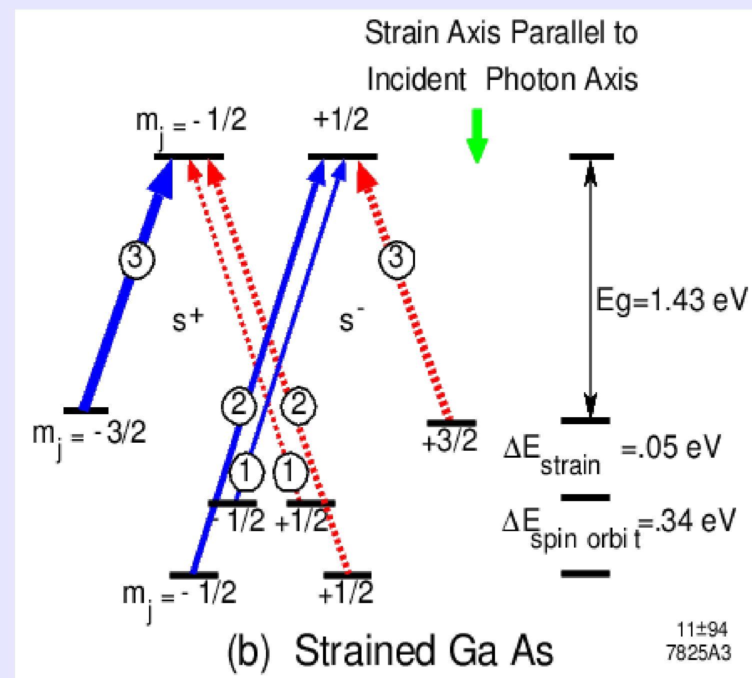
- Bulk GaAs (Γ point) has states : J=3/2 and 1/2.
- Transition probability by circularity polarized photons($s_z=\pm1$) is described by Clebsh – Gordon co-efficients ($3/2 \oplus 1$ and $1/2 \oplus 1$) .
- If the photon energy is adjusted to excite only J=3/2 states, electron polarization becomes 50% (75% s_z=-1,25% s_z=+1)



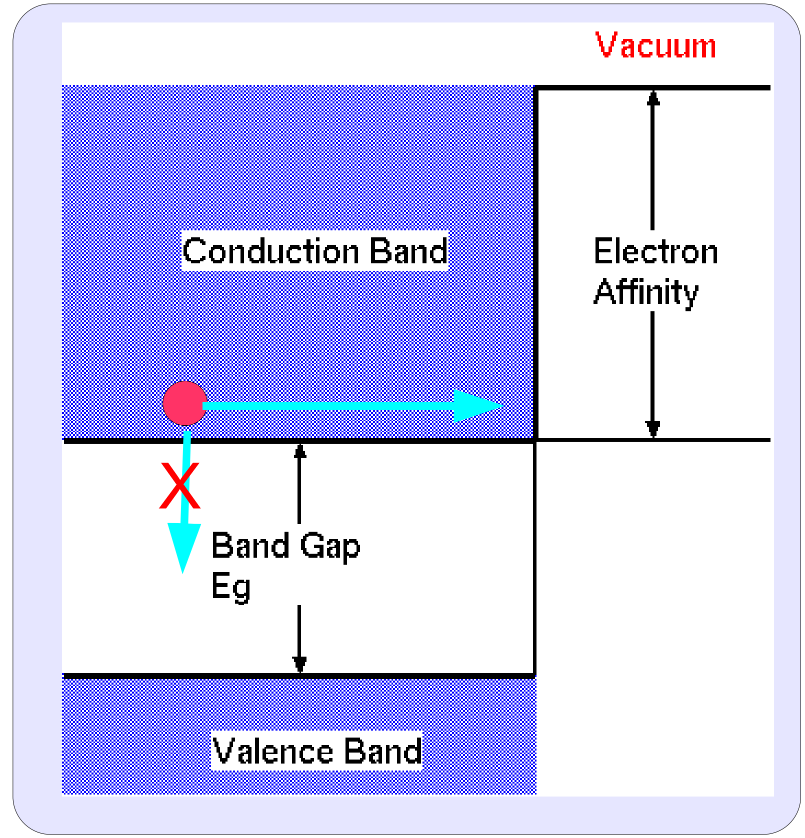
$$P=\frac{N_p-N_n}{N_p+N_n}$$

Polarized Electron (3)

- If the degenerated states are untied, one transition is enhanced and the polarization can be more than 50%.
- Constraint (lattice mismatch) or super-lattice (layer structure with different lattice constant) realize the band split.
- *As consequence, 90% polarization is realized.*

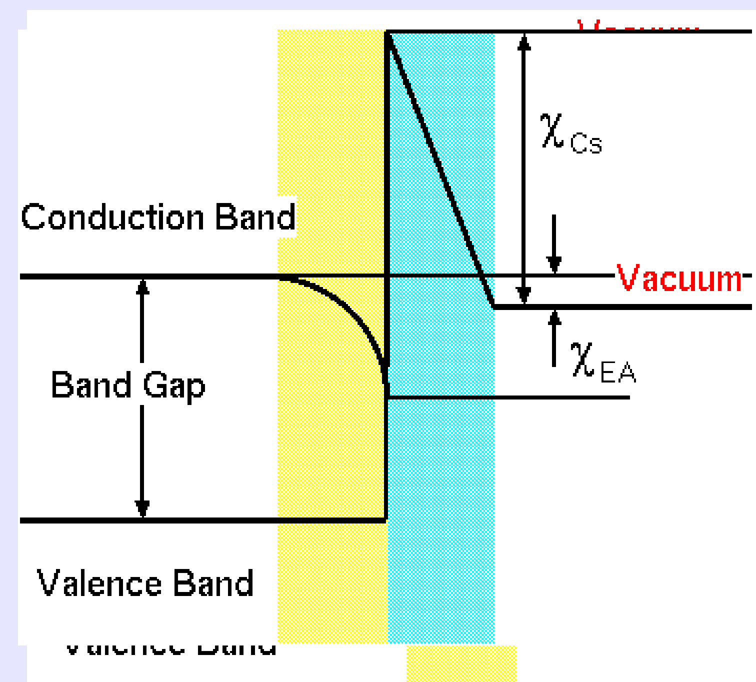


- The polarized electron is excited selectively; The electron is near of the bottom of the conduction band.
- Interaction to electrons in the valence band is compensated because any electrons can not be in the band gap: forbidden band.
- The polarized electron arrives to the surface.



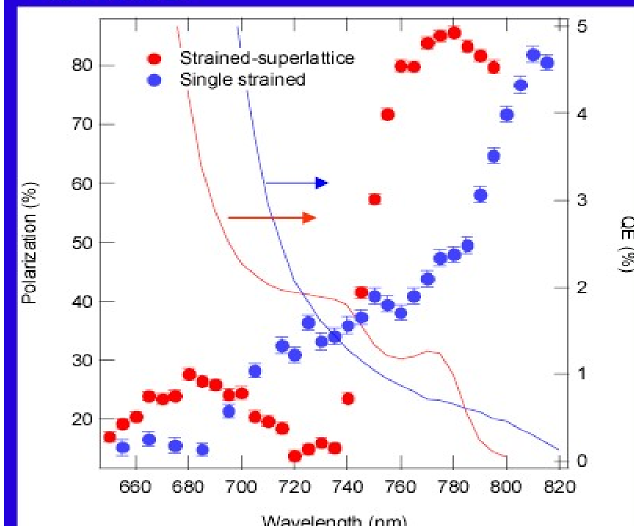
Polarized Electron (5)

- Nominal material has positive electron affinity; Electrons are confined in the well potential.
- The electron affinity can be negative (NEA surface) by two treatments:
  - Band bending: Zn doping makes hole states, which attract un-paired electrons, resulting potential bending.
  - Dipole layer by Cs and O_2 pulls down the vacuum level.
- Polarized electron in the conduction band can be extracted to the vacuum.

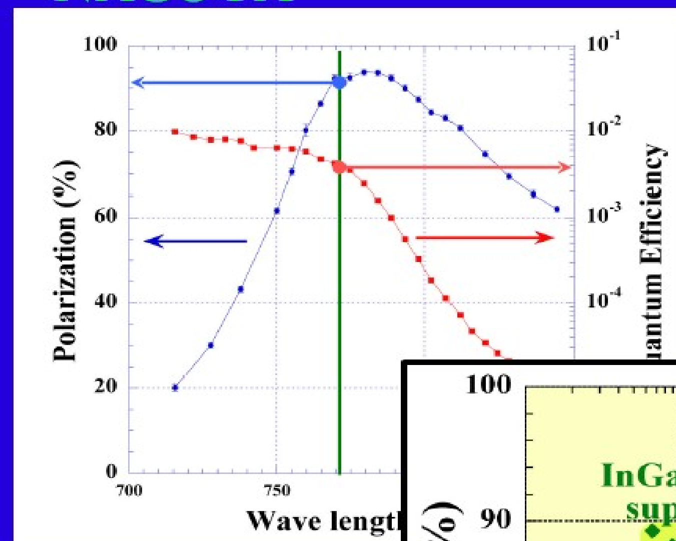


Performance of GaAs/GaAsP superlattice

SLAC

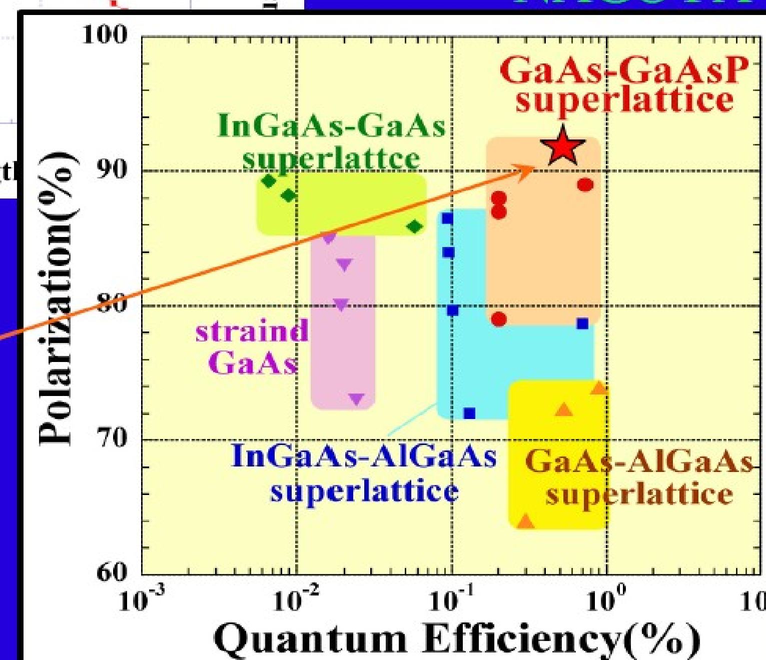


NAGOYA



By N. Yamamoto (Nagoya Univ.)

NAGOYA



GaAs-GaAsP superlattice shows the best performance !

@778nm

Polarization ~ 90%
Q.E. ~ 0.5%

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 is still conventional, but RF gun becomes recently more popular.
- Photo-cathode DC gun is used for special case like Linear Colliders, ERL, etc.

Thermionic Gun

- Emission from a thermionic cathode is purely continuous. Grid electrode control the extracted beam.
- The pulse length is limited down to ~1ns.
- Need bunchers to shorten the bunch length for RF acceleration.
- Any thermionic cathodes can not generate polarized electron.

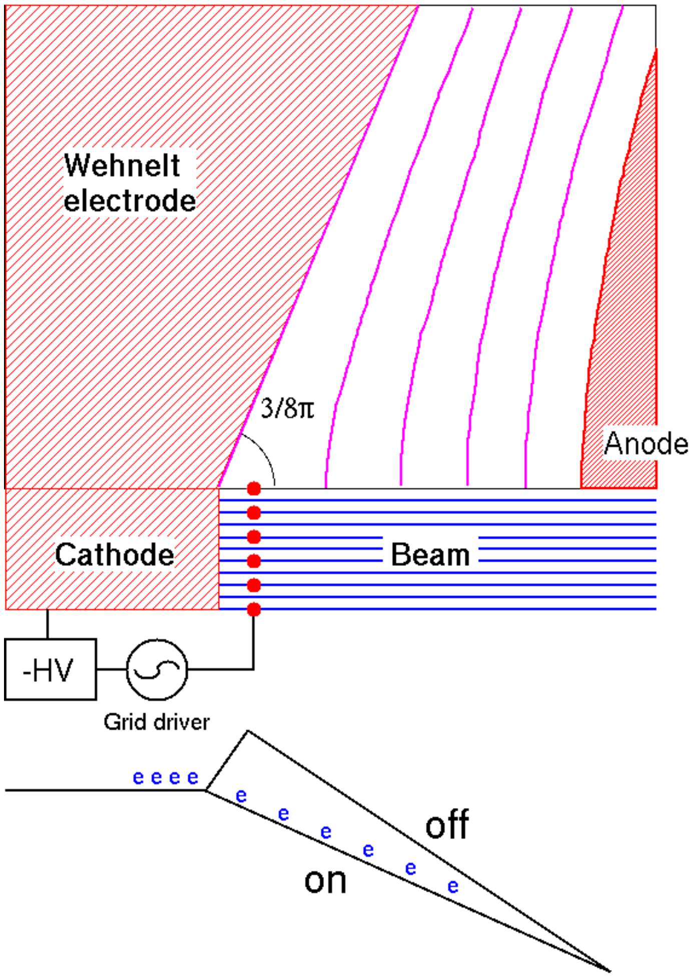
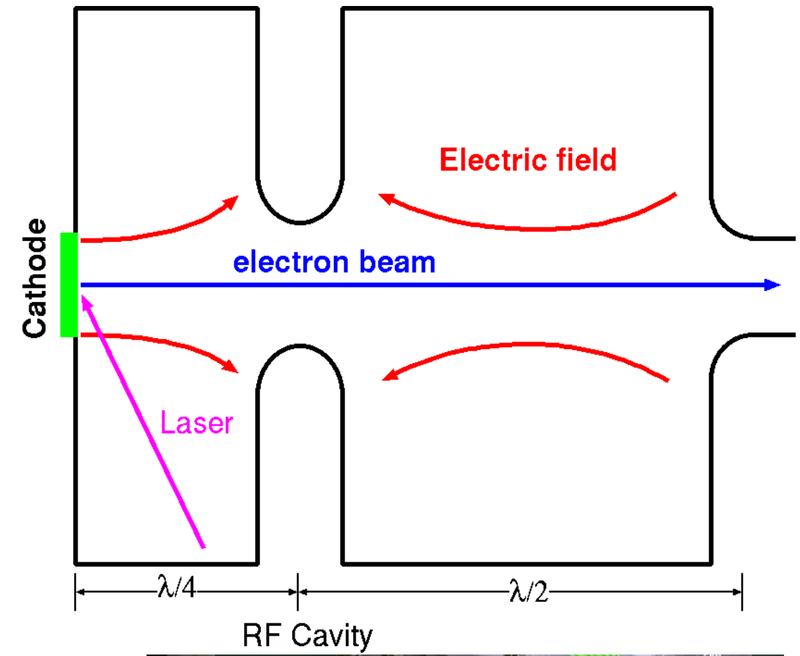
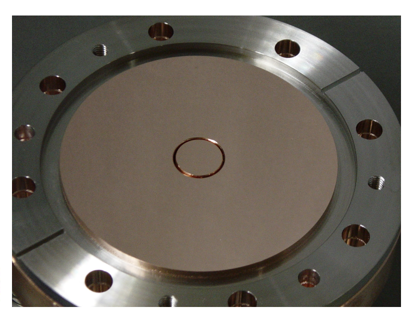


Photo-Cathode RF Gun

- Electron Emission
- Polarized Electron
- **Electron Gun**
- ILC Electron Source
- Laser
- Summary

- Electron beam is generated by photo-electron with laser.
- Typical field: several 10MV/m ~ 150 MV/m, which is impossible in DC gun.
- The beam is accelerated up to several MeVs immediately. The beam bunch length is short; No bunching.
- GaAs cathode has never been used in any RF guns.





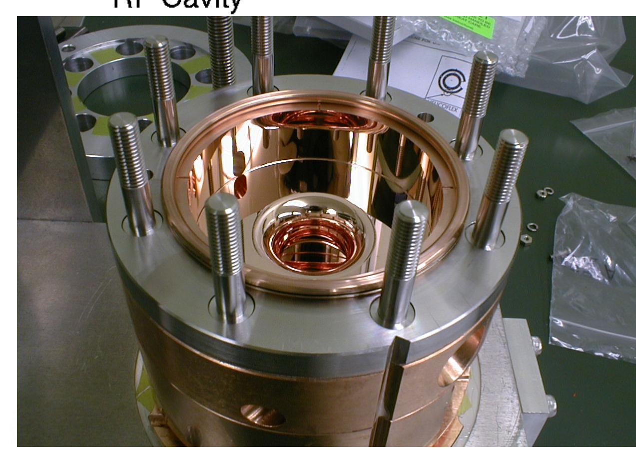
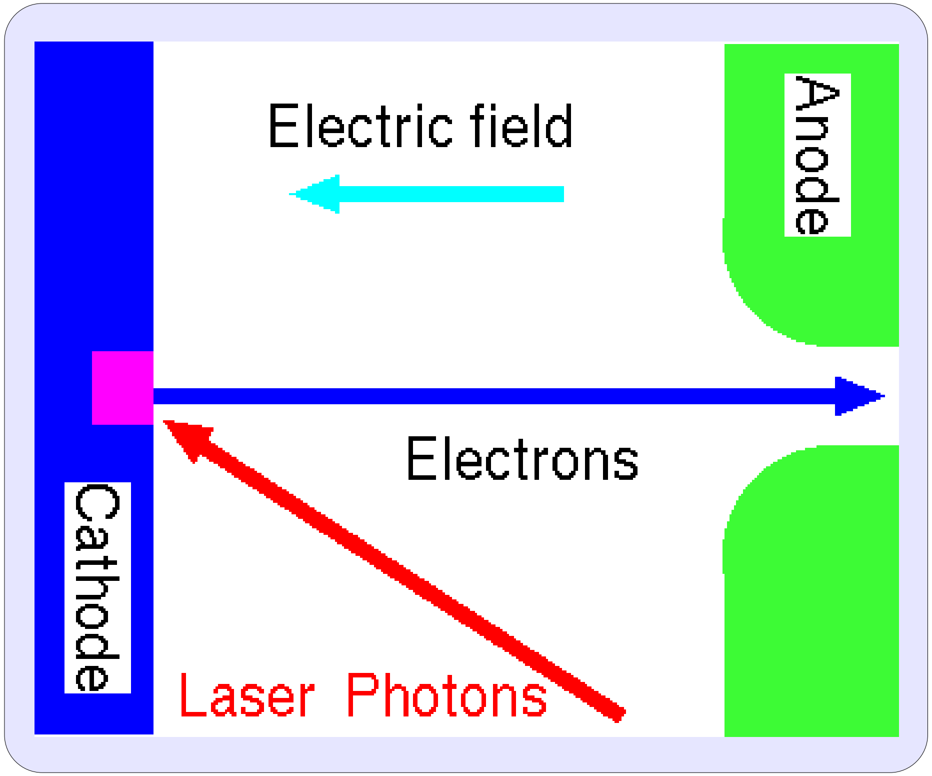


Photo-Cathode DC Gun

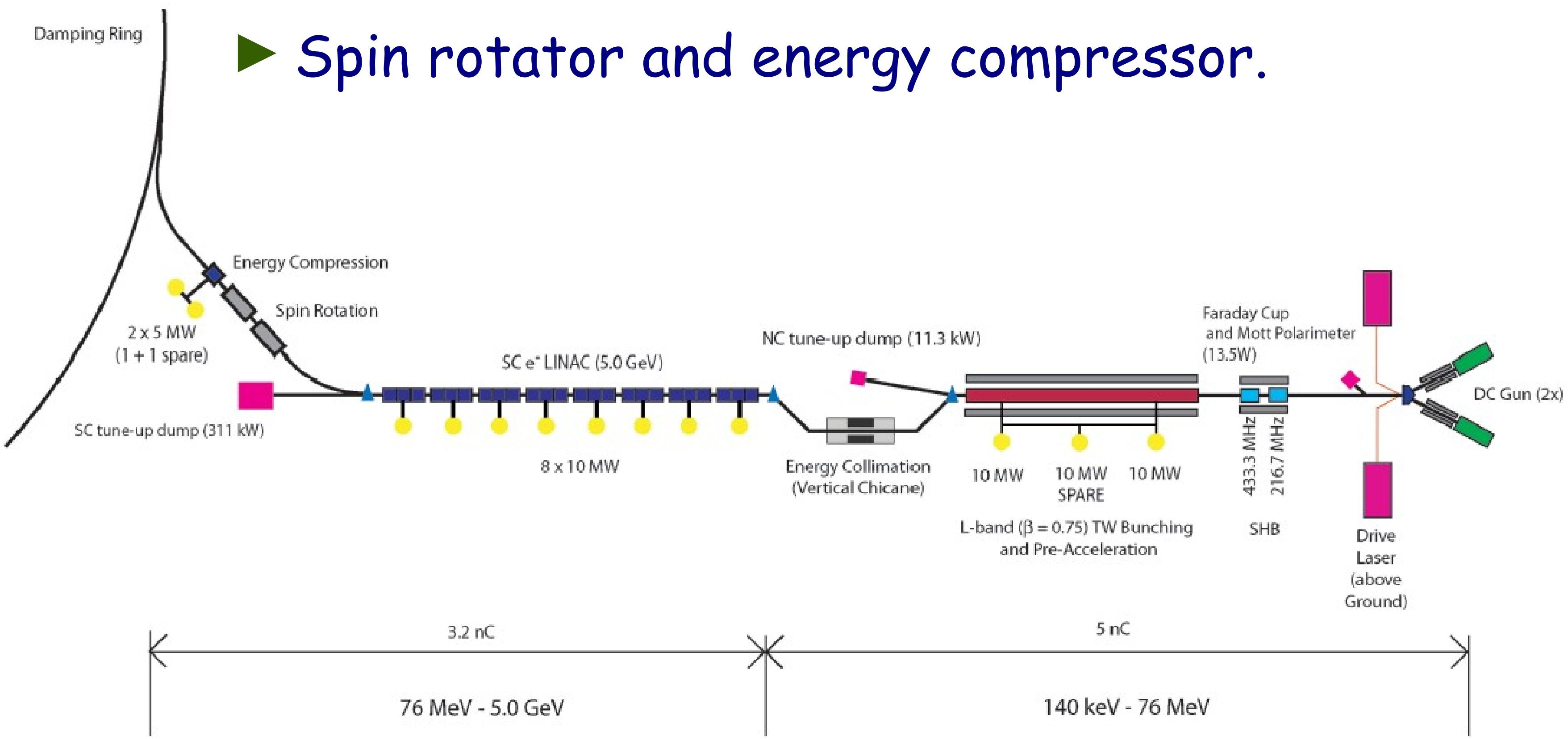
- Electron Emission
- Polarized Electron
- **Electron Gun**
- ILC Electron Source
- Laser
- Summary

- Electron beam is generated by Photo-emission with laser.
- Beam extraction by a static electric field (100 - 300 kV).
- GaAs for polarized electron beam, can be used. It is for ILC.



ILC Electron Source

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

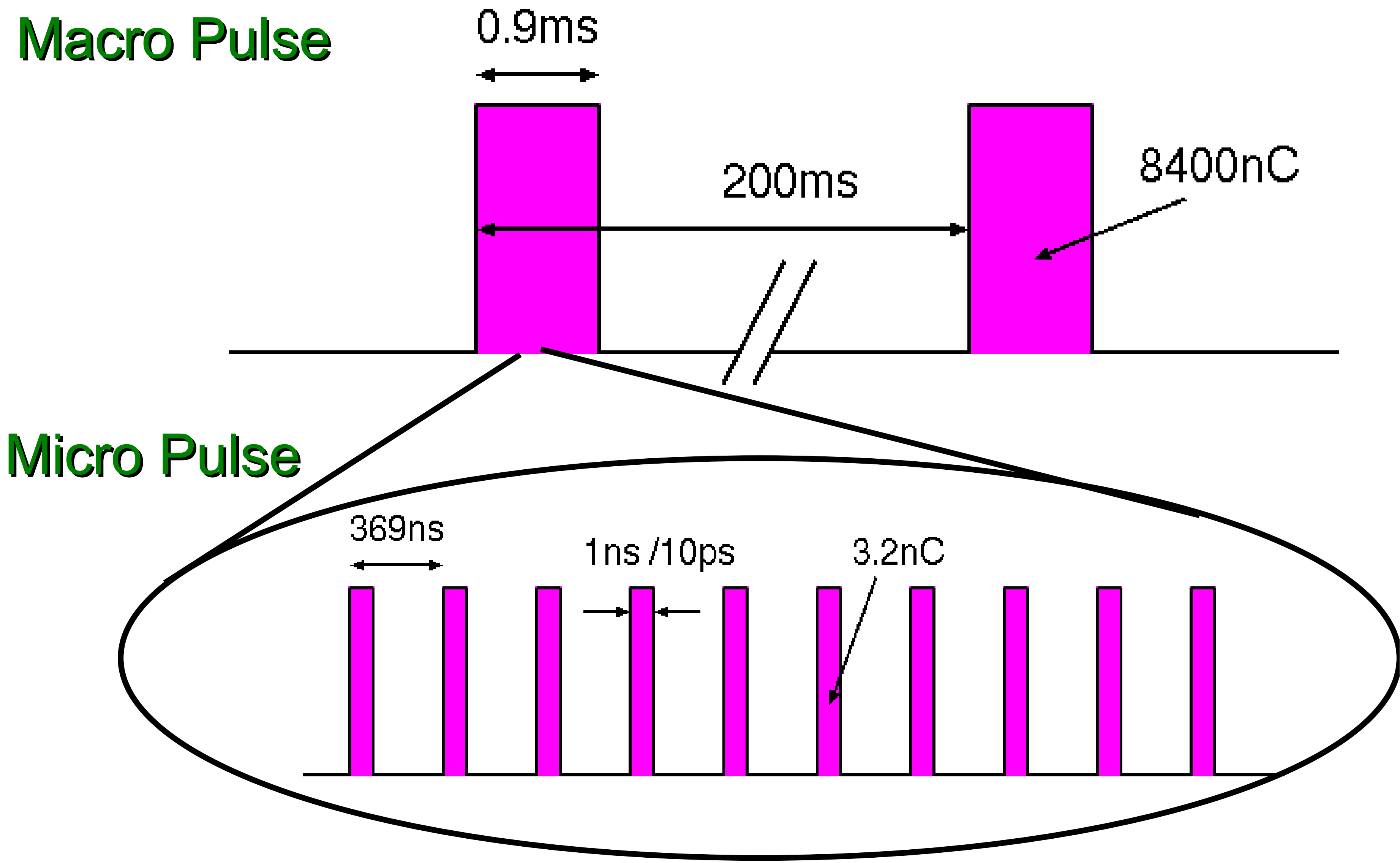


Requirements

- Electron Emission
- Polarized Electron
- Electron Gun
- **ILC Electron Source**
- Laser
- Summary

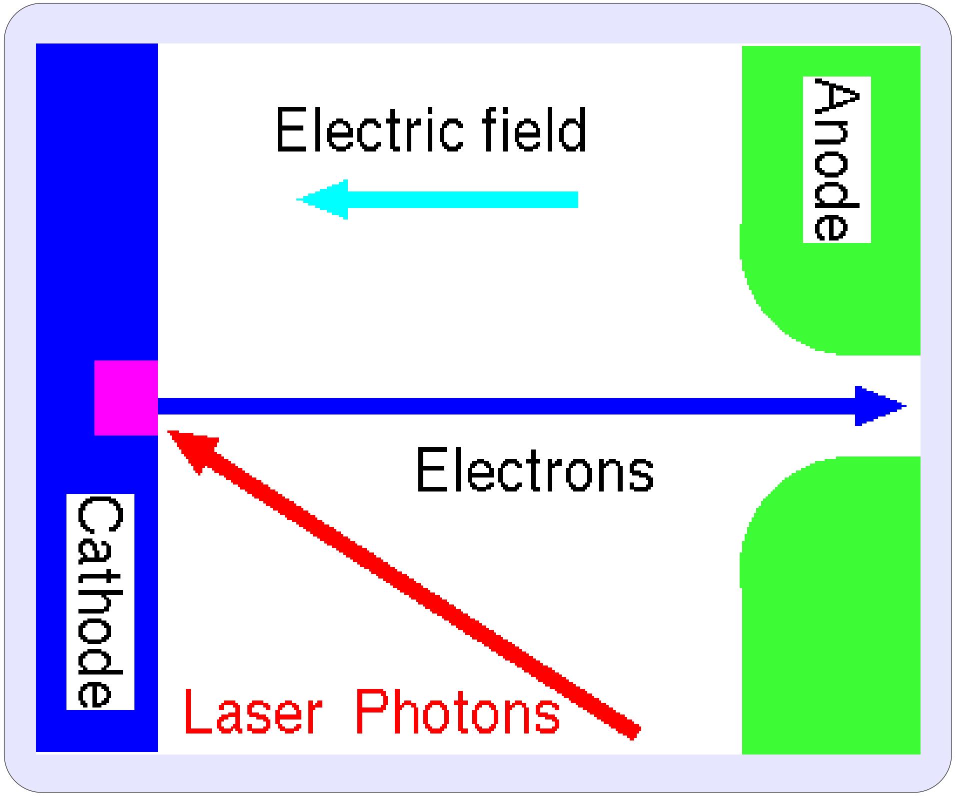
Parameters	
Pulse length	0.9ms
Pulse reputation	5Hz
# of micro bunches in a pulse	2625 (5120)
Bunch separation	369(189)ns
Bunch charge	3.2(1.6)nC
Micro bunch length at source	1ns
Peak current	3.2(1.6)A
Electron Polarization	80%

Pulse structure



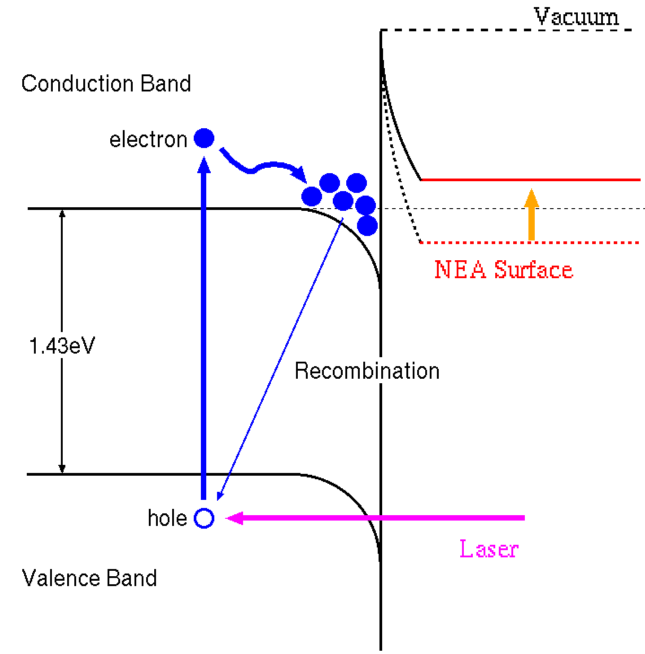
Basic Concept

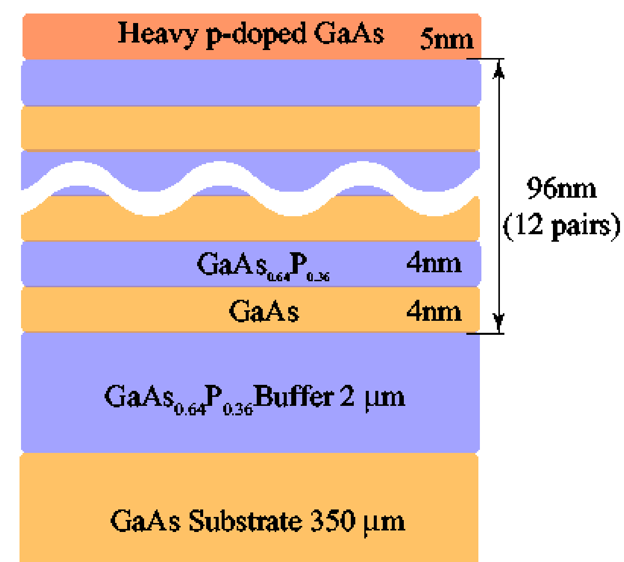
- Circularly polarized photons are injected to NEA GaAS cathode; polarized electrons are generated.
- Beam extraction by a static electric field, 120kV.
- The extraction current is limited up to 3.1A by space charge, 1.1ns for 3.2nC.



Super-lattice Cathode

- GaAs/GaAsP super lattice cathode for high polarization (90%) and high QE (0.5%).
- Surface charge limit: electrons captured at near of the band bending, that raises the effective vacuum states and limit the emission current.
- Heavy P (Zn) -doped GaAs surface layer accelerates the recombination process of the captured electrons to holes; emission is recovered up to ~5A/cm^2.
- Emission is now limited by space charge.



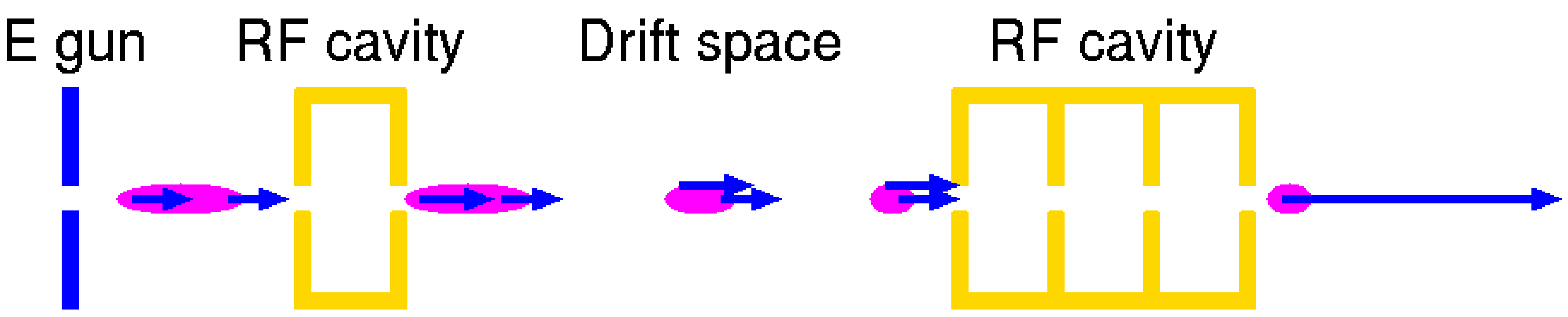


Bunching(1)

- 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 : 216.7 MHz + 433 Mhz。
  - Buncher : 1.3 G Hz NC tube.

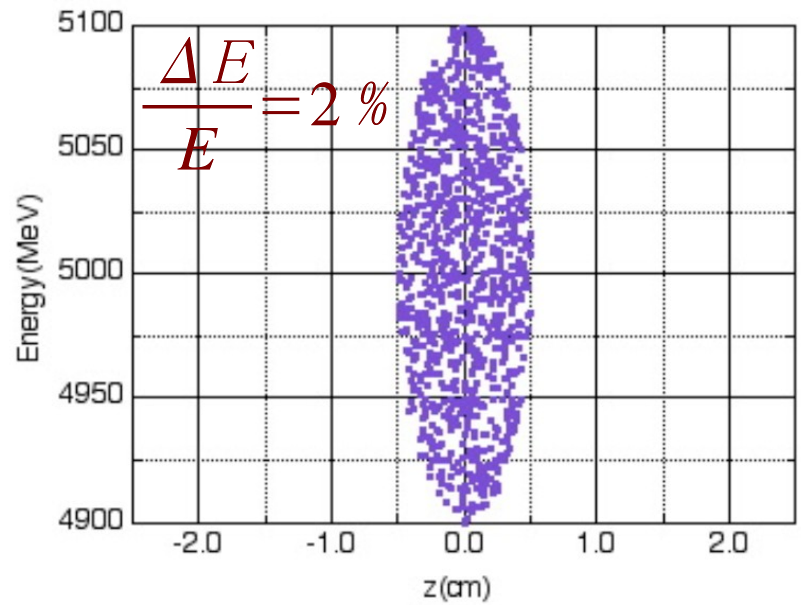
Bunching (2)

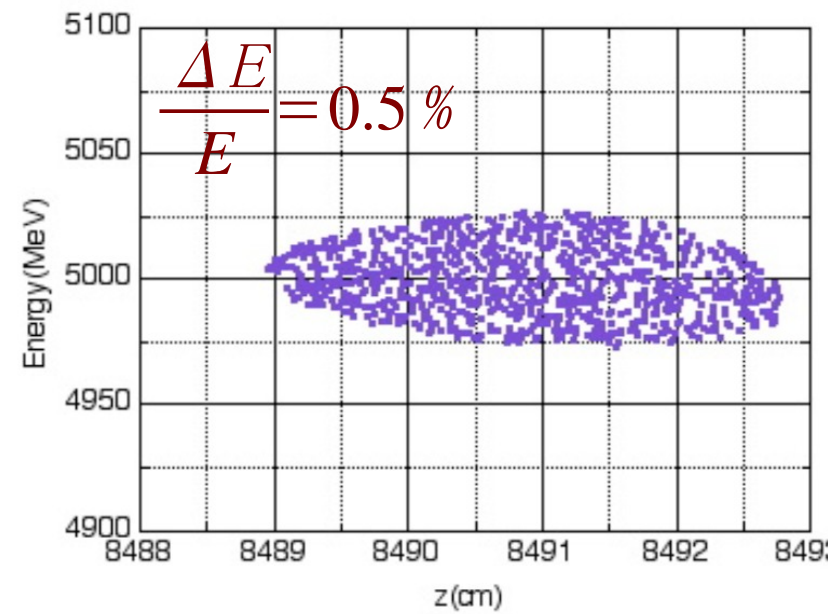
- Bunch length is 1ns at the exit of Electron gun.
- RF cavity make velocity modulation within the bunch.
  - Bunch head is decelerated -> slower.
  - Bunch tail is accelerated -> faster.
- By drifting a correct length, the bunch length becomes shorter.
- Acceleration by high gradient RF cavity for the whole bunch, compensates the velocity modulation and the beam becomes rigid.



Energy Compression

- According to a simulation, the energy spread is 2%, which is larger than DR acceptance, 1%.
- Energy compressor by de/acceleration at the dispersive area is added before the DR.
- After the energy compression, the energy spread is 0.5%, which is in tolerance.





HV Operation (1)

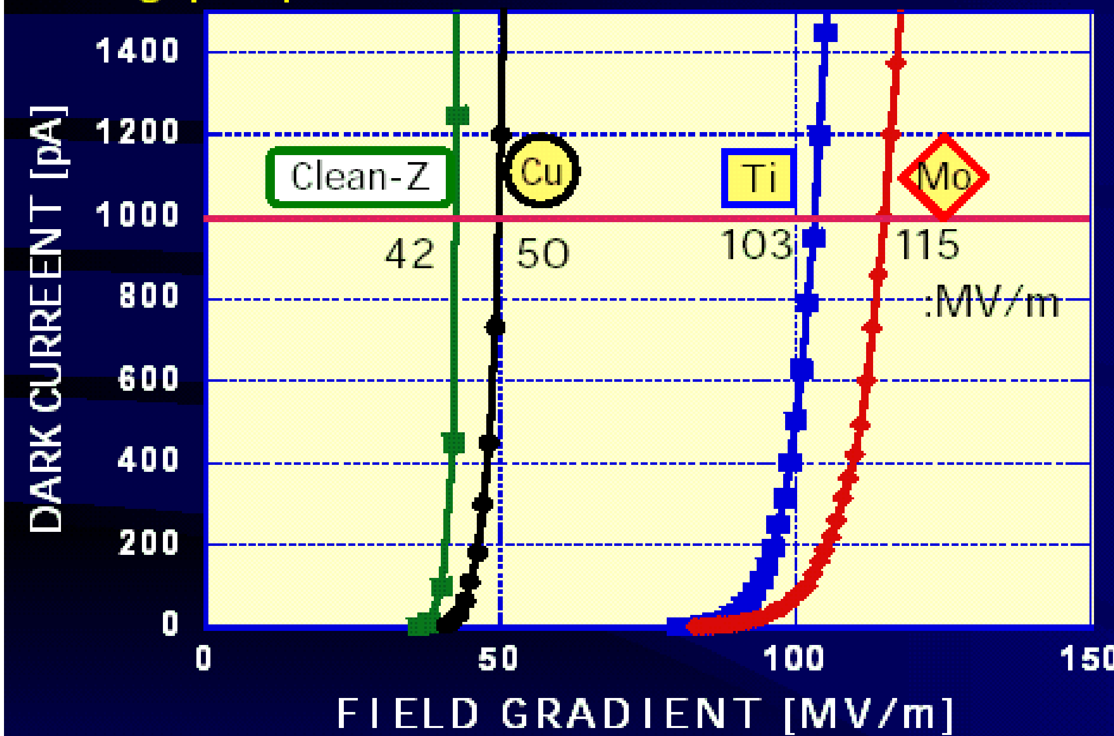
- Instead of the energy compressor, shorter bunch length in accelerator make the energy spread after acceleration smaller.
- Since the bunch length at the gun exit is determined by the space charge limit, higher voltage operation makes a higher peak current and bunch length can be shorter.
- Short bunch length has merits
  - Simpler bunching section
  - Energy spread after acceleration is smaller and possibly omitting the energy compressor section.
- 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

Nagoya & KEK

gap separation=0.5mm   Vac : ~1e-9 Pa



Materials & Finishing

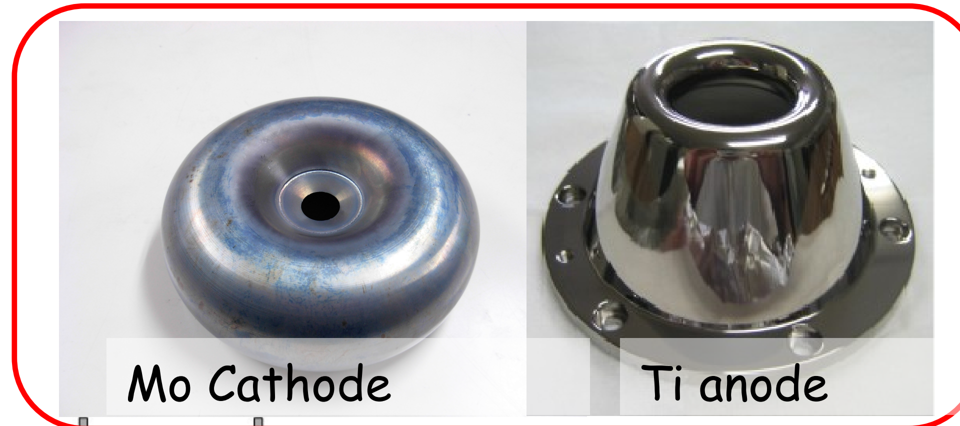
- **Clean-Z** (Re-Melted SUS316L)
  Electro-buff polishing
- **Copper (OFHC)**
  precision diamond machining
  (no polishing)
- **Pure Ti** (JIS grade-2)
  Only buff polishing
- **Pure Mo** (poly-crystal 5N)
  Only diamond buff polishing

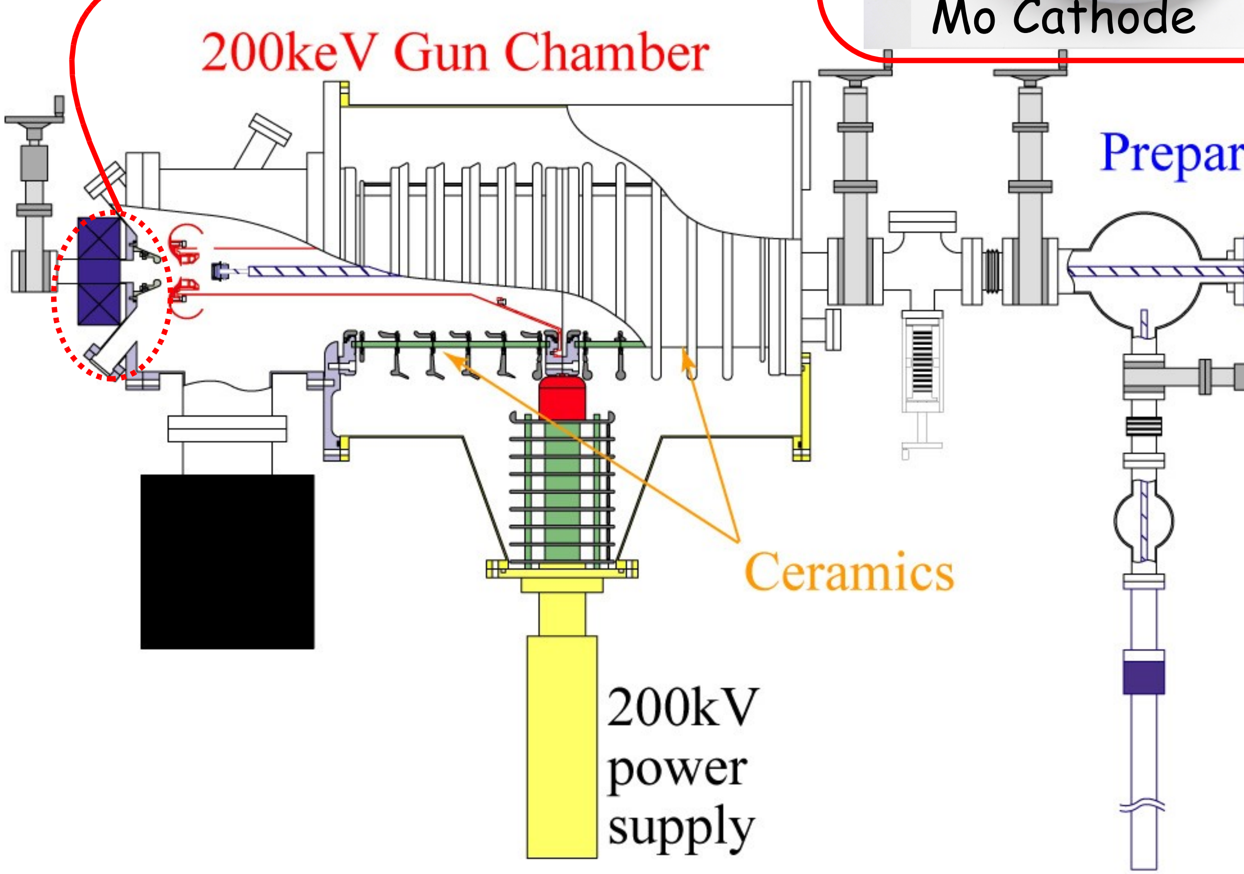
A point to note ...

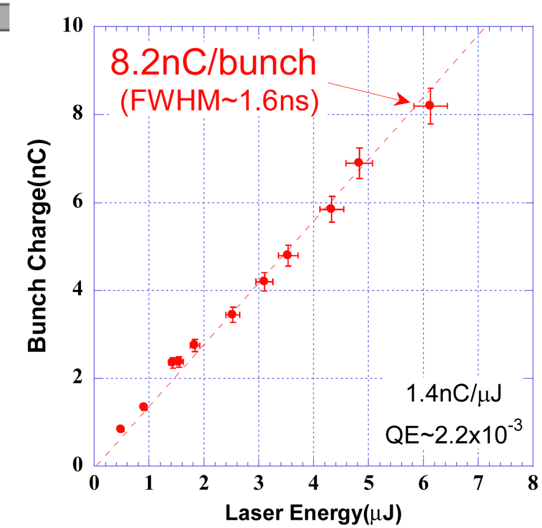
Only 7mm^2 area exposed maximum field gradient.

ILCWS2005, Snowmass

High field DC Polarized Electron Gun@Nagoya







Laser for Photo-Cathode

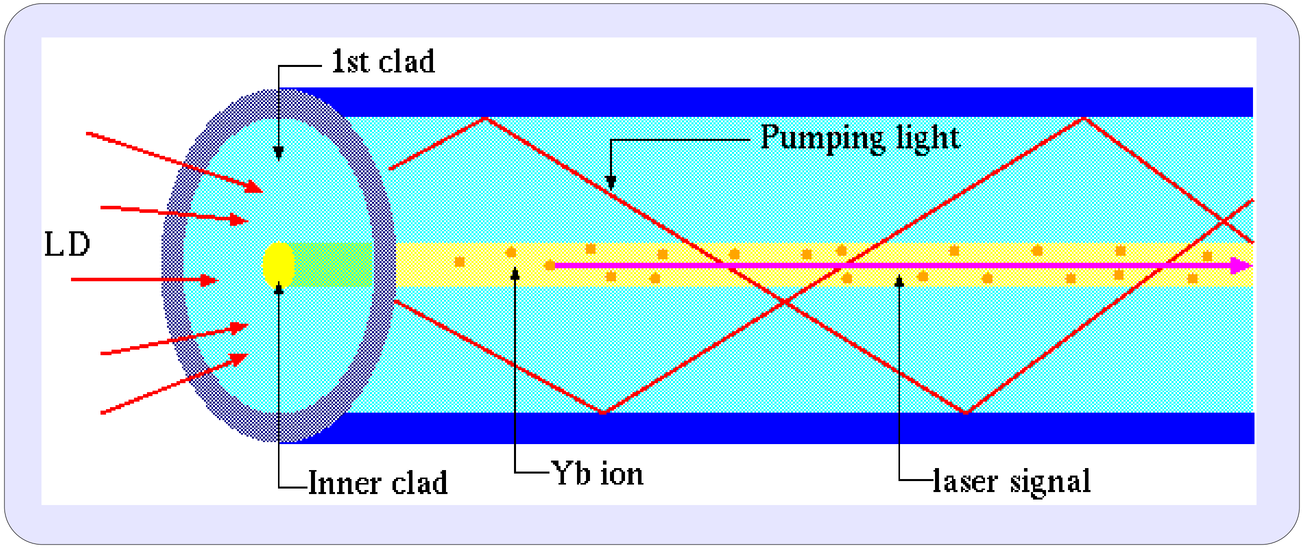
- Laser is one of the most important element of the photo-cathode gun, especially, the ILC electron gun.
- Beam performance is mostly determined by the laser.
  - Temporal structure : 1ns bunch length, 3MHz repetition, 0.9 ms macro pulse.
  - Beam emittance : 10 μrad.
  - Polarization :circular polarization and wave length optimization around 800nm.
- A laser system, which meets fully ILC requirements, is not available commercially.

$Ti:Al_2O_3$

- Spontaneous mode-locking by Carr effect, bunch length > 17fs 。
- Wide band width for lasing (700-1100nm), wave length tune-ability by filtering.
- Require 488nm light for pumping; SH of Nd:YAG/YLF is employed limiting the efficiency from the pumping power to the laser light.
- Luminescence time is 3.2 μs, which is not suitable to form a long macro pulse.

Yb fiber laser

- Double clad-core optical fiber.
- Light from InGaAs LD (940nm) is introduce to 1st clad for pumping.
- Signal propagates in the inner core, where Yb ion is doped, and is amplified by stimulated emission.
- High efficiency, low-loss, high-power, very stable.

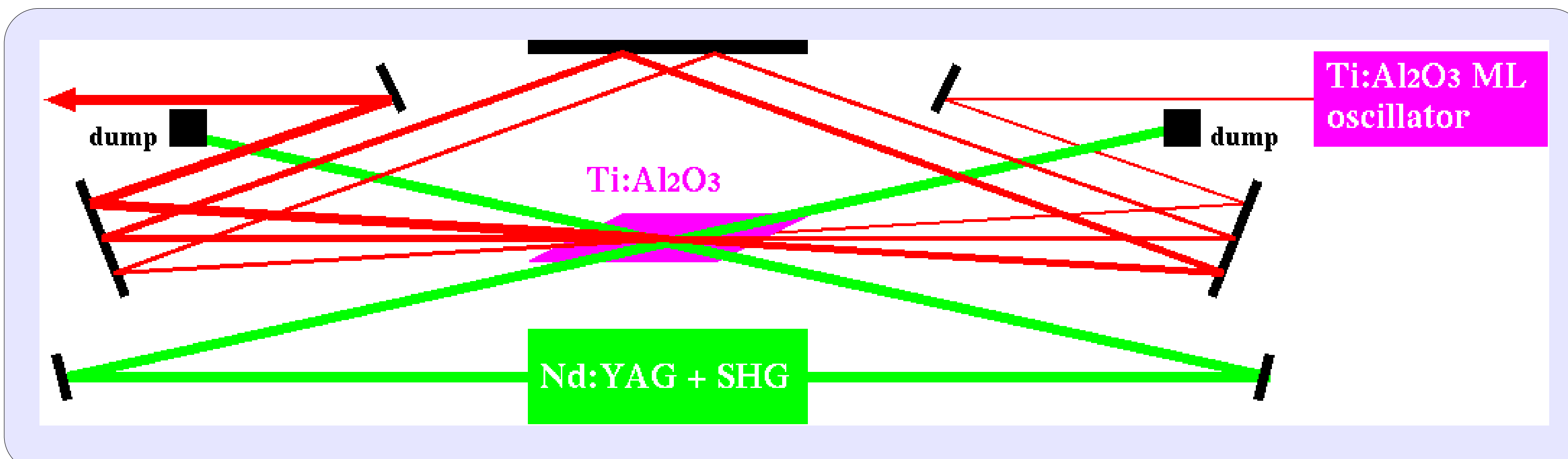


Laser Medium Summary

Laser Crystal	Ti:Al_2O_3	Nd:YAG	Yb:YAG	Yb fbr
Wave length (nm)	700-1100	1064	1030	1050
Wave length tune-ability	Yes	No	No	No
Luminescence time	3 µs	550 µs	1000	1000
Pump light (nm)	488	-800	940	940
Stability	Marginal	Marginal	Good	Excellent
Note	Wavelength is tunable, unstable	CW operation	High stability by LD pumping	Excellent stability by LD pumping, High power
Feasibility as ILC driver	Feasible, but macro pulse generation is an issue.	Pumping source for Ti:S	Feasible if the wave length can be tunable.	Feasible if the wave length can be tunable.

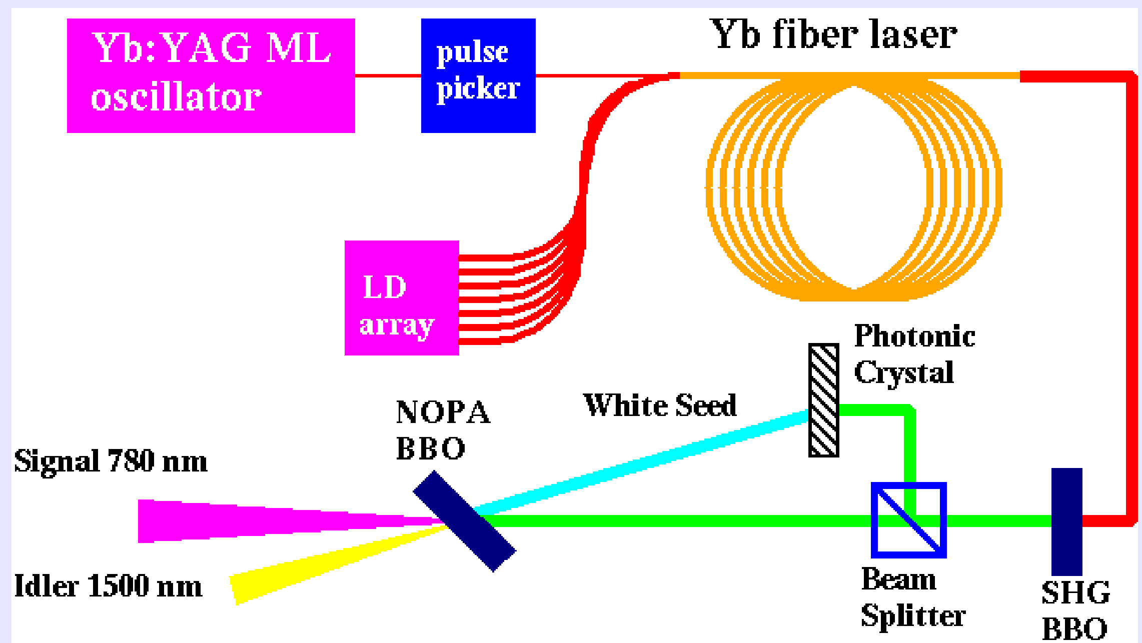
Laser : ILC Baseline Design (SLAC)

- Ti:Al_2O_3 mode lock + 3MHz pulse picker by Pockels cell makes a pulse train.
- Macro-pulse amplification by Ti:Al_2O_3 crystal pumped by SH of Nd:YAG.
- Wave length is tunable. It is an extension of the existing technology, but the stability could not be adequate.



Yb:YAG fiber laser + OPA

- Yb:YAG mode lock + PP + Yb: fiber laser amp. + NOPA。
- LD pumped-full solid super stable laser.
- Yb fiber laser allows high power up to several kW and high stability.
- Wave length tunability by NOPA.

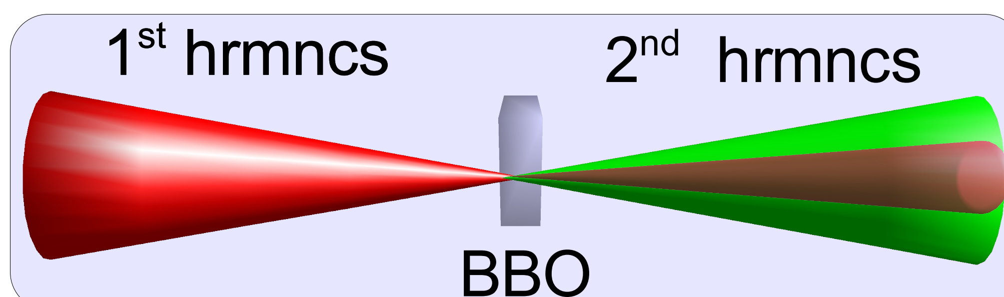


Parametric Amplification

- Wave-length tunability is implemented by Optical Parametric effects.
- Harmonic Generation : ω⇒2ω, 3ω, ...
  - Non-linear polarization of atom is induced by focusing laser light in the non-linear crystal (KPD,BBO,etc).
  - If the phase matching condition is satisfied, higher harmonics is emitted from the polarized atoms.
  - Generally, diffraction index is increased by frequency (normal dispersion); the matching condition is satisfied only by material, which has double refraction.

Phase matching

$$n_1\omega_1 + n_1\omega_1 = n_2\omega_2$$



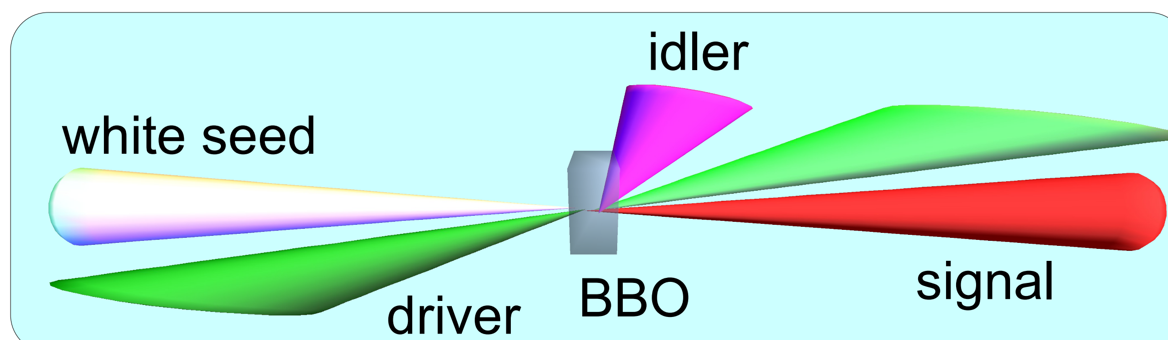
NOPA*

***Non-collinear Parametric Amplification**

- Parametric amplification with non-collinear condition make a wave length tune-ability by changing the angle.
  - For example, 515nm (Driver) -> 800nm(signal) + 1500nm (Idler).
- It extends our selection range for laser system.
  - Yb:YAG + Yb fiber for ILC/ERL driver.

Phase Matching

$$n_1\omega_1+n_2\omega_2=n_3\omega_3$$



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.
- Laser is an important device, which determine performance of photo-cathode gun.
- ILC electron source is DC bias gun with NEA GaAs.