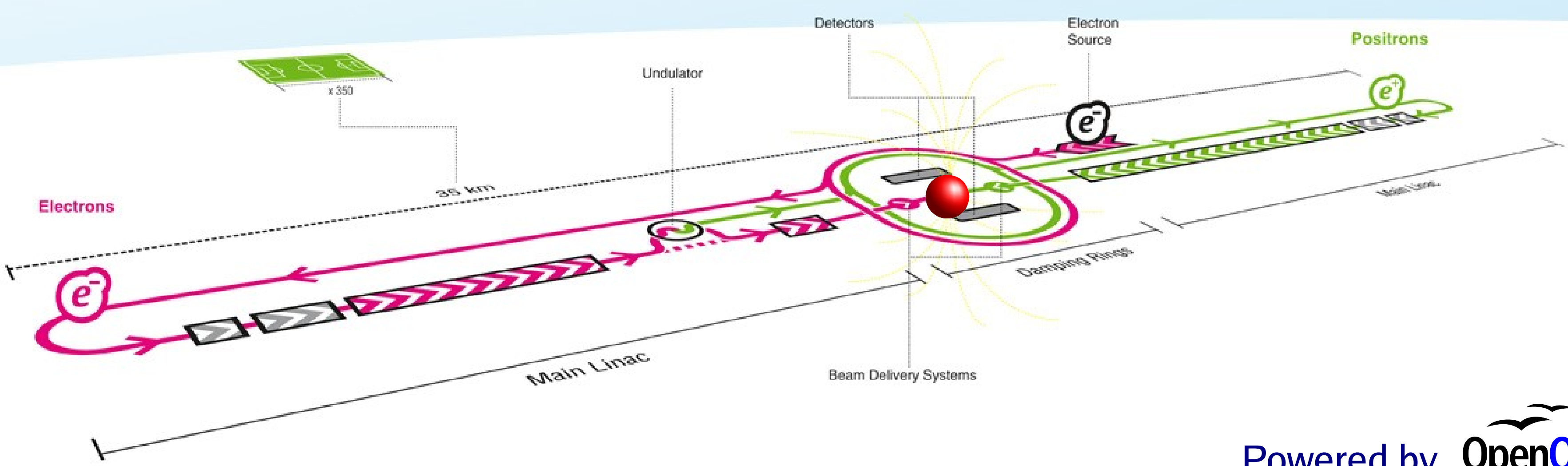
Electron source for Linear Colliders

KURIKI Masao (Hiroshima/KEK)



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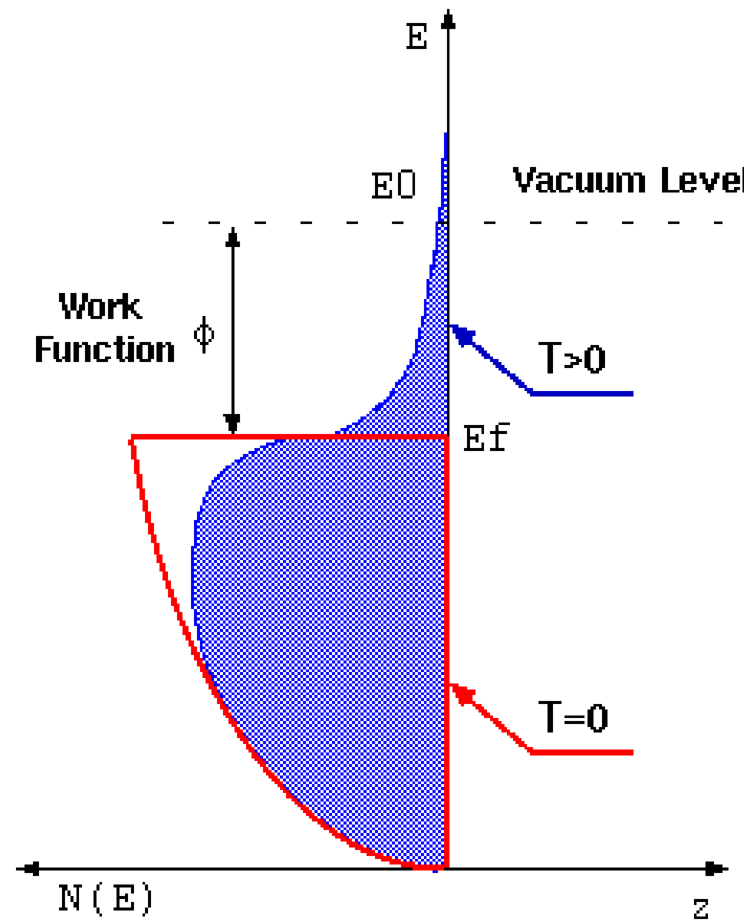
- Summary

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.

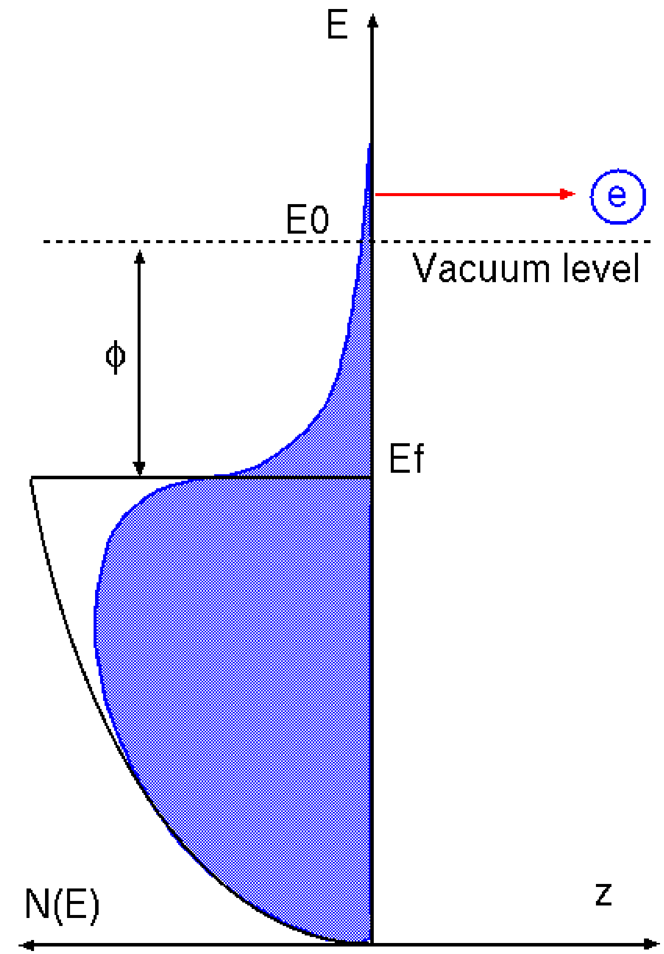
Fermi-Dirac Distribution

- Electrons in a metal are 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), ectron escapes out to the outside.
- The gap between the vacuum level and the Fermi energy is Work function, ϕ. The electron energy has to be more than the vacuum level.



Richardson-Dushman Equation

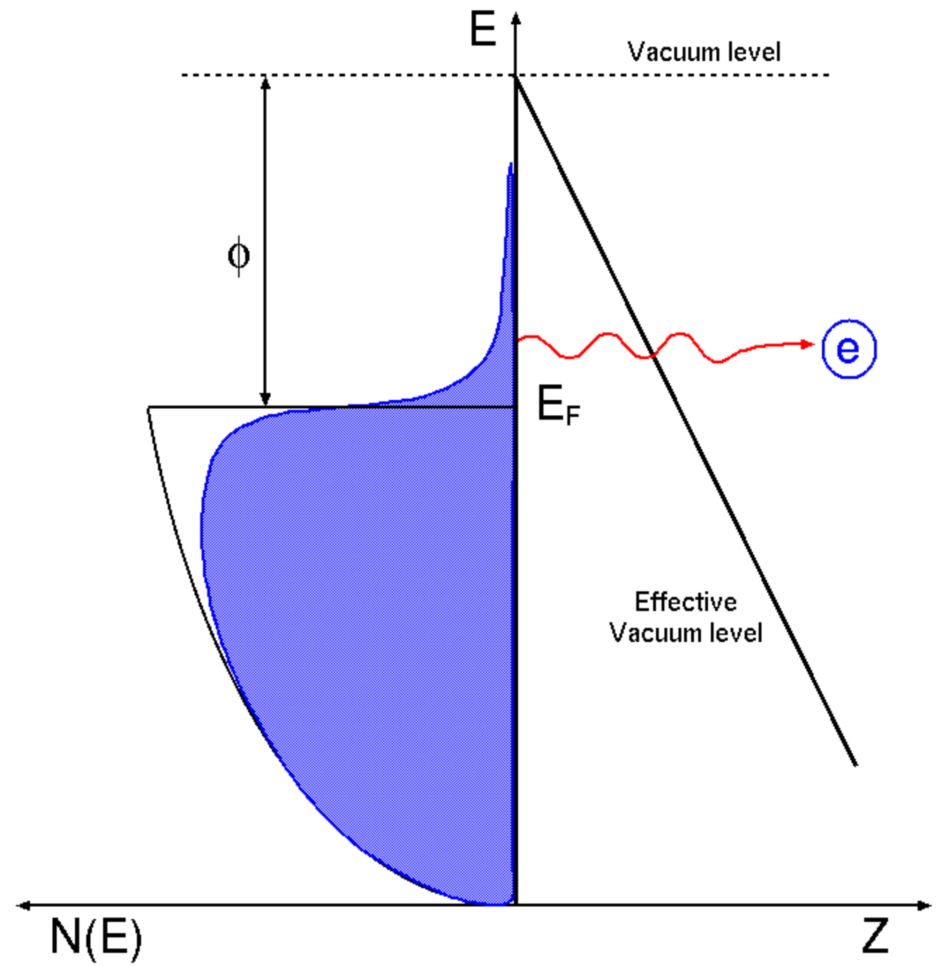
$$J = AT^2 e^{\frac{-\phi}{kT}}$$

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

- *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 the larger surface field, the potential barrier to the outside becomes 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

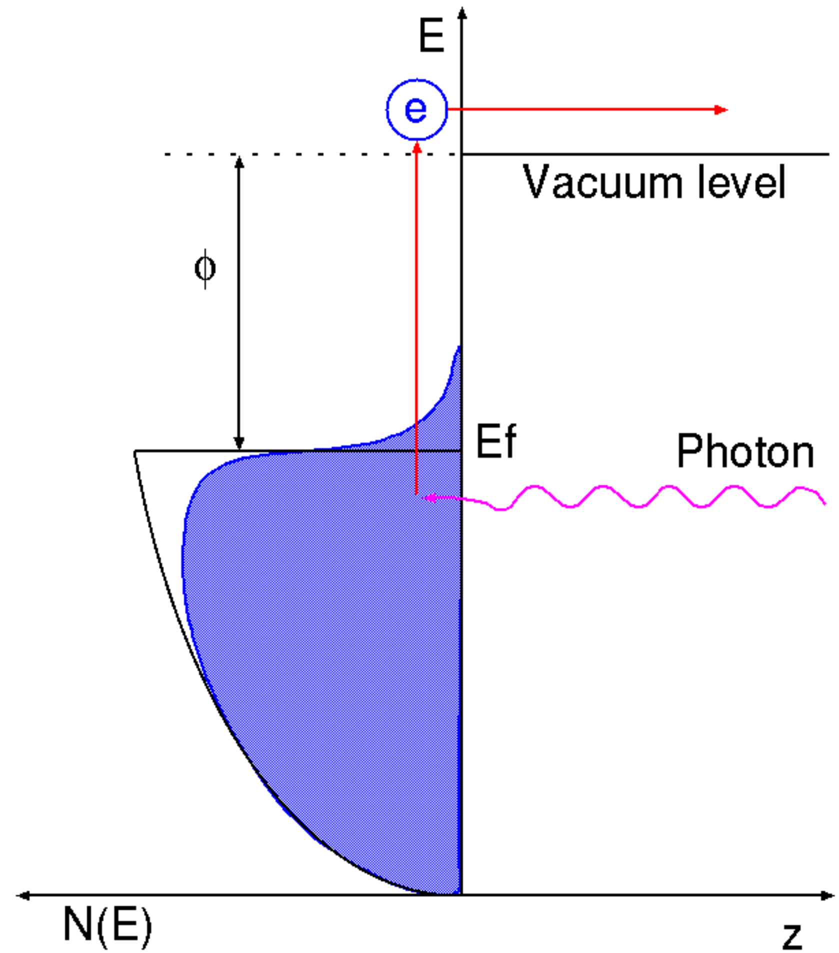
- The emission current is expressed by Fowler-Nordheim formula with *F*, surface field;

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

- 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

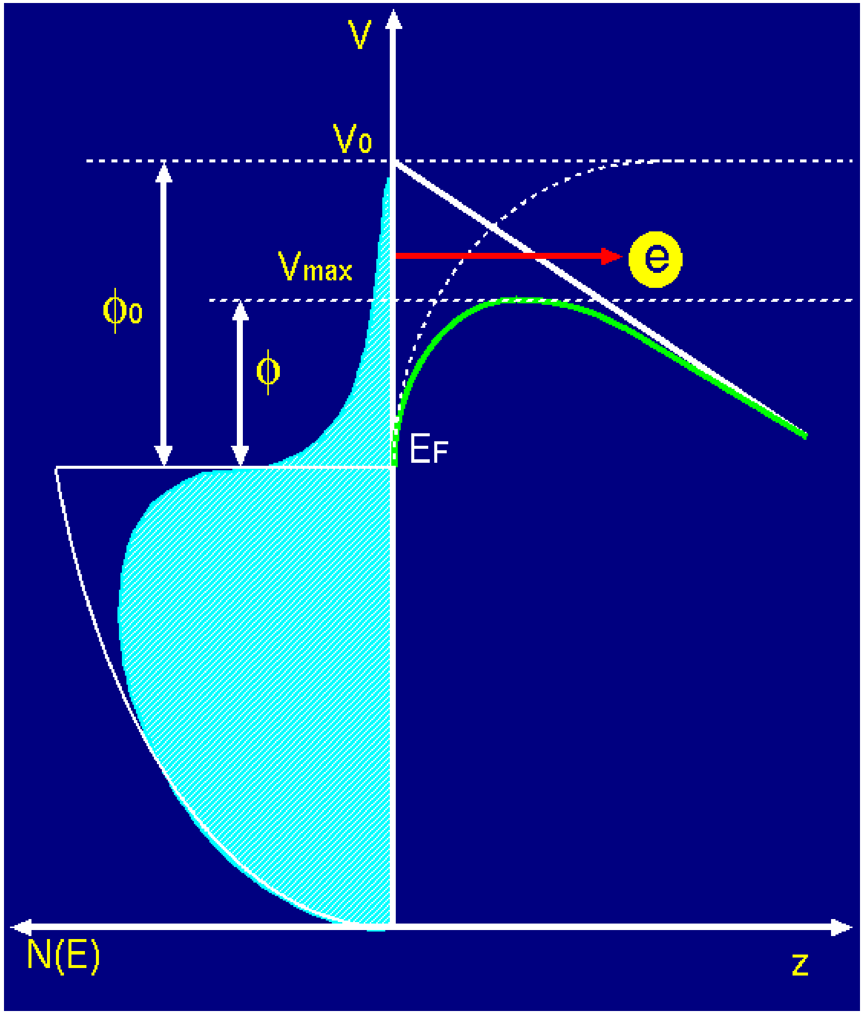
$$V(z)=V_0-\frac{e^2}{16\pi\epsilon z}-eEz$$

- Crest of the potential curve is

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

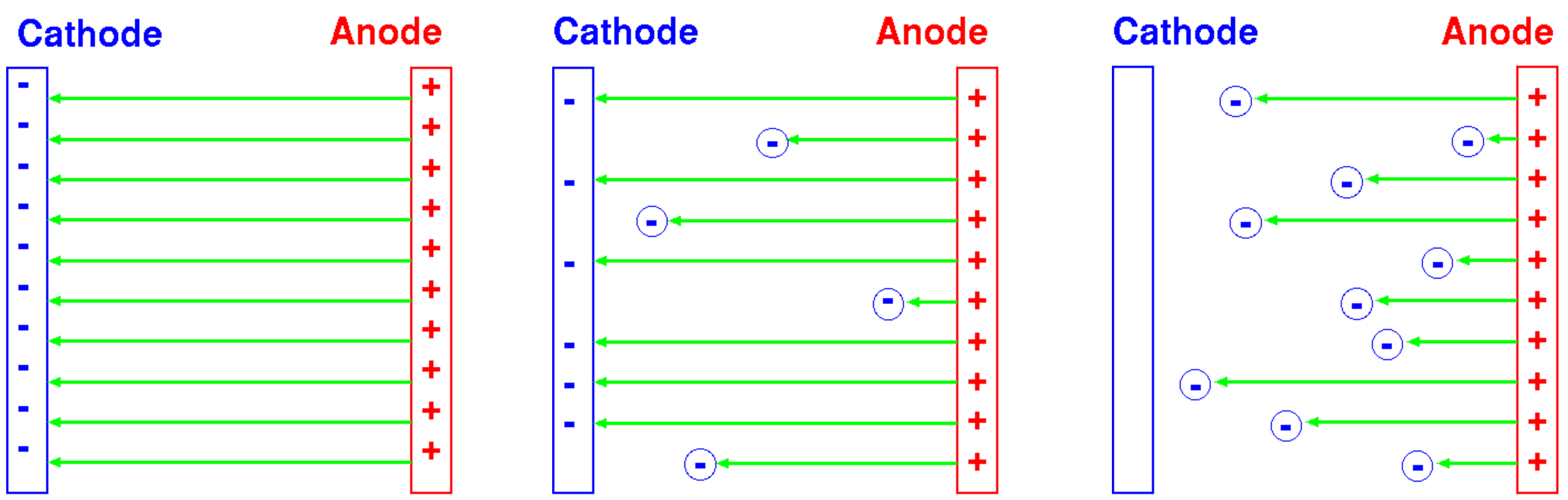
- The effective work function is

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



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; the space charge limit.



Child-Langmuir Law

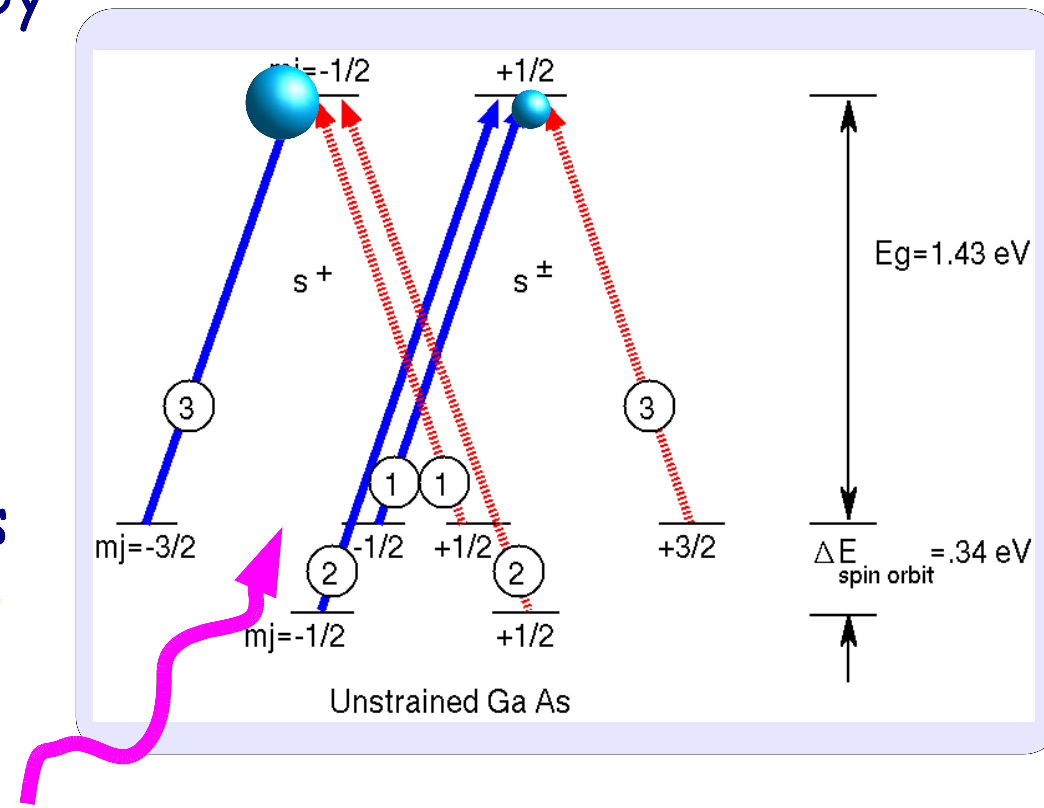
- In the space charge limit, the dynamics of the electron cluster decides the electron current, rather than the emission from the cathode.
- In diode geometry - two electrodes and one dimension – the current is;

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

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

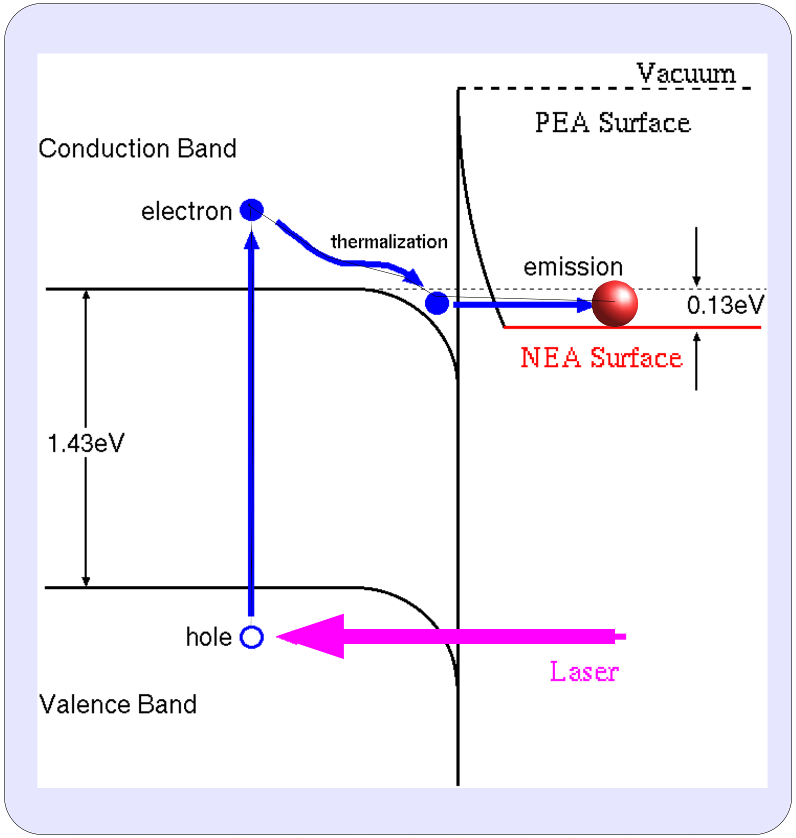
Polarized Electron (1)

- GaAs hole states : J=3/2 and 1/2.
- Transition probability by circularity polarized photons($s_z=\pm1$) is described by Clebsh - Gordon co-efficients ($3/2\otimes1$ and $1/2\otimes1$) .
- If the photon energy is adjusted to excite only J=3/2 states, electron polarization becomes 50% (75% $s_z=-1$,25% $s_z=+1$)



Polarized Electron (2)

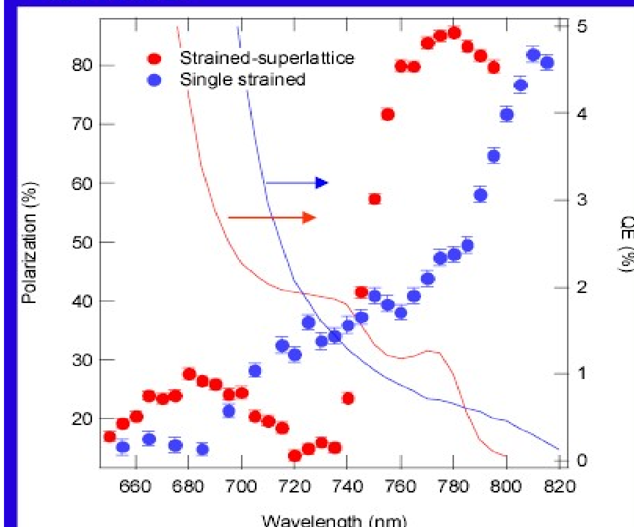
- If the degenerated states are untied, the transition from states of |J=3/2, m_j=±3/2> is enhanced and the polarization can be more than 50%.
- Electrons excited with the photons adjusted to the band gap energy are in the lowest state of the conduction band. The vacuum state is higher (PEA, Positive Electron Affinity) and electrons can not escape.
- NEA(Negative Electron Affinity) surface made by introducing Cs and Oxygen helps the electron escape.



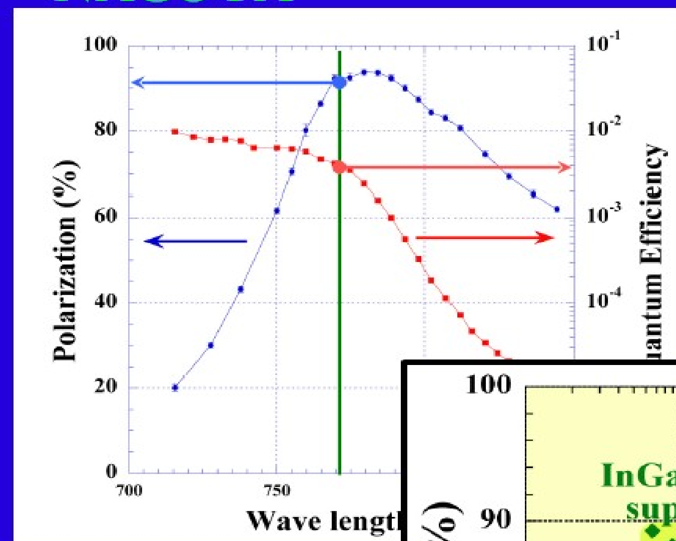
Polarized Electron (3)

Performance of GaAs/GaAsP superlattice

SLAC

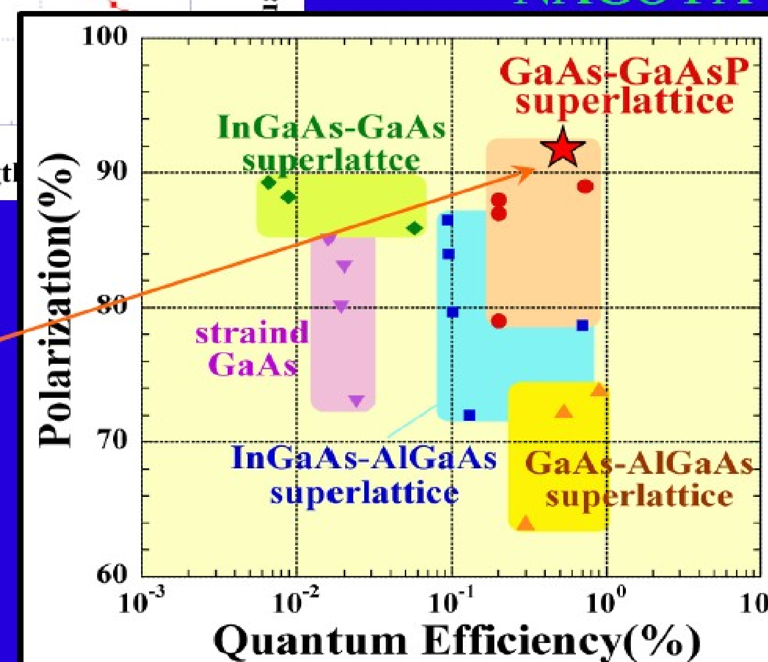


NAGOYA



By N. Yamamoto (Nagoya Univ.)

NAGOYA



GaAs-GaAsP superlattice shows the best performance !

@778nm

Polarization ~ 90%

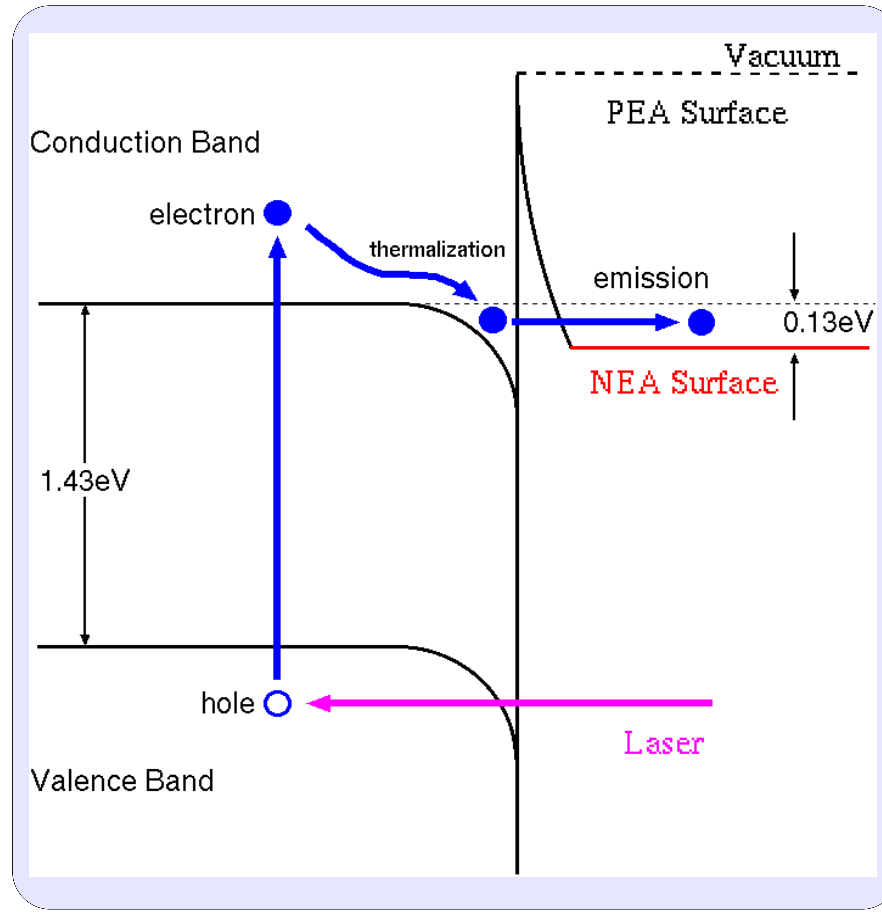
Q.E. ~ 0.5%

Polarized Electron (4)

- Electrons emitted from NEA cathode has a small excess energy due to optimized laser wave length and thermalization.
- Initial emittance

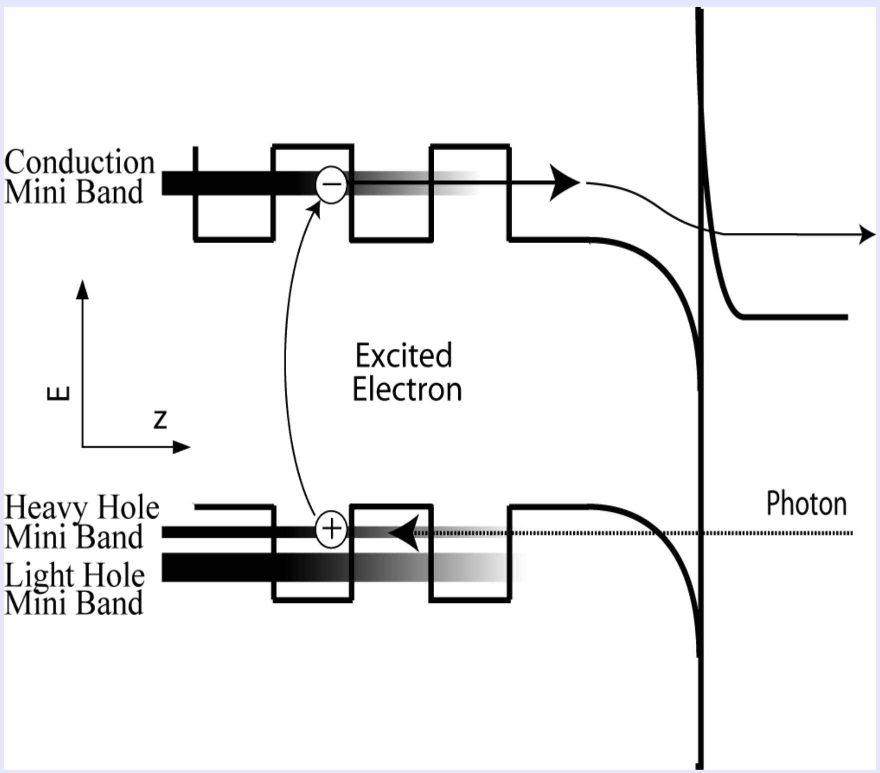
$$\epsilon_x = \frac{R}{2}\sqrt{\frac{h\nu - \phi_0}{3mc^2} + \frac{kT}{mc^2}}$$

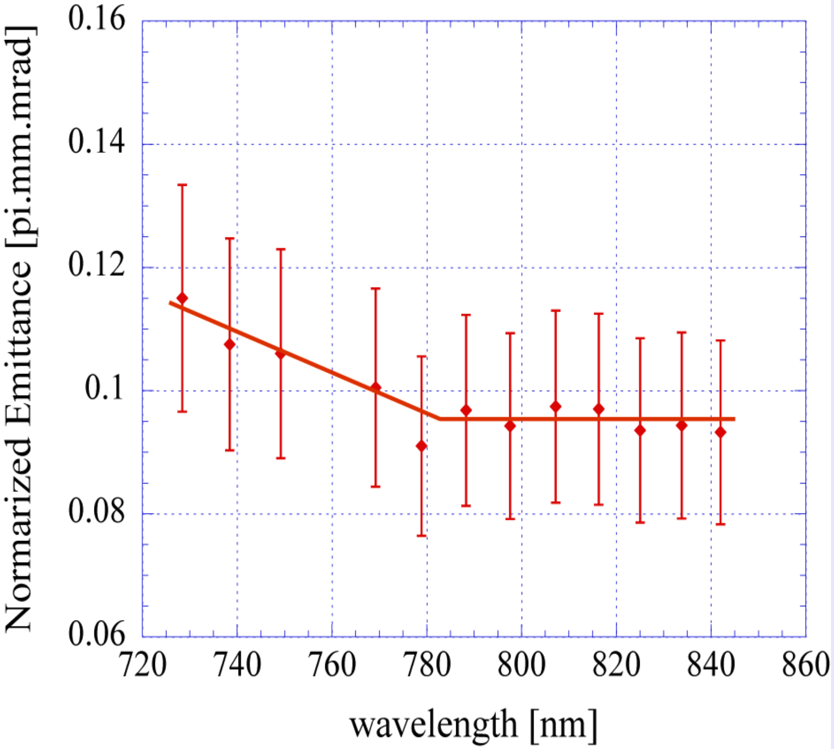
- $h\nu - \phi_0$ can be 20meV, R=1mm -> ε~0.01nm @5GeV (0.1 µrad norm)
- It corresponds to the diffraction limit at 1 Å wave length, which requires in the 4th generation light source.



Polarized Electron (5)

- 0.1 μrad (norm) is demonstrated by GaAs super-lattice cathode (N. Yamamoto et al., J Appl. Phys. 102, 024904, 2007)





Electron Gun

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

	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.

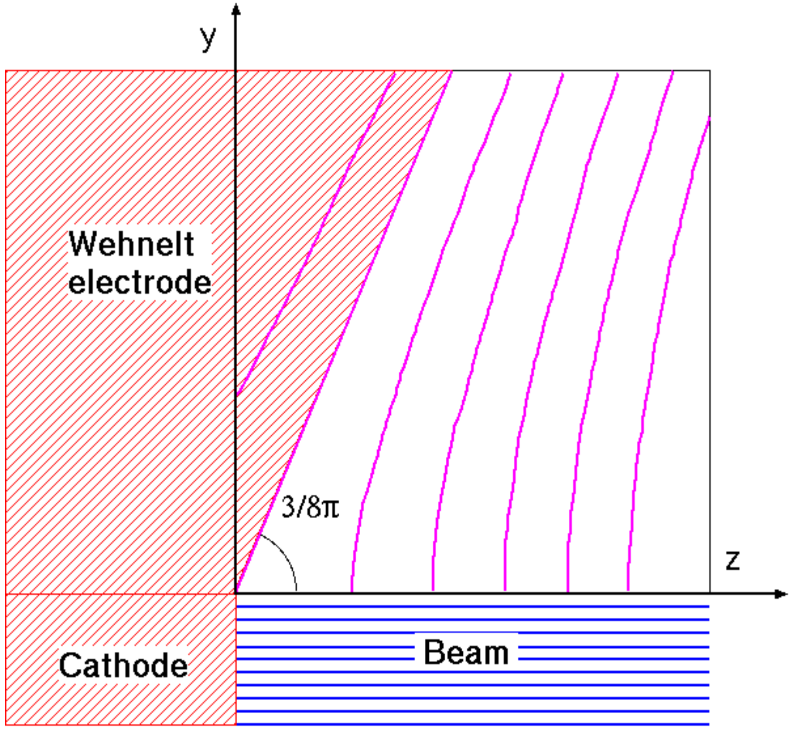
Thermionic Gun (1)

- For high density thermionic emission, the following properties are important:
  - **Low work function, ϕ**
  - **High operation temperature, T_e**
- Cs has ϕ =1.9eV, but T_e is only 320K.
- Metal cathode: Ta(4.1eV, 2680K), Mo(4.2eV,2230), W (4.5eV, 2860)
- BaO cathode: ϕ ~1eV, but the emission is lost by air exposure. Impregnated cathode (sinter of W and BaO) is widely used nowadays ; BaO is provided slowly to the surface.
- CeB6, LaB6 (2.5eV, 1800K) are good for high brightness.

Thermionic Gun (2)

- Space charge limit - parallel flow is realized with the following geometry.
- 2d example:
  - Poisson equation : y<0
  - Laplace equation : y>0
  - Smooth connection at y=0.

$$V = \frac{V_A}{d^{4/3}} \Re (z + i\, y)^{4/3}$$



Thermionic Gun (3)

- Wehnelt electrode for the collimated space charge flux.
- Grid electrode to control the emission.
- The pulse length is limited down to ~1ns due to the switching speed of the driver circuit.
- This long pulse can be considered to be a continuous beam, in which the gun is operated in the space charge limit.
- Need bunchers to shorten the bunch length for RF acceleration.

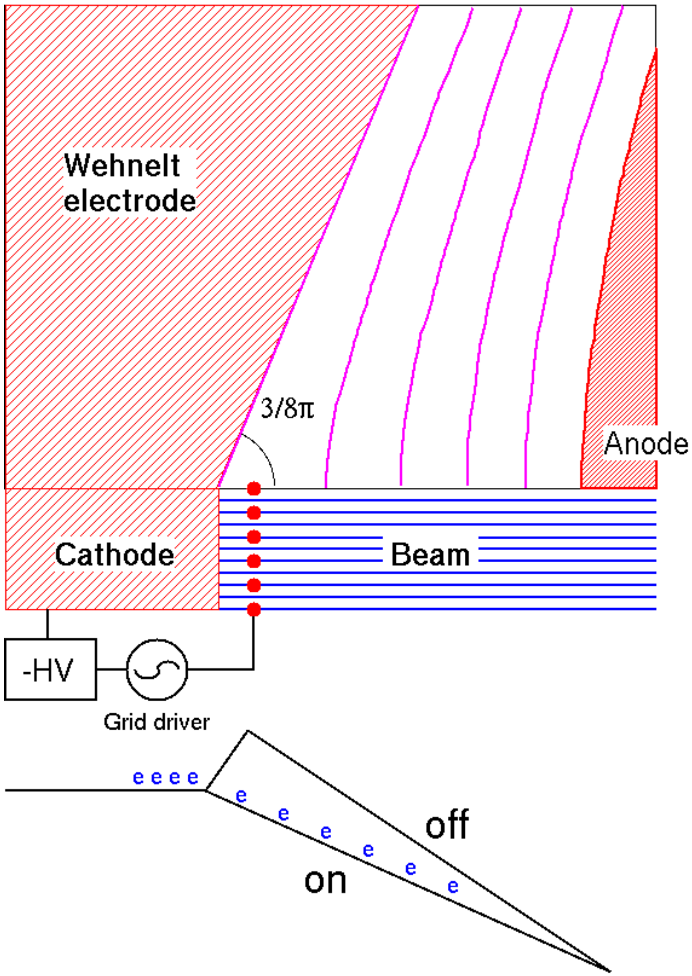
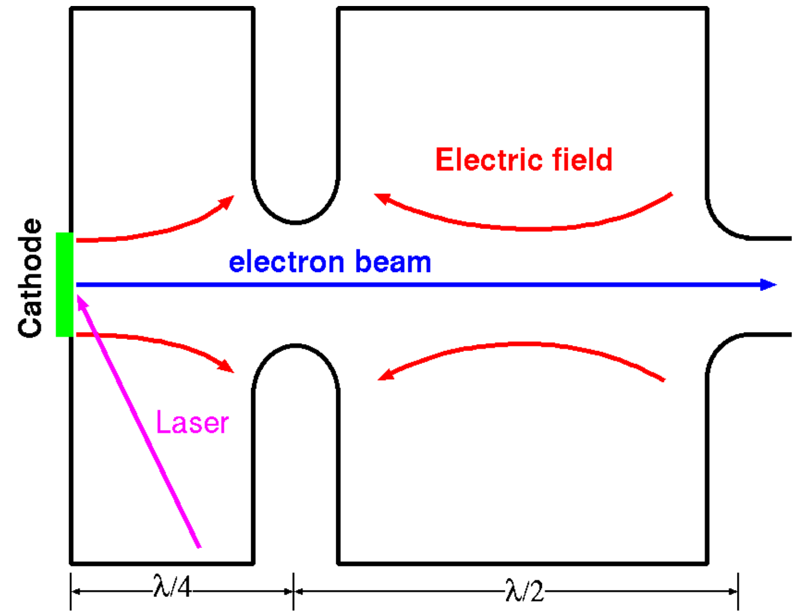


Photo-Cathode

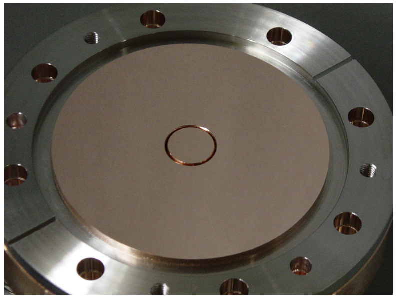
- Metal Cathode: Low QE, robust, UV.
  - Cu, Mg, Pb, Nb, etc.
- Alkali semi-conductor cathode: High QE, weak, UV.
  - CsTe, KCsTe, etc.
- Diamond cathode: High QE, robust, deep UV.
- GaAs semi-cond.: High QE, weak, Visible - IR.
  - Polarized electron, low emittance,..

Photo-Cathode RF Gun

- Electron beam is generated in inside of RF cavity.
- 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.



RF Cavity



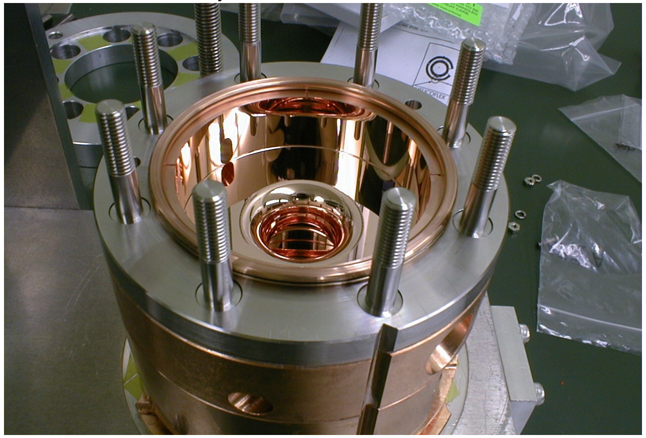
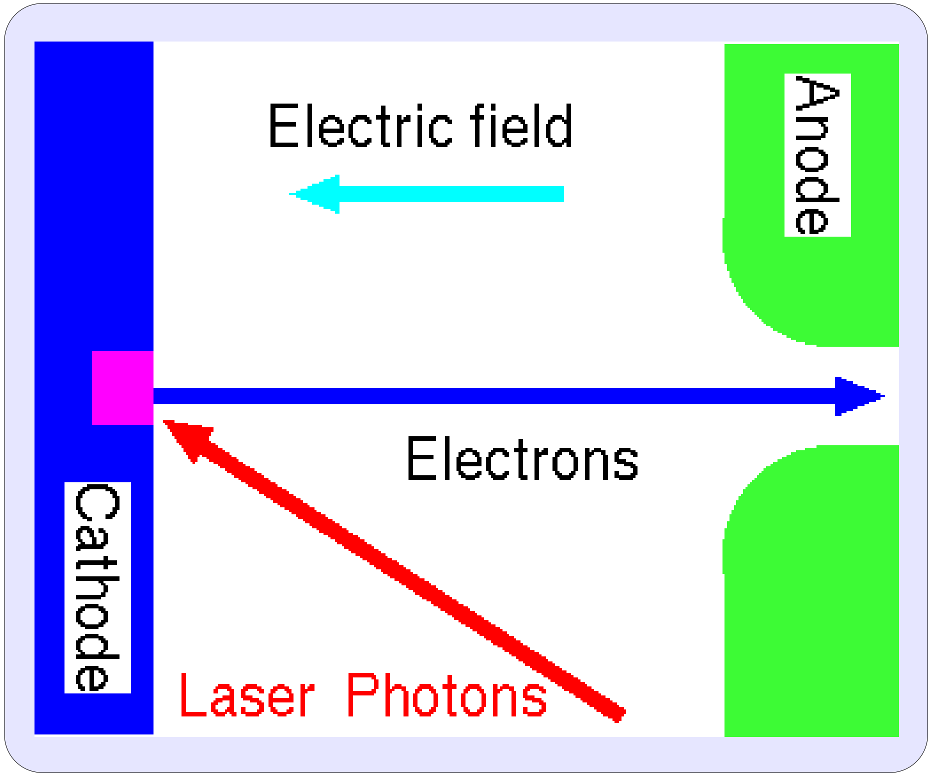


Photo-Cathode DC Gun

- Electron beam is generated by Photo-emission with short pulse laser.
- Beam extraction by a static electric field (100 – 200 kV).
- Short bunch electron beam can be generated, but sometimes it could be long due to the space charge limitation.



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 :wave length optimization around 800nm.
- A laser system, which meets fully ILC requirements, is not available commercially.

$Ti:Al_2O_3$

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

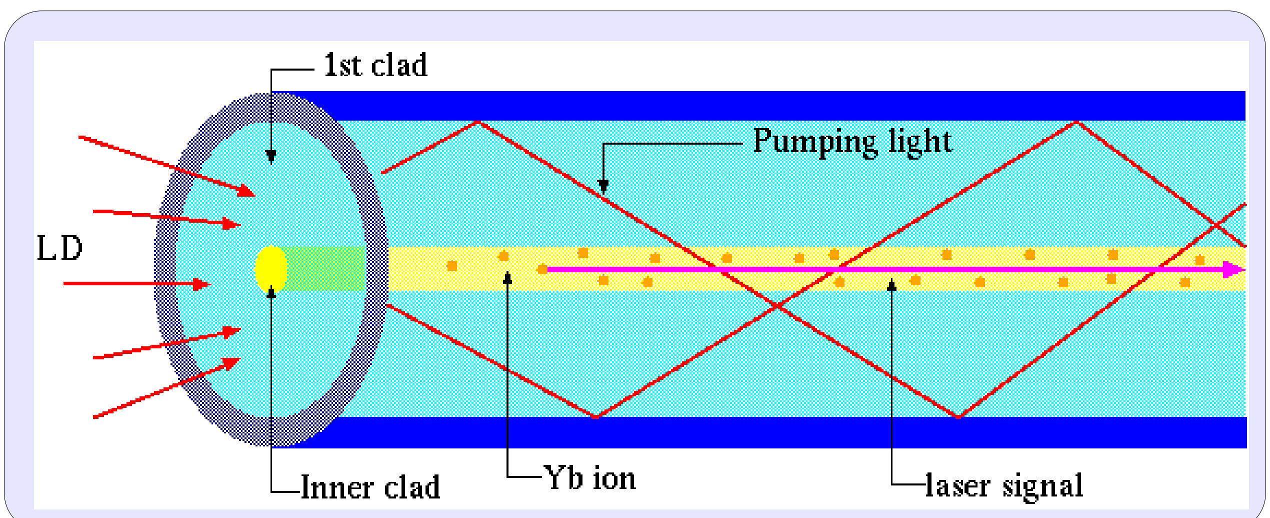
- Spontaneous mode-locking by Carr effect, bunch length > 17fs
- Wide band width for lasing (700-1100nm), wave length tune-ability by filtering.
- Require 488nm light for pumping; Fundamental mode of Laser Diode, LD (940nm) can not be used; SH of Nd:YAG/YLF is employed limiting the efficiency from the pumping power to the laser light.
- Luminescence time is 3.2 μs, which is not suitable to form a long macro pulse.

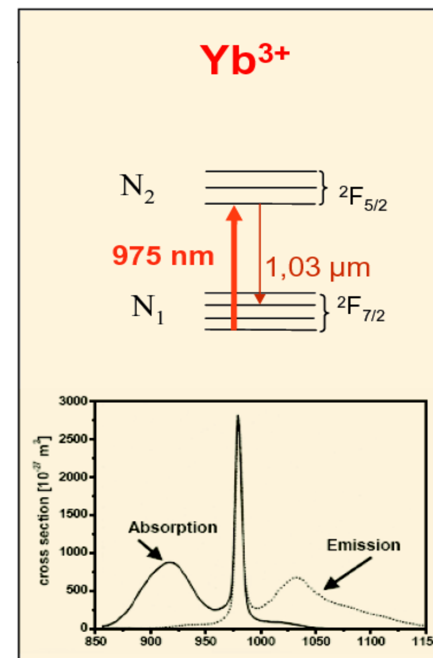
Yb:YAG Laser

- Laser wave length 1030 nm
- Band width 10 nm, which allows 100fs pulse length by mode-locking.
- Pumping light wave length is 940 nm; LD (InGaAs laser diode) can be employed; Yb:YAG is a candidate of full solid stable high-power laser system.
- Luminescence time is 1 ms, which is suitable to form a 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

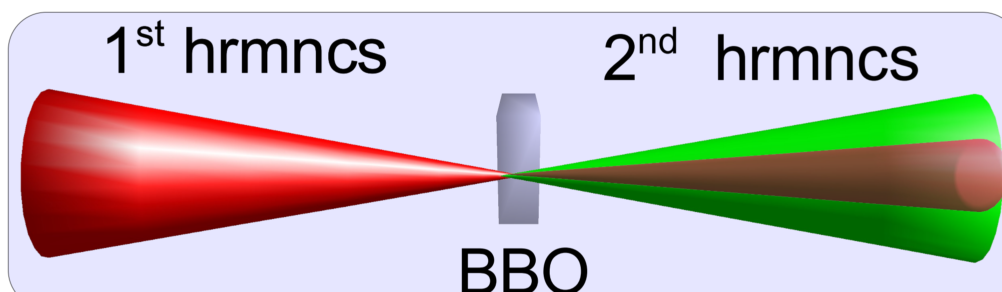
Laser Crystal	Ti:Al203	Nd:YAG	Yb:YAG	Yb fbr
Wave length (nm)	700-1100	1064	1030	1050
Wave length tune-ability	Yes	No	No	No
Luminescence time	3 μs	550 μs	1000	1000
Pump light (nm)	488	-800	940	940
Stability	Marginal	Marginal	Good	Excellent
Note	Wavelength is tunable, unstable	CW operation	High stability 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.

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

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



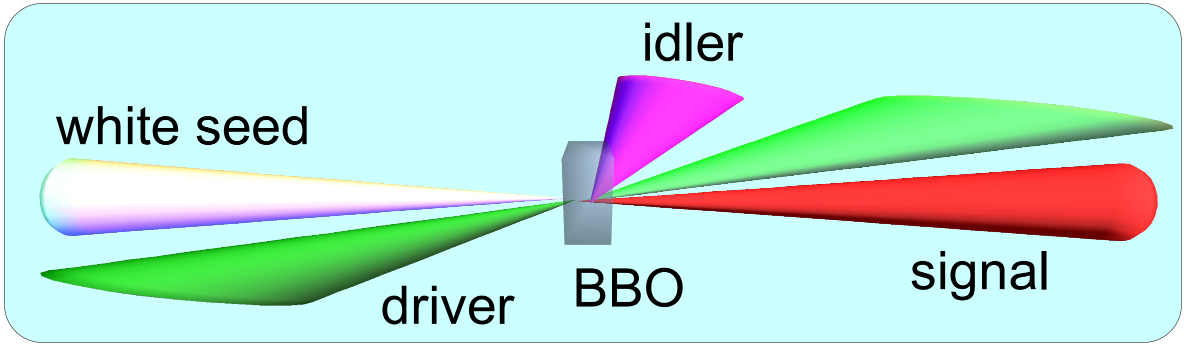
NOPA*

*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.

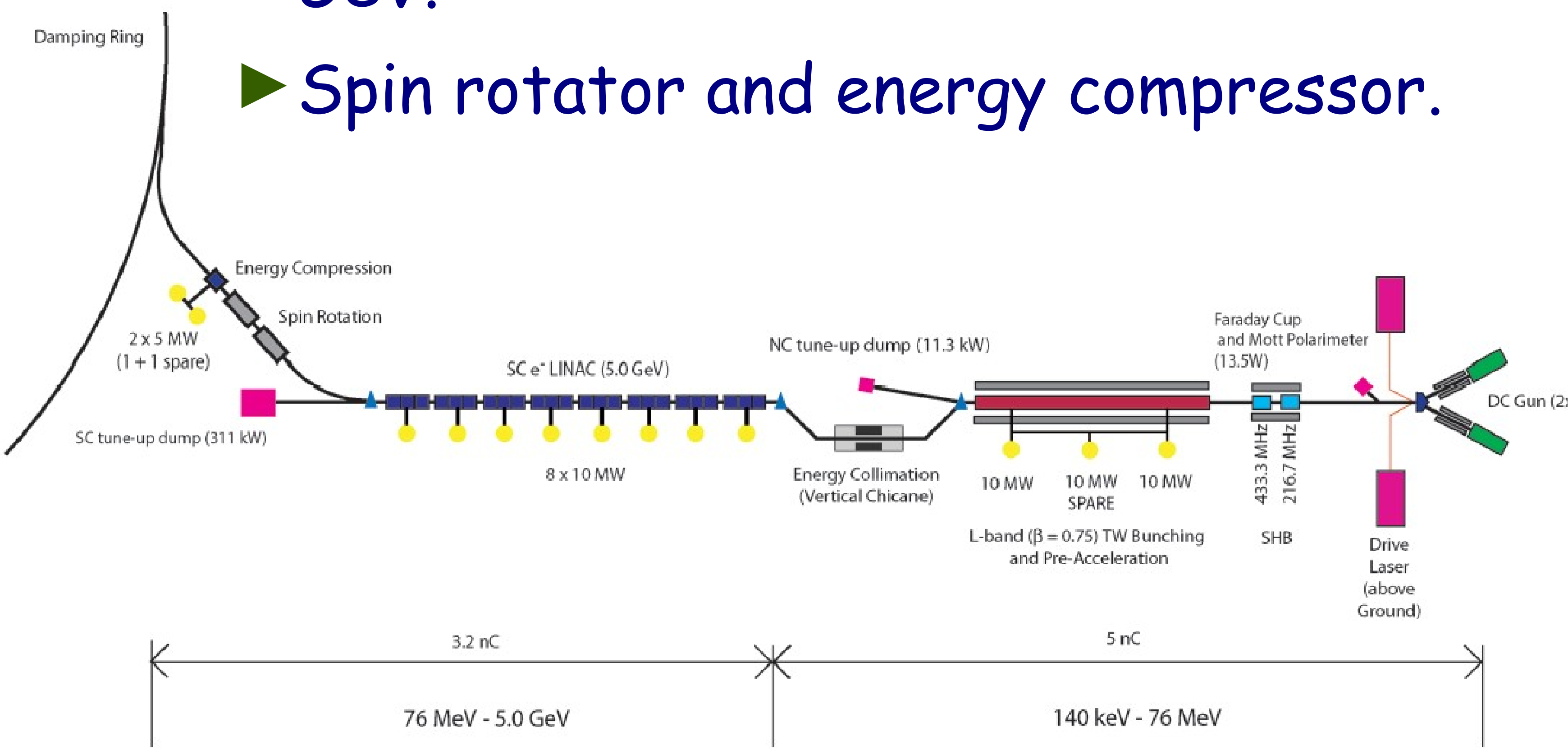
Phase Matching

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



Layout

- Dual guns and lasers for redundancy.
- NC up to 76 MeV followed by SC up to 5 GeV.
- Spin rotator and energy compressor.



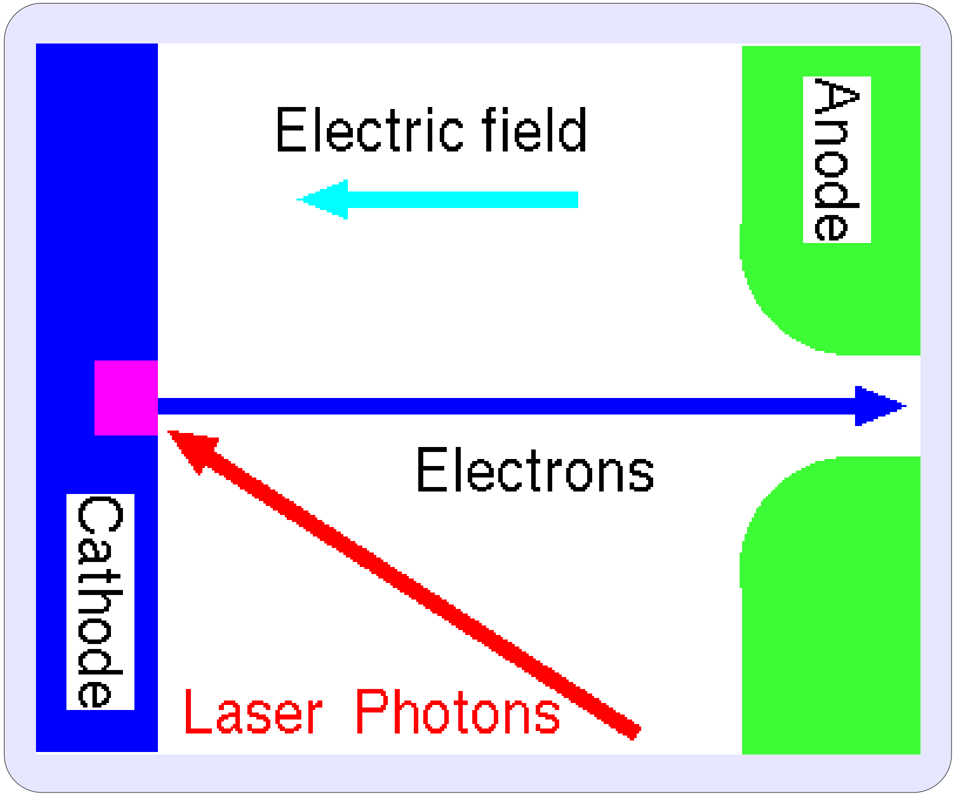
Requirements

Electron Emission
Polarized Electron
Electron Gun
Laser
ILC Electron Source
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	0.5-1ns
Peak current	12.8A(0.5ns)
Electron Polarization	80%

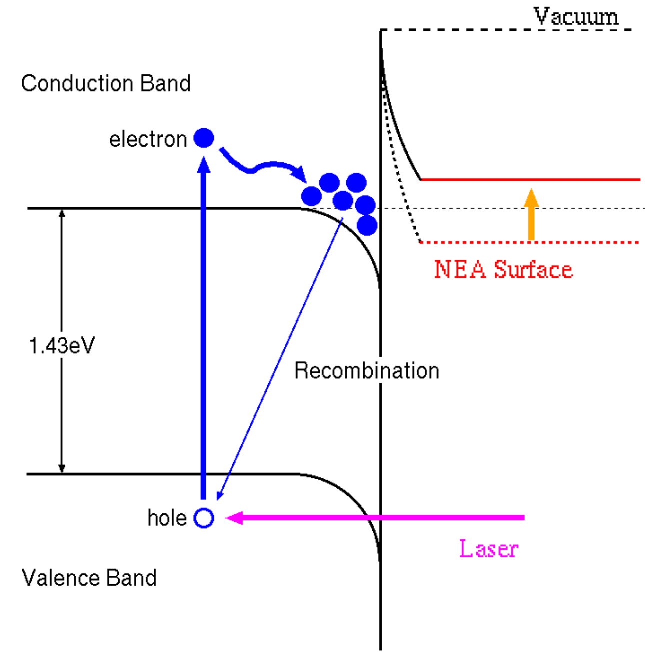
Basic Concept

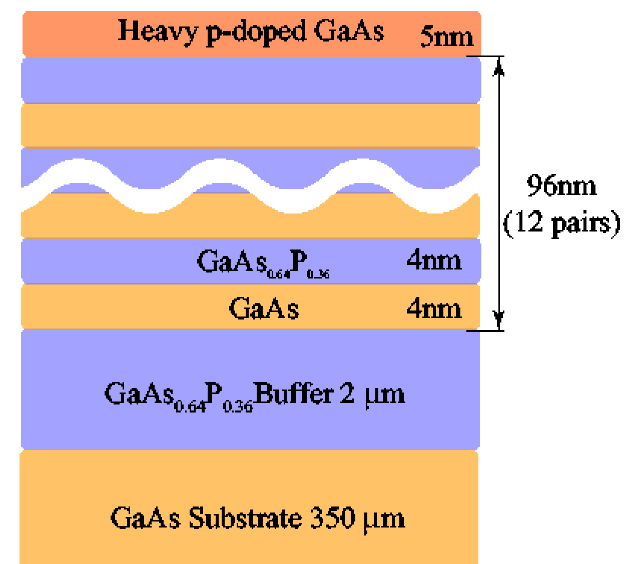
- Circularly polarized photons are injected to NEA GaAS cathode; polarized electrons are generated through photo-electron emission.
- Beam extraction by a static electric field, 120 – 200 kV.
- The emission peak current is limited by Space charge.



GaAs/GaAsP Super-lattice Cathode

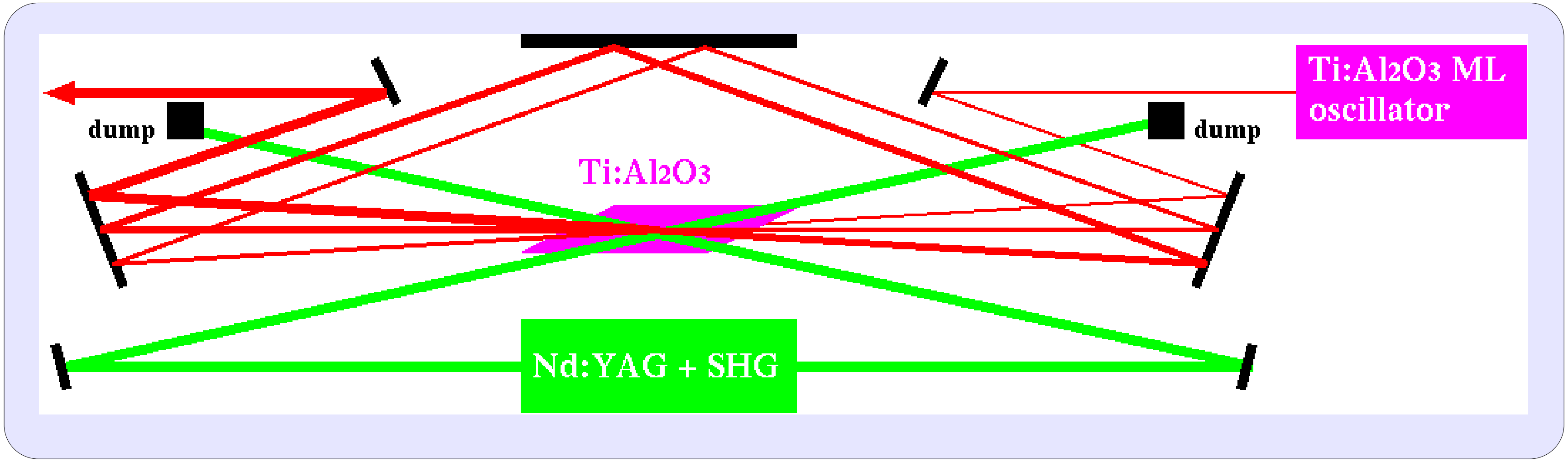
- Surface charge limit: electrons captured at near of the band bending, that raises the effective vacuum states and limit the emission current.
- Heavy P (Zn) -doped GaAs surface layer accelerates the recombination process of the captured electrons to holes; emission is recovered up to ~5A/cm^2.
- Emission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





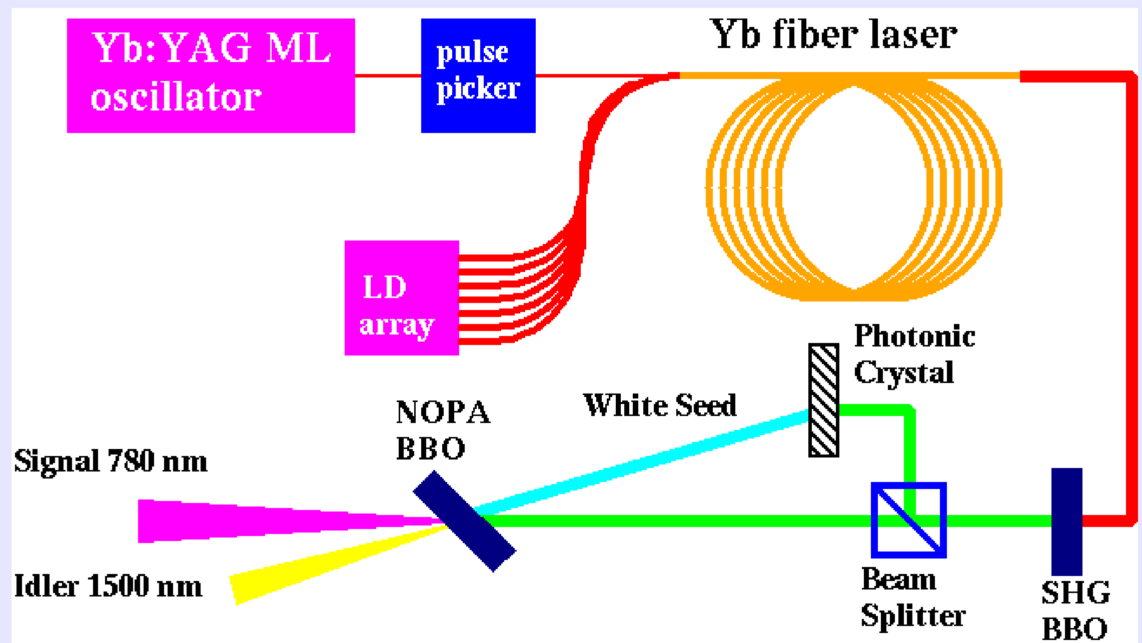
Laser : ILC Baseline Design (SLAC)

- 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.

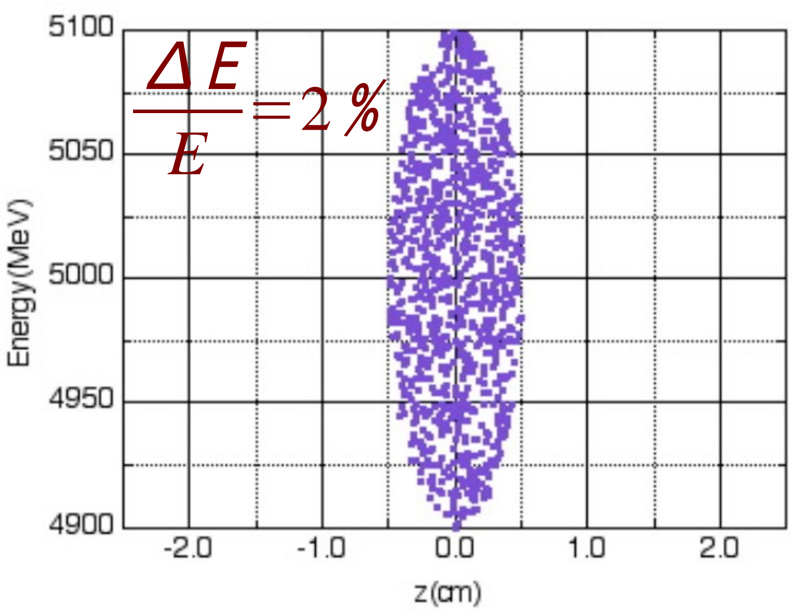


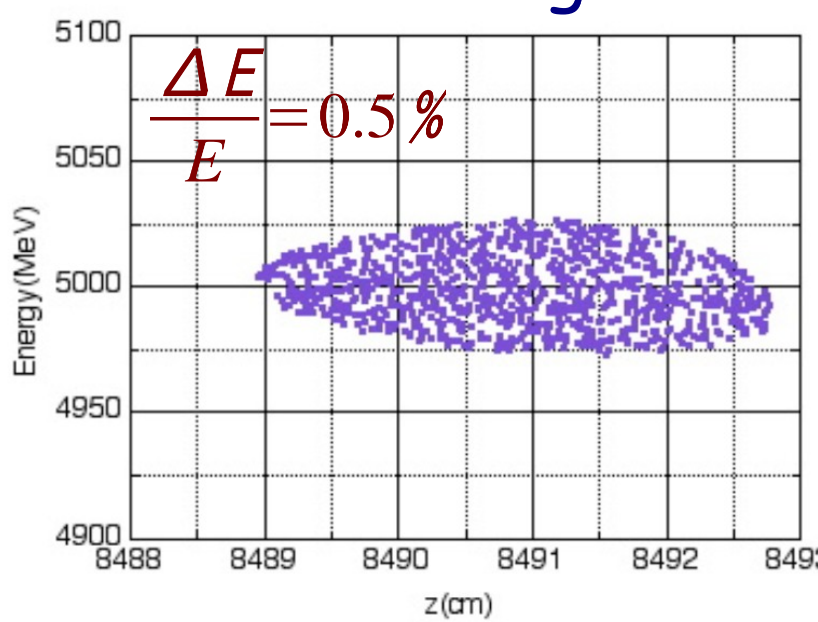
Bunching

- Peak current is limited by space charge effect described by Child-Langmuir law; Assuming 120kV, d~5cm, and 1cm diameter, the peak current is ~3A. It takes 1.1ns for 3.2nC.
- Absolutely need a bunching section for a reasonable bunch length for acceleration, 10ps.
  - SHB : 216.7 MHz + 433 Mhz
  - Buncher : 1.3 G Hz NC tube.

Energy Compression

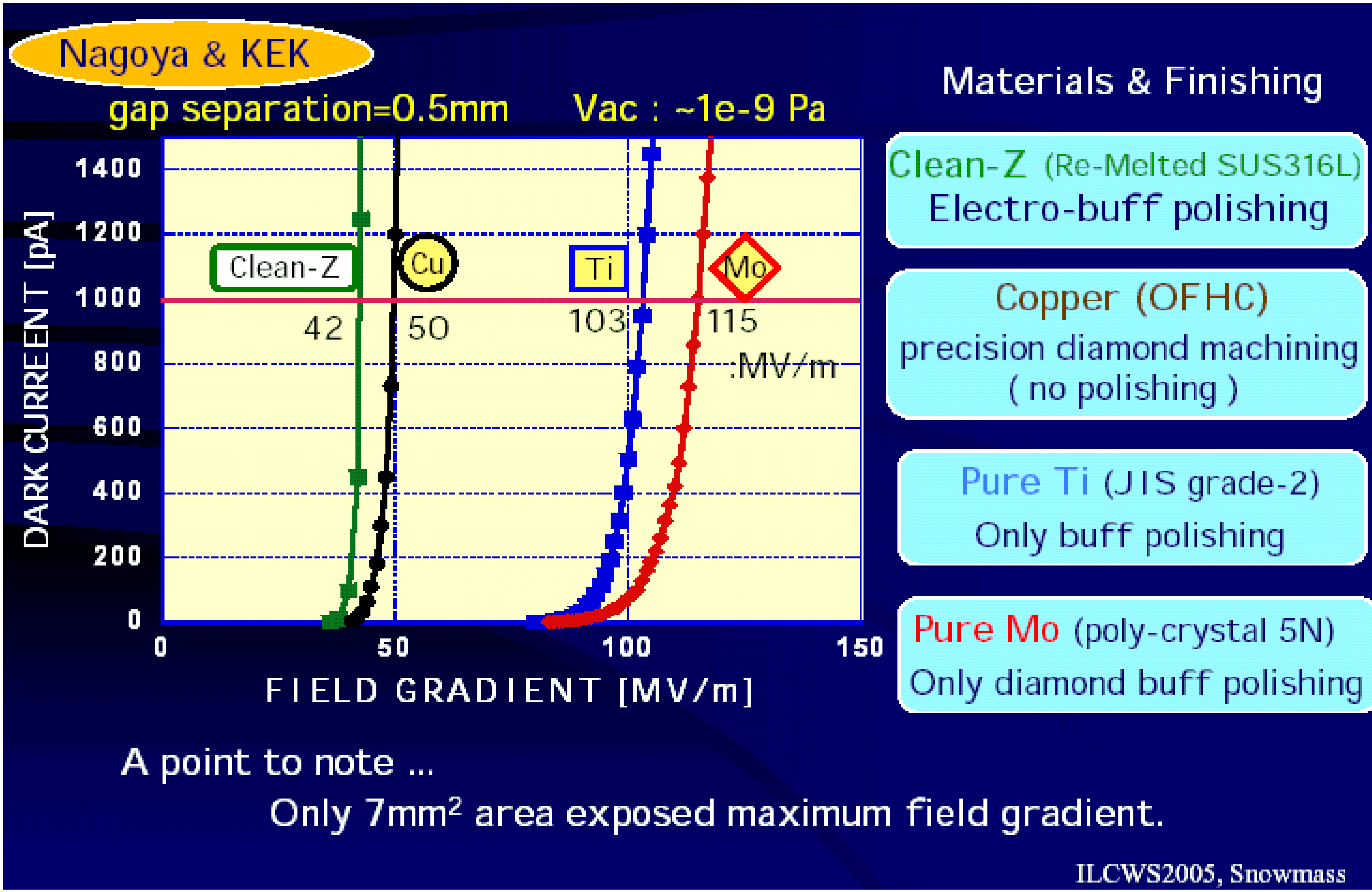
- According a simulation, the energy spread becomes larger than DR acceptance.
- Energy compressor by de/acceleration at the dispersive area is added before the DR.
- The current design 120kV Gun HV is quite conservative. It could be 200kV or higher.





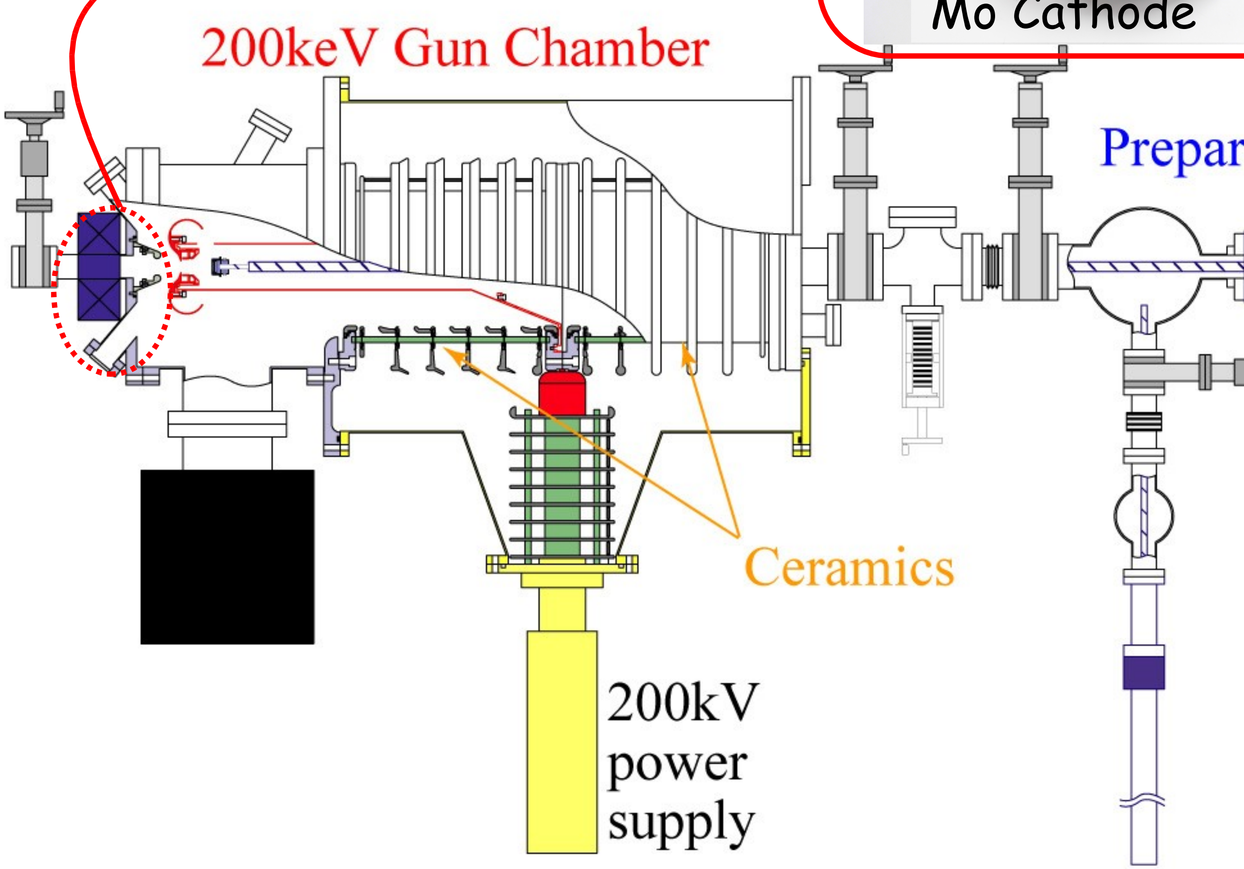
HV Operation (1)

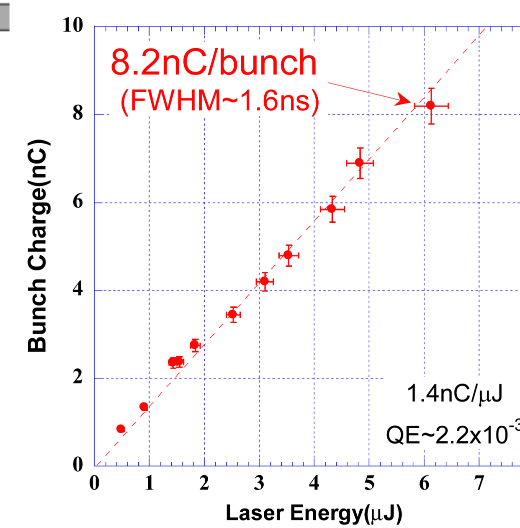
M. Yamamoto on behalf of F. Furuta



HV Operation (2)

High field DC Polarized Electron Gun@Nagoya





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.

References

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

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Home Work

1-1) Derive the following equation from the definition of Quantum efficiency (page 10).

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

1-2) How much laser power do we need to generate ILC beam (3.2nC $\times$ 2625 bunches with 369ns spacing $\times$ 5Hz) ? Calculate energy per bunch, power in a macro pulse, and average power.

- Electronic charge : 1.60E-19 C
- Laser wave length : 800nm
- Planck constant : 6.63E-34 Js
- Speed of light : 3.00E+8 m/s
- Quantum efficiency : 0.5%