Electron Gun

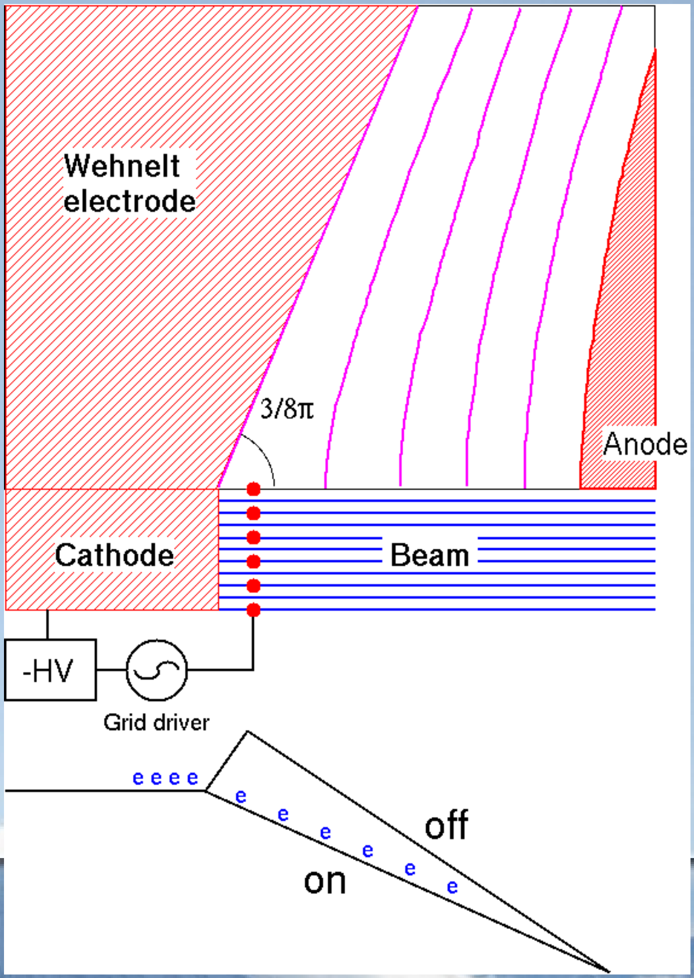
Electron Gun

	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

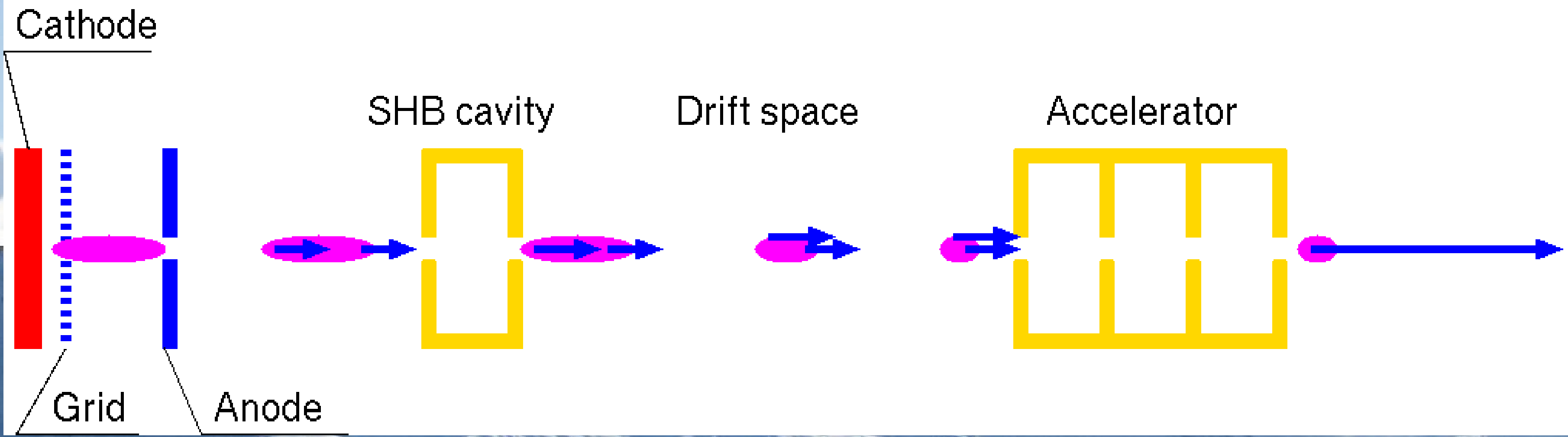
- Thermionic cathode with DC bias.
- It is a conventional gun widely used.
- Continous beam or
- Bunched beam by grid switching, but the bunch length is down to ~1ns.
- Energy at the gun exit is

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



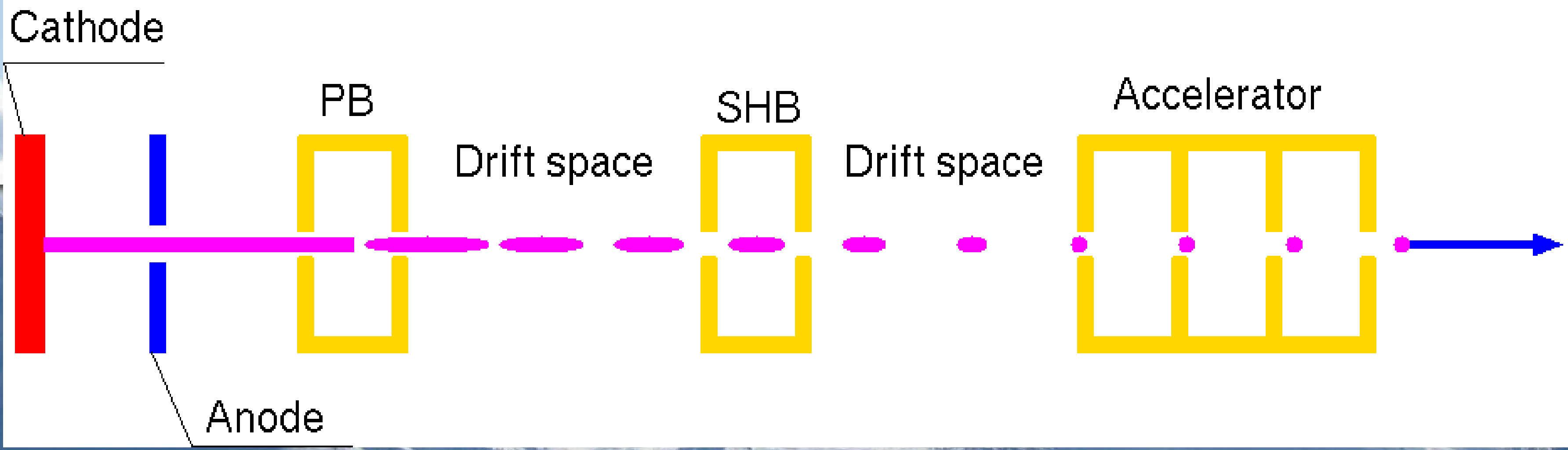
Thermionic Gun: A typical configuration (1)

- 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 ,

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

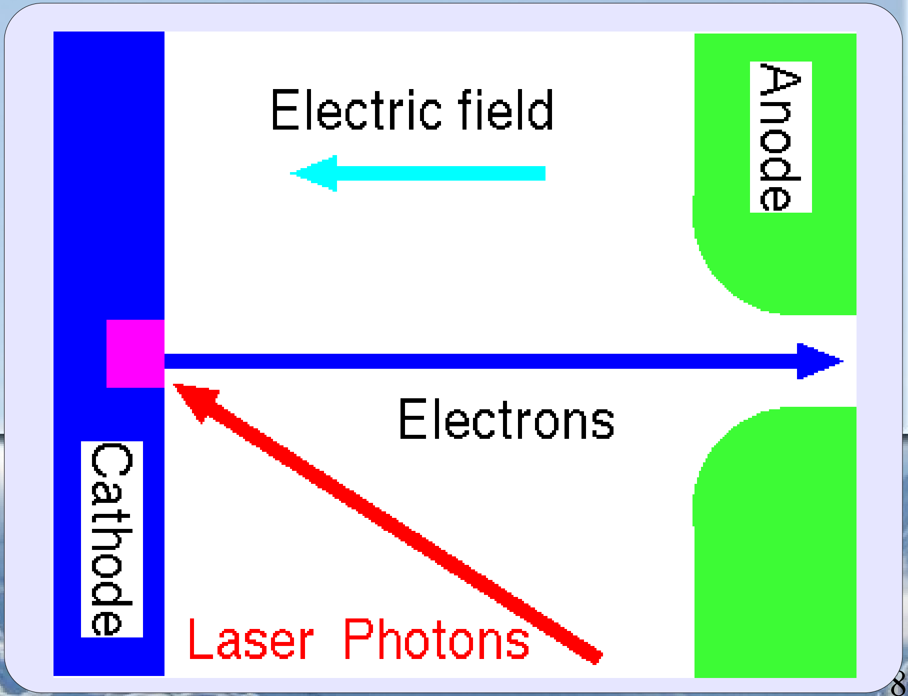


Photo-Cathode DC Gun (2)

- 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.

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

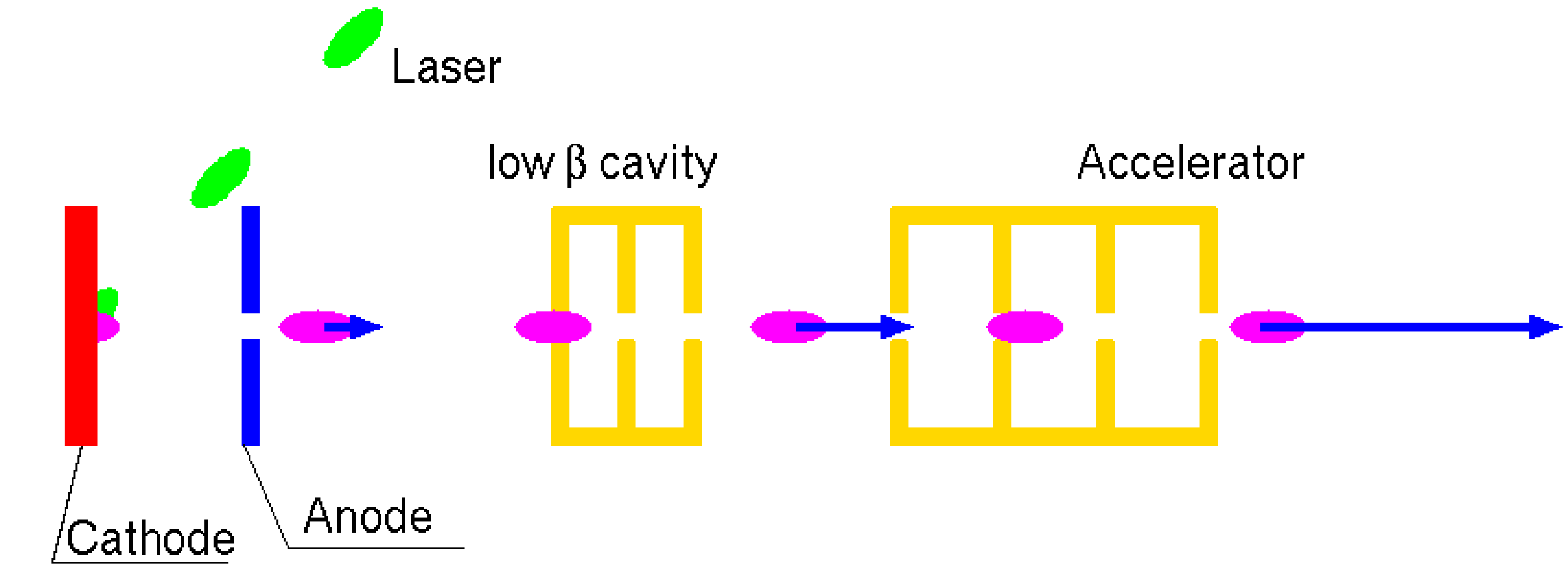
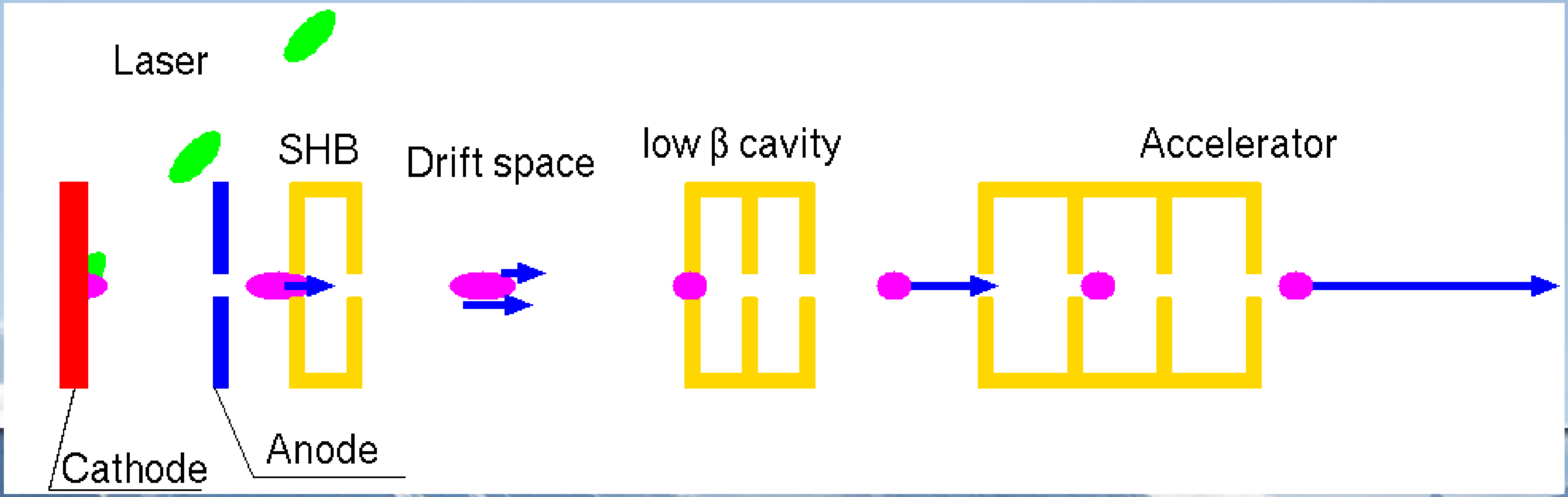


Photo-Cathode DC Gun (3)

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



HV Operation (1)

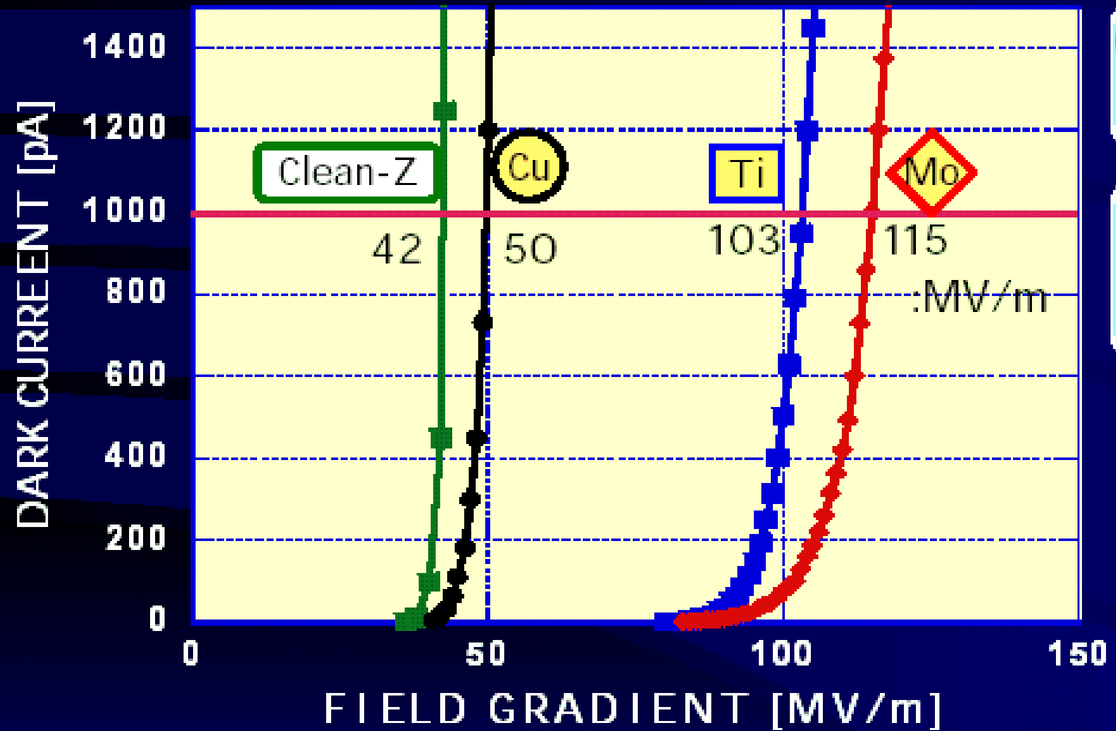
- Since the bunch length at the gun exit is determined by the space charge limit, higher voltage operation makes a higher peak current and bunch length can be shorter.
- Short bunch length from gun has merits
  - Simpler bunching section,
  - Energy spread after acceleration is smaller,
- For higher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

HV Operation (2)

M. Yamamoto on behalf of F. Furuta

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

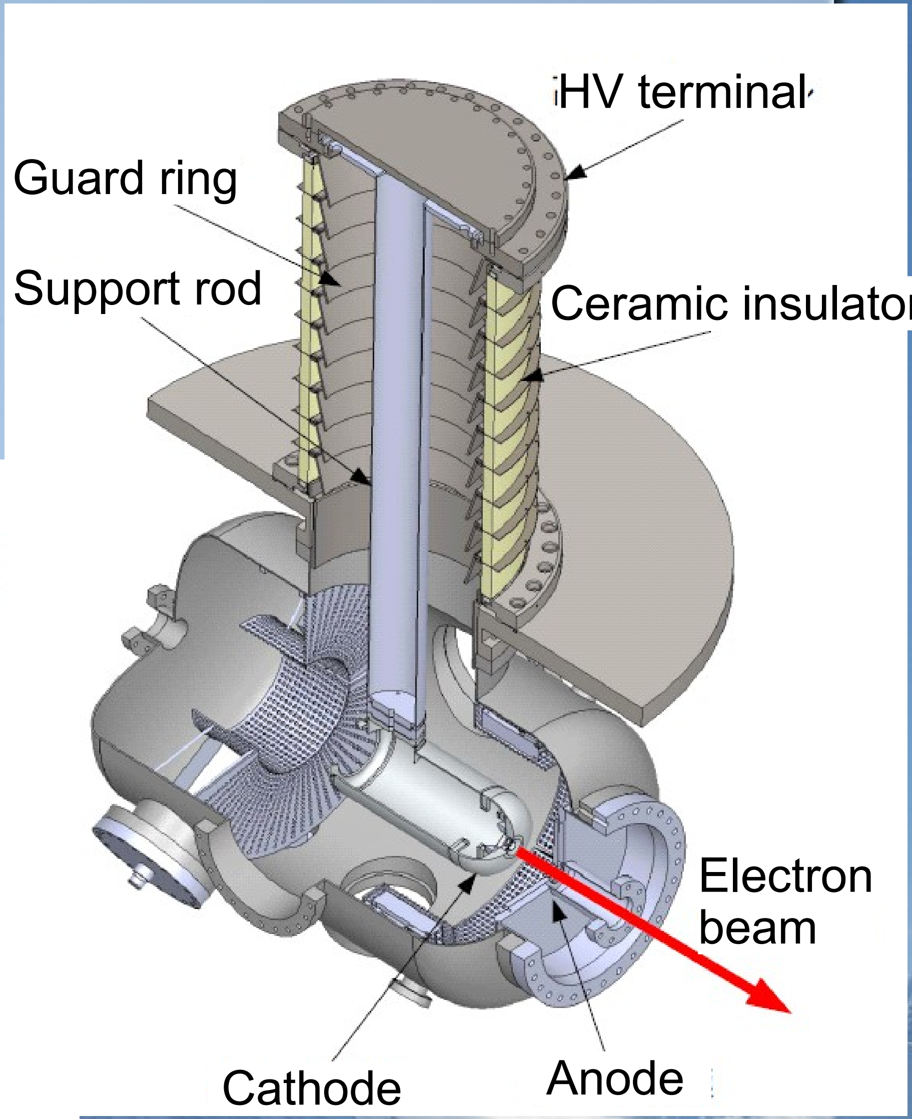
Pure Mo (poly-crystal 5N)
Only diamond buff polishing

A point to note ...

Only 7mm² area exposed maximum field gradient.

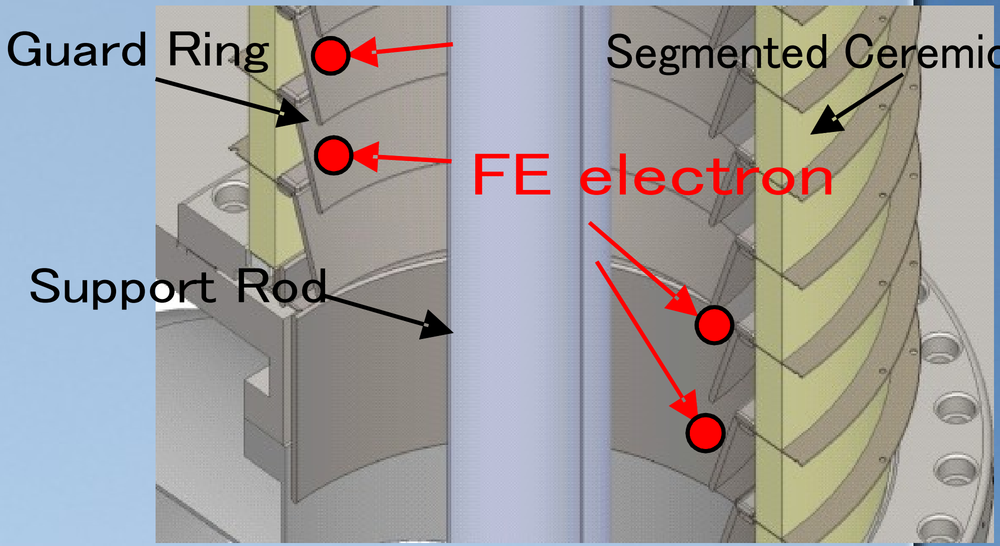
HV Operation (3)

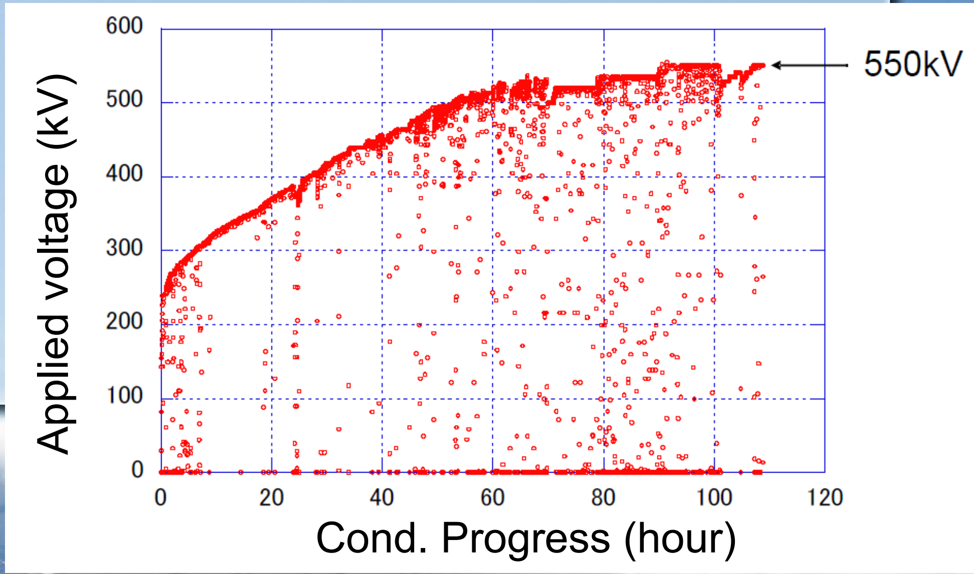
- Future light source based on ERL employs PC-DC gun.
- For extremely low emittance, HV operation is essential.



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.

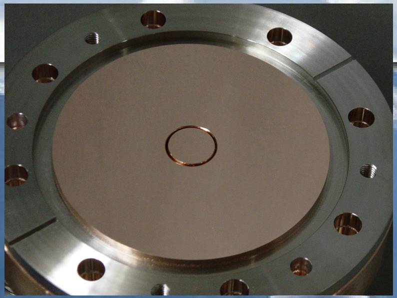


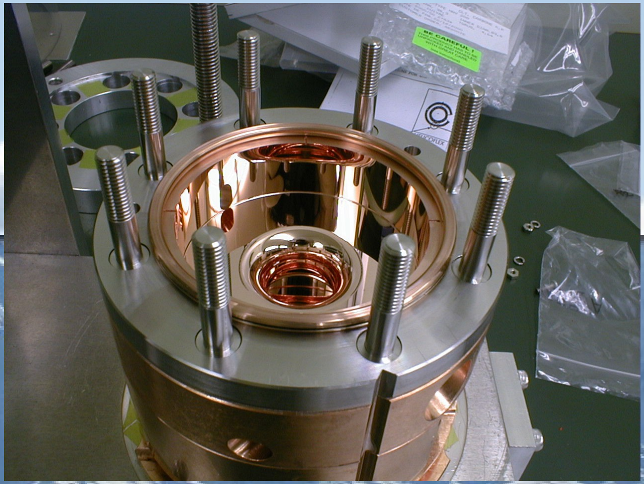


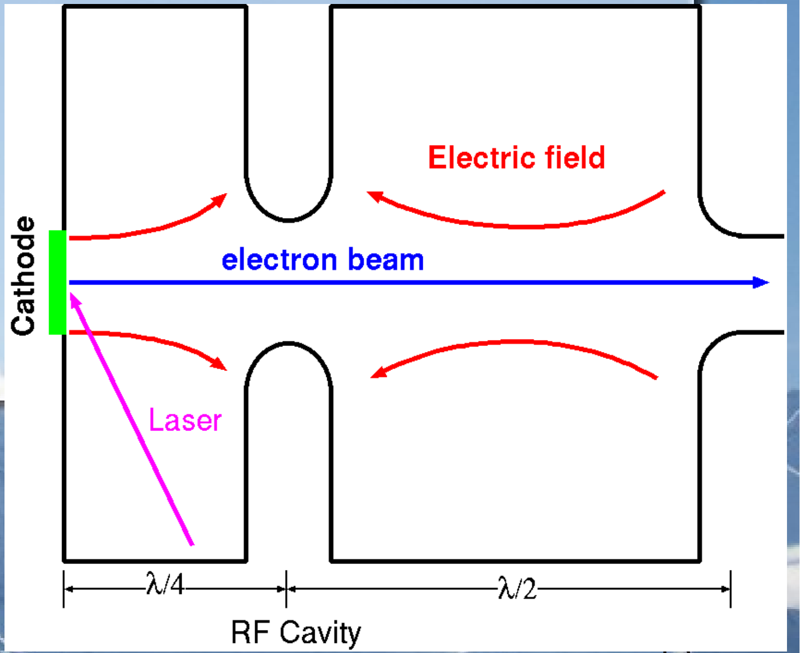
R. Nagai, RSI(81)033304(2010)

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}~10^{-5}, response is fast in fs.
- Alkali cathode (CsTe, CsKSb) high η and medium response.
  - η is typically 10^{-1}~10^{-2}, response is in sub ps.
- NEA GaAs cathode has high η and slow response.
  - η is typically 10^{-1}~10^{-2}, response is 10s ps

Electron source for Linear Colliders

Design Criteria

- Polarized Electron is essential for linear colliders; The electron must be polarized.
- Higher polarization is better. The world record is 90%, but the specification is determined from technical feasibility, i.e. reproduciability, stability, QE, etc.
- Depending on the polarization, the luminosity is decided to produce enough event rate for physics.
- The linear collider needs $2\times10^{34}\,cm^{-2}s^{-1}$ luminosity with 80% polarization.

$$N_{event} = \sigma \times L \qquad L = \frac{f_{rep}\, n_b N^2}{4\pi\sigma_x\sigma_y}$$

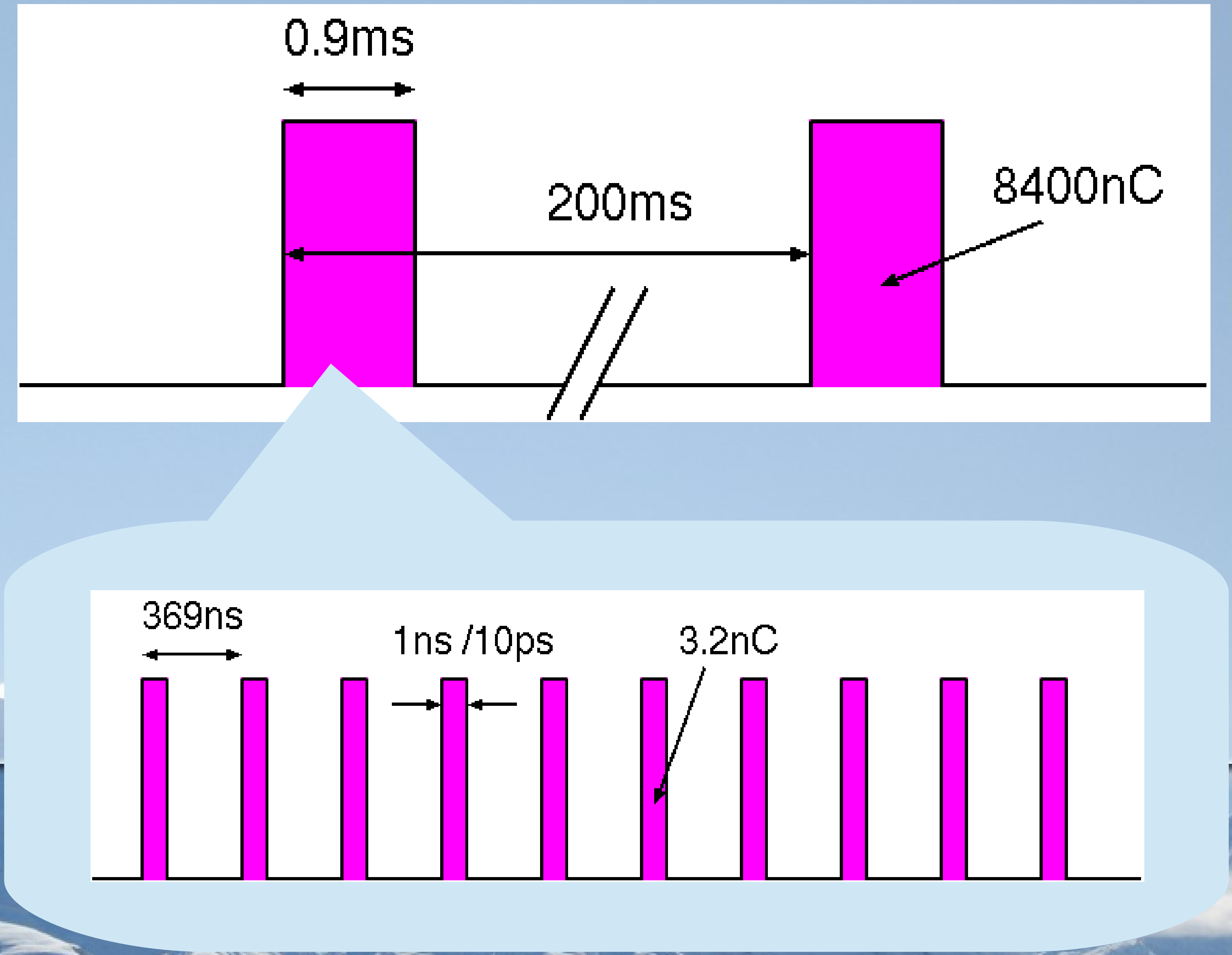
ILC Requirements

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

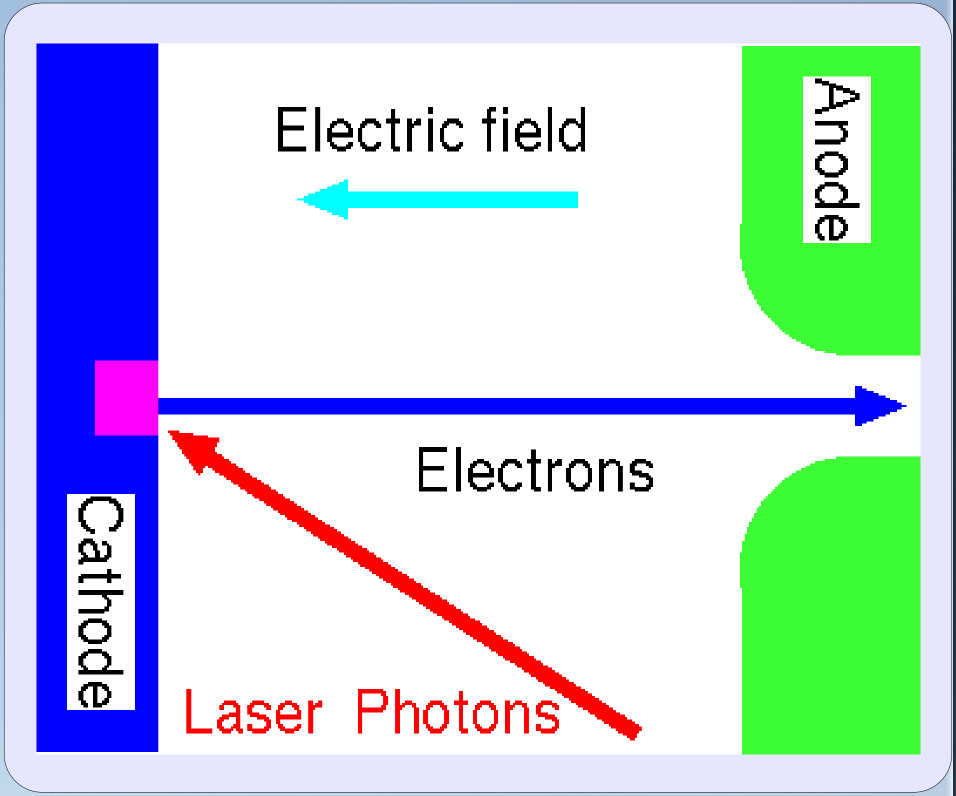
Macro Pulse

Micro Pulse



Basic Concept

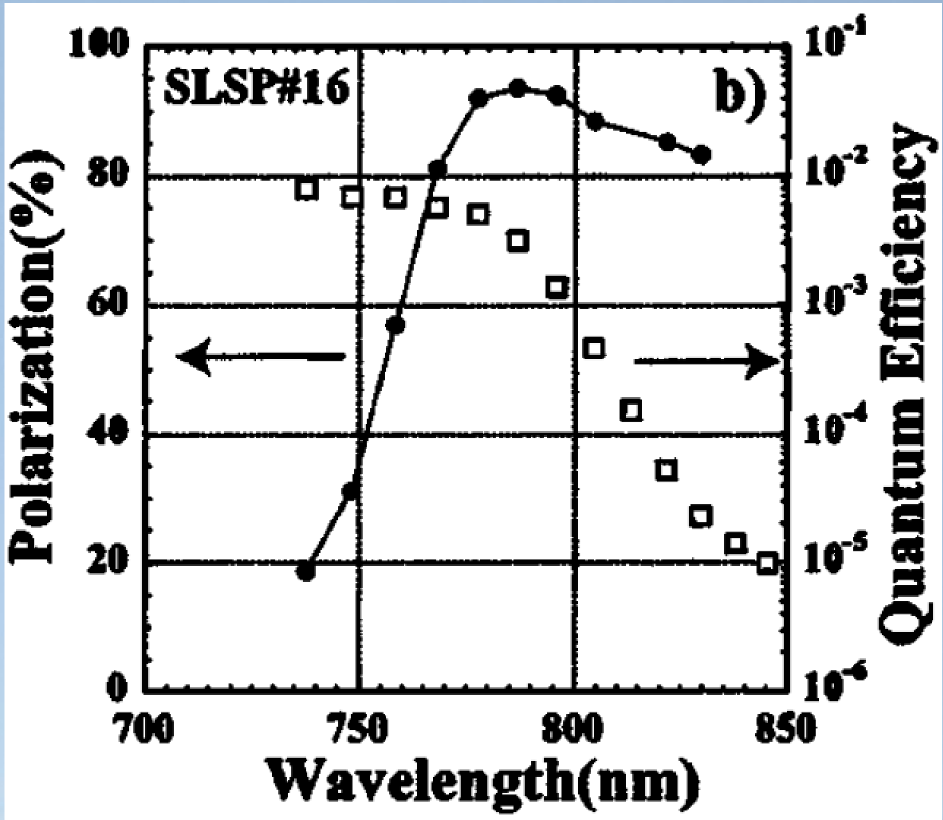
- NEA GaAS cathode with circularly polarized laser is the only solution for polarized electrons.
- Beam extraction by a static electric field (DC photo-cathode gun) because RF gun is not compatible with GaAs cathode.



Bunch extraction
Required Laser Pulse Energy

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

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



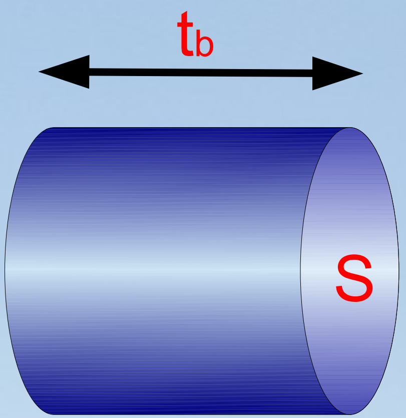
T. Nishitani et al., J of Appl. Phy. 97,094907(2005)

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

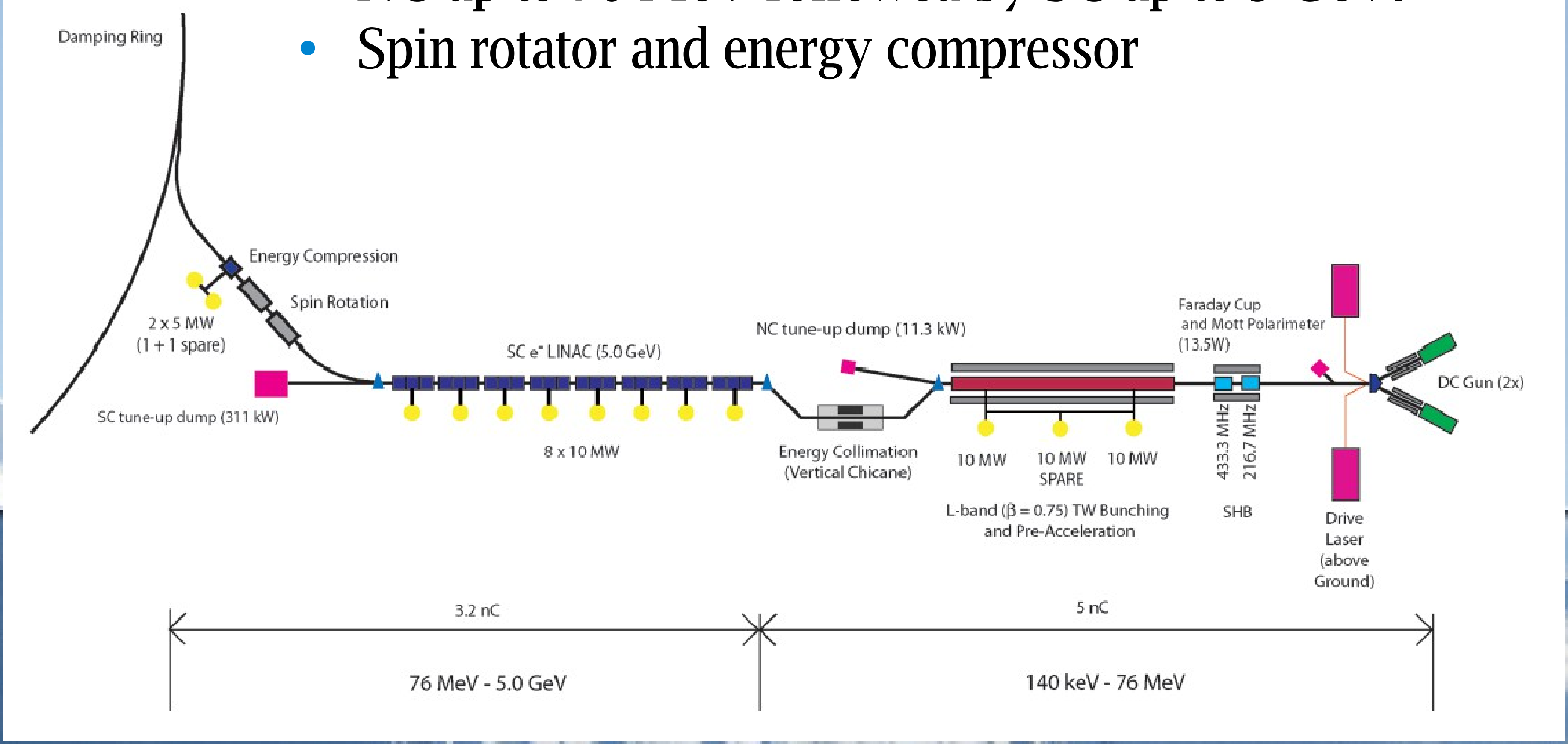
- If the bunch length at gun t_b is adequate for RF acceleration, any bunching section is not needed.
- Otherwise, we need a bunching section.
- RF period for the bunching should be long enough comparing to t_b for linear modulation.
- RF frequency for the bunching should be harmonics of bunch repetition,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

$$T_{bunching} \gg t_b$$

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

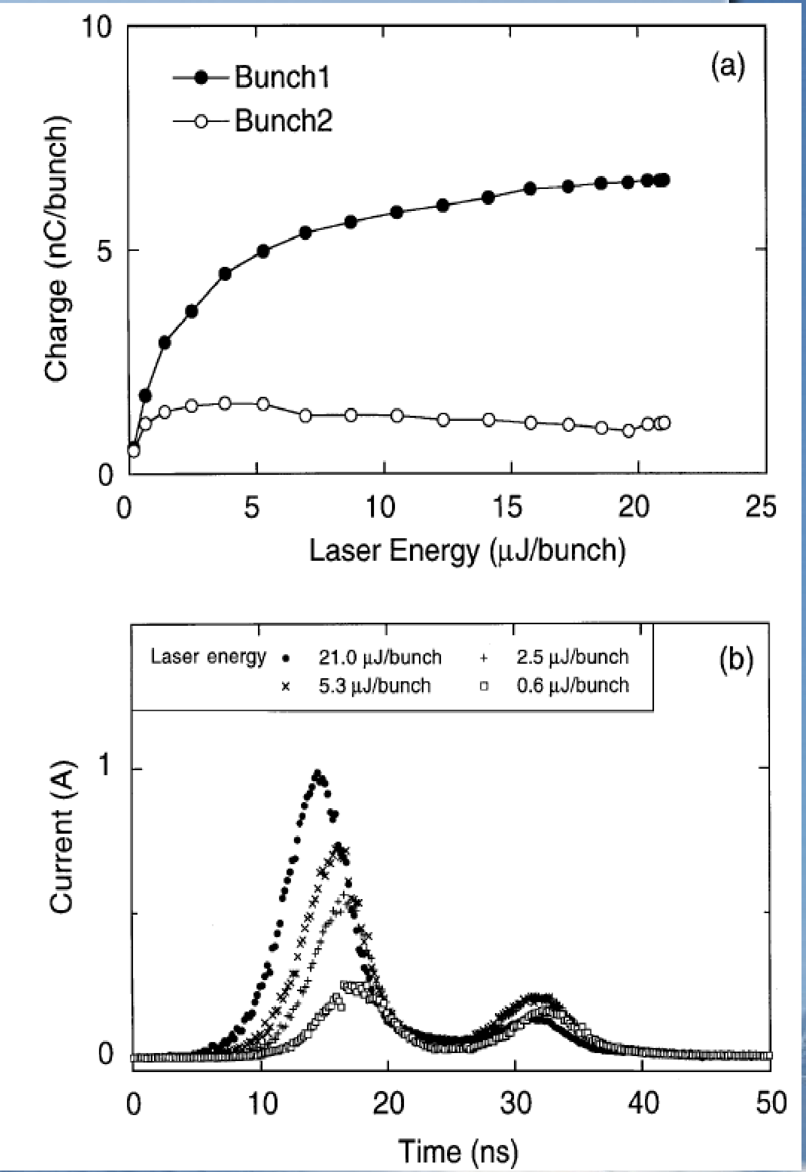
ILC Electron Source

- 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.

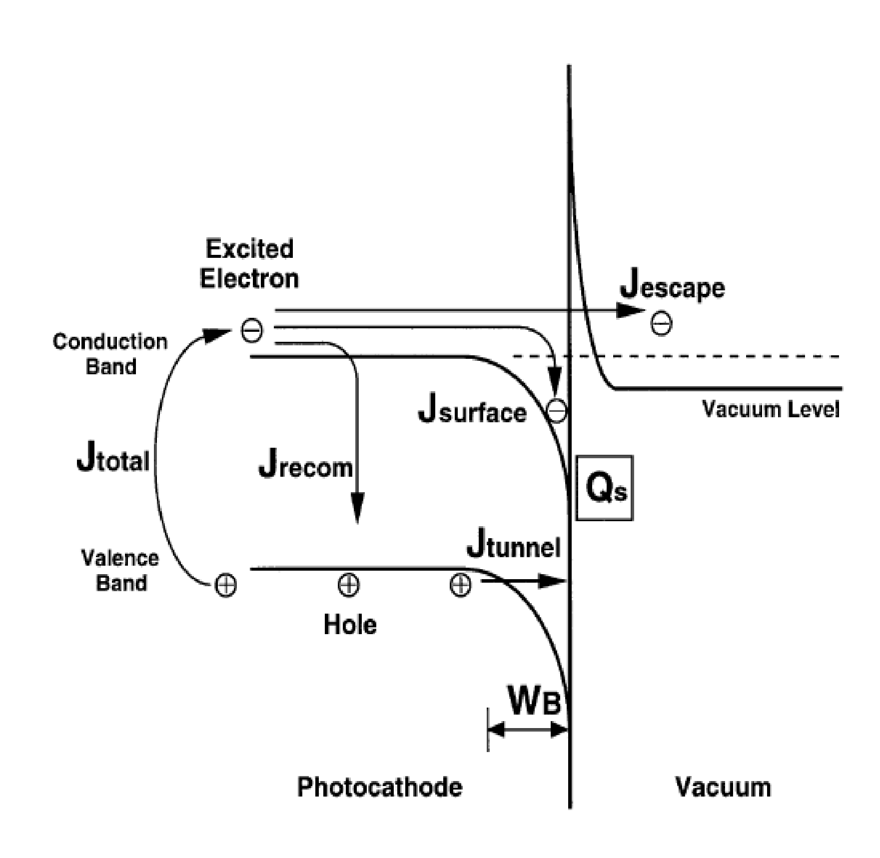


K. Togawa, NIM A 414 (1998) 431-445

GaAs with a Be-dope 5E+18cm^3

Surface Charge Limit (2)

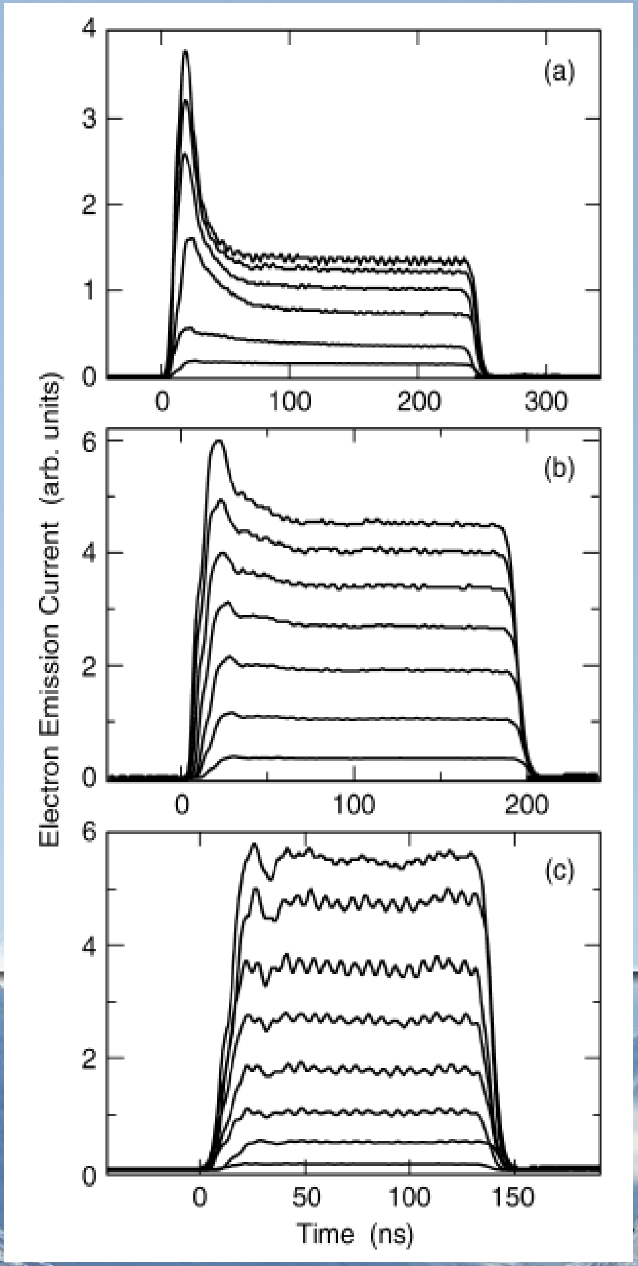
- The surface charge limit is caused by Photo-voltage effects;
- Some electrons, $J_{surface}$ is captured at BBR(Band Bending Region).
- By the captured electrons, the effective vacuum level is increased.
- Photo-voltage effects decrease size of EA and limit the current.



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.

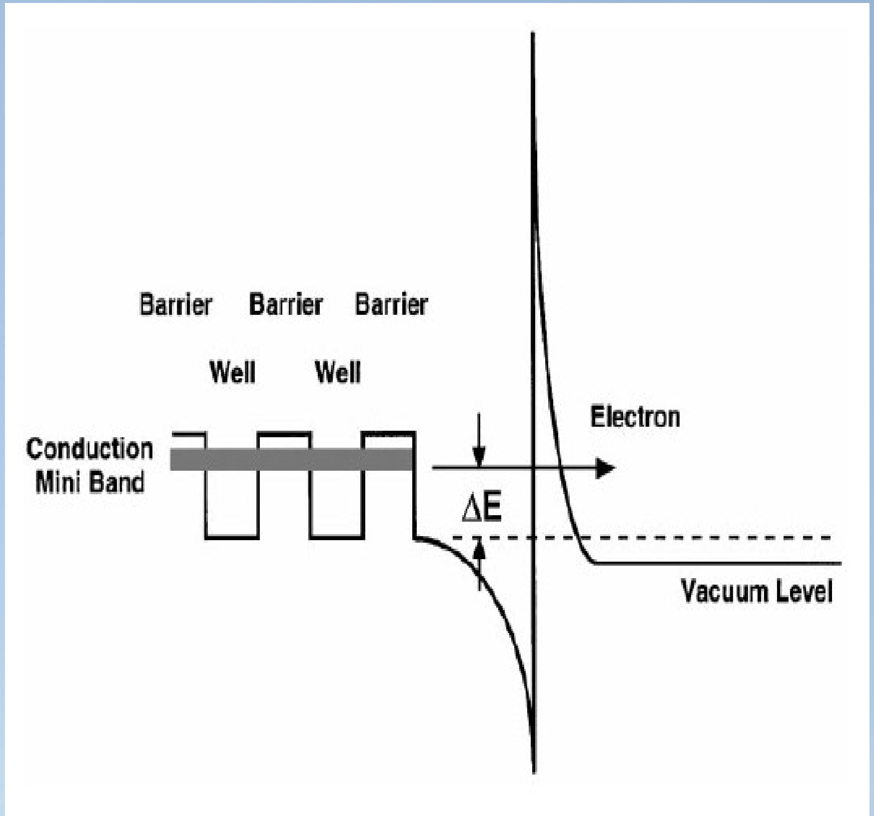


(a) sample 1b(Na=0.5),
(b) sample 2a(Na=1.0), and
(c) sample 3(Na=2.0). The laser intensity is 1 to 150 W/cm2.

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

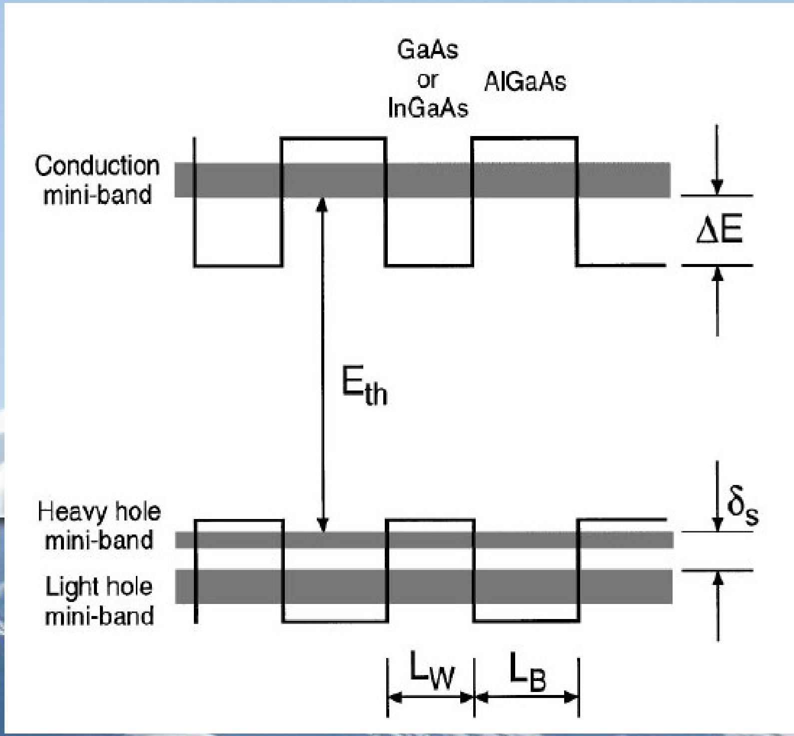
Surface Charge Limit (4)

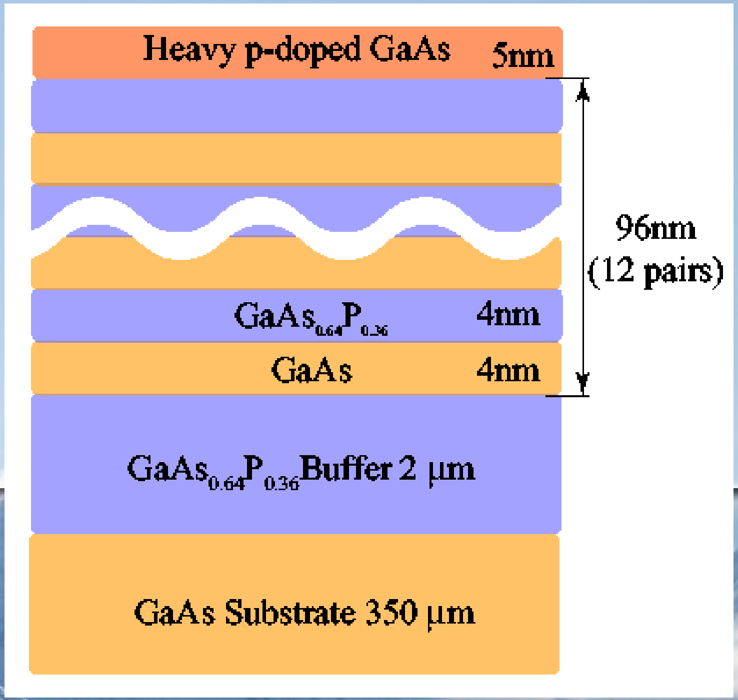
- Super-lattice Cathode has an advantage against SCL.
- J_{escape} is proportional to the size of NEA.
- The effective size of NEA in Super-lattice cathode is larger than that of bulk-GaAs.
- The escape probability, $J_{esacape}/J_{total}$ is larger for Super-lattice cathode. SCL current should be higher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



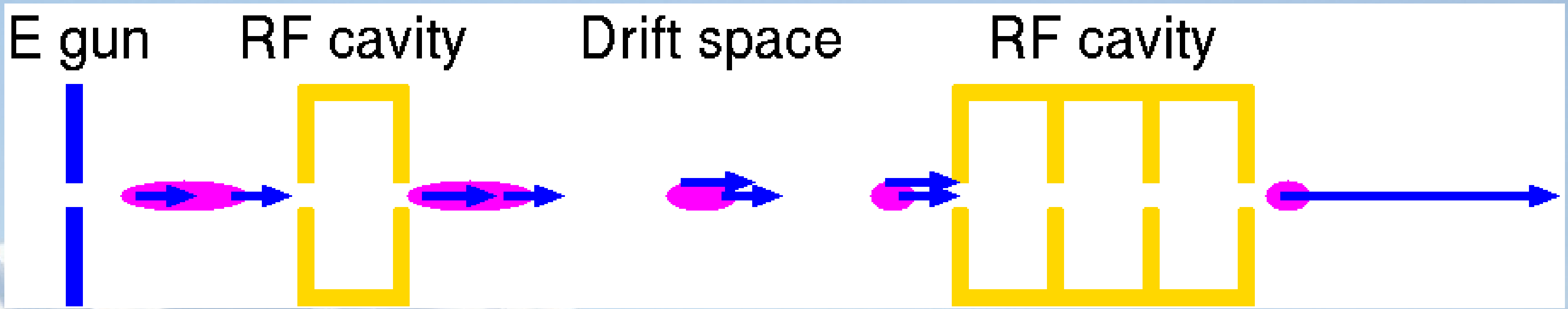


Bunching(1)

- 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)

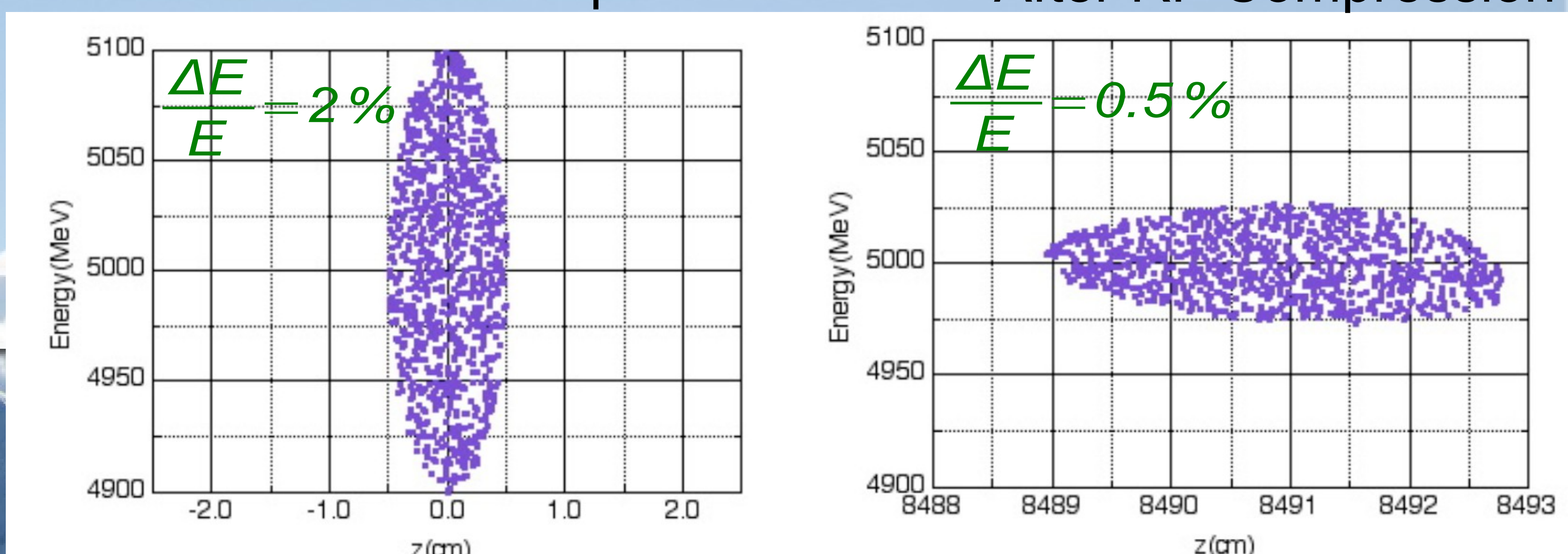
- Bunch length is 1ns at the exit of Electron gun.
- Velocity bunching to shorten the bunch length for RF acceleration.
- Acceleration by high gradient RF cavity for the whole bunch, compensates the velocity modulation and the beam becomes rigid.



Energy Compression (1)

- 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.

Before RF Compression   After RF Compression



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.

Laser for Photo-cathode

Laser for Photo-Cathode

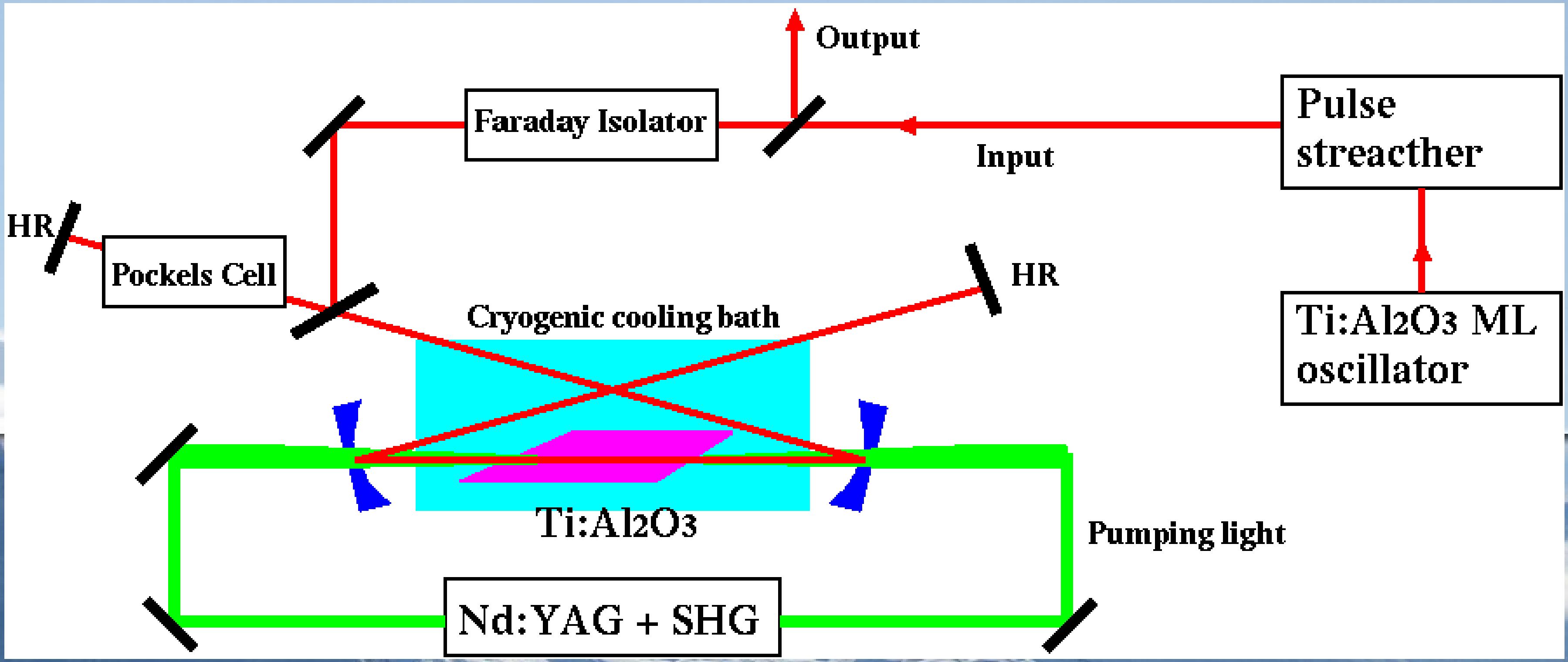
- Laser is one of the most important element of the photo-cathode gun.
- Beam properties depend on the laser.
  - Temporal structure : 3MHz repetition, 0.9 ms macro pulse.
  - Beam emittance : 10 μrad.
  - Polarization :circular polarization and tunable around 700nm.
- A laser system, which meets fully LC requirements, is not available commercially.
- Several candidates for ILC.
  - **Ti:Al_2O_3 : baseline**
  - **Yb fiber laser : possible alternative**

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 ms, which is not suitable to form a long macro pulse.

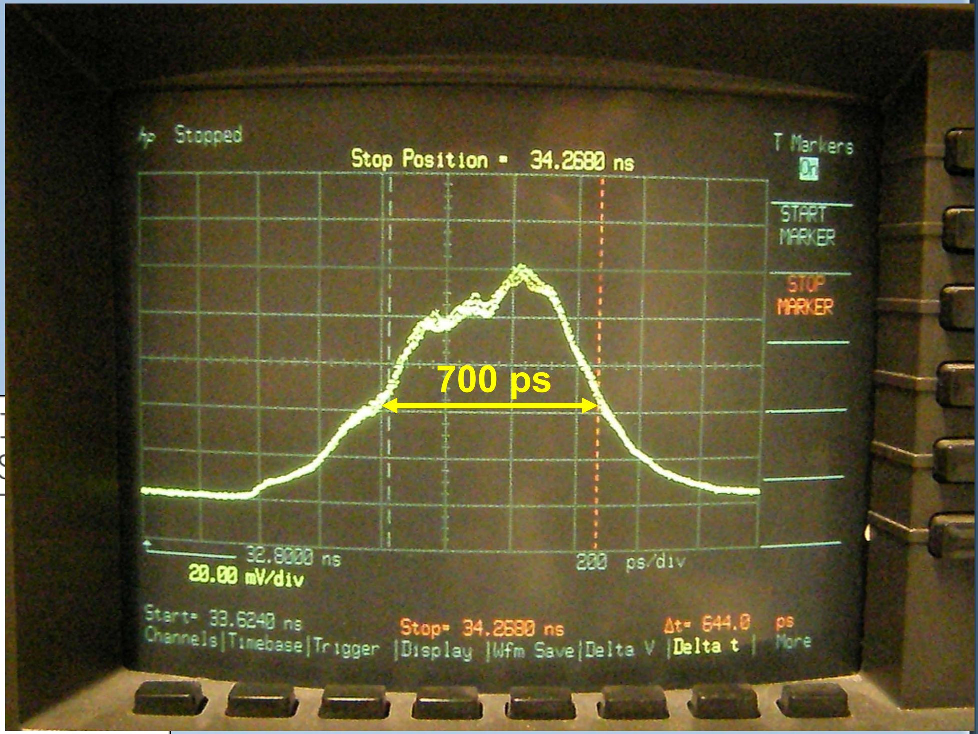
ILC Baseline Design

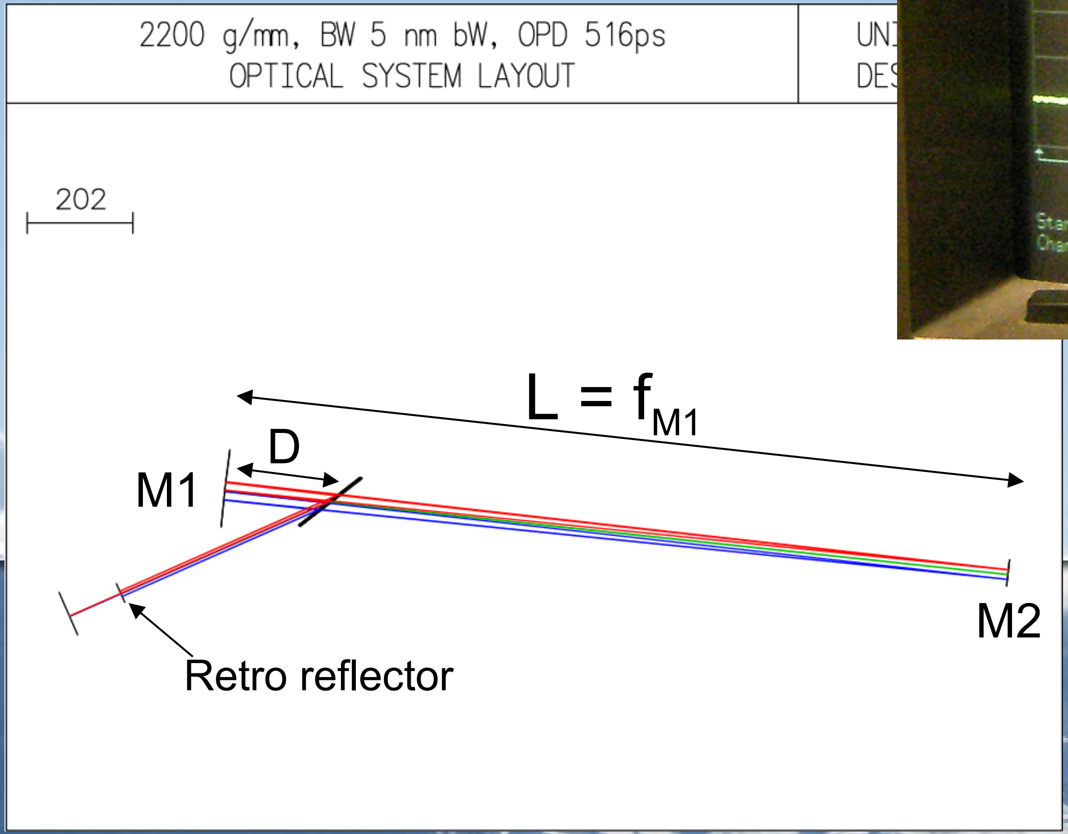
- $Ti:Al_2O_3$ mode lock + 3MHz pulse picker by Pockels cell makes a pulse train.
- Macro-pulse amplification by $Ti:Al_2O_3$ regenerative amplifier pumped by SH of Nd:YAG.
- Wave length is tunable. The stability is a challenging issue.



Pulse stretcher

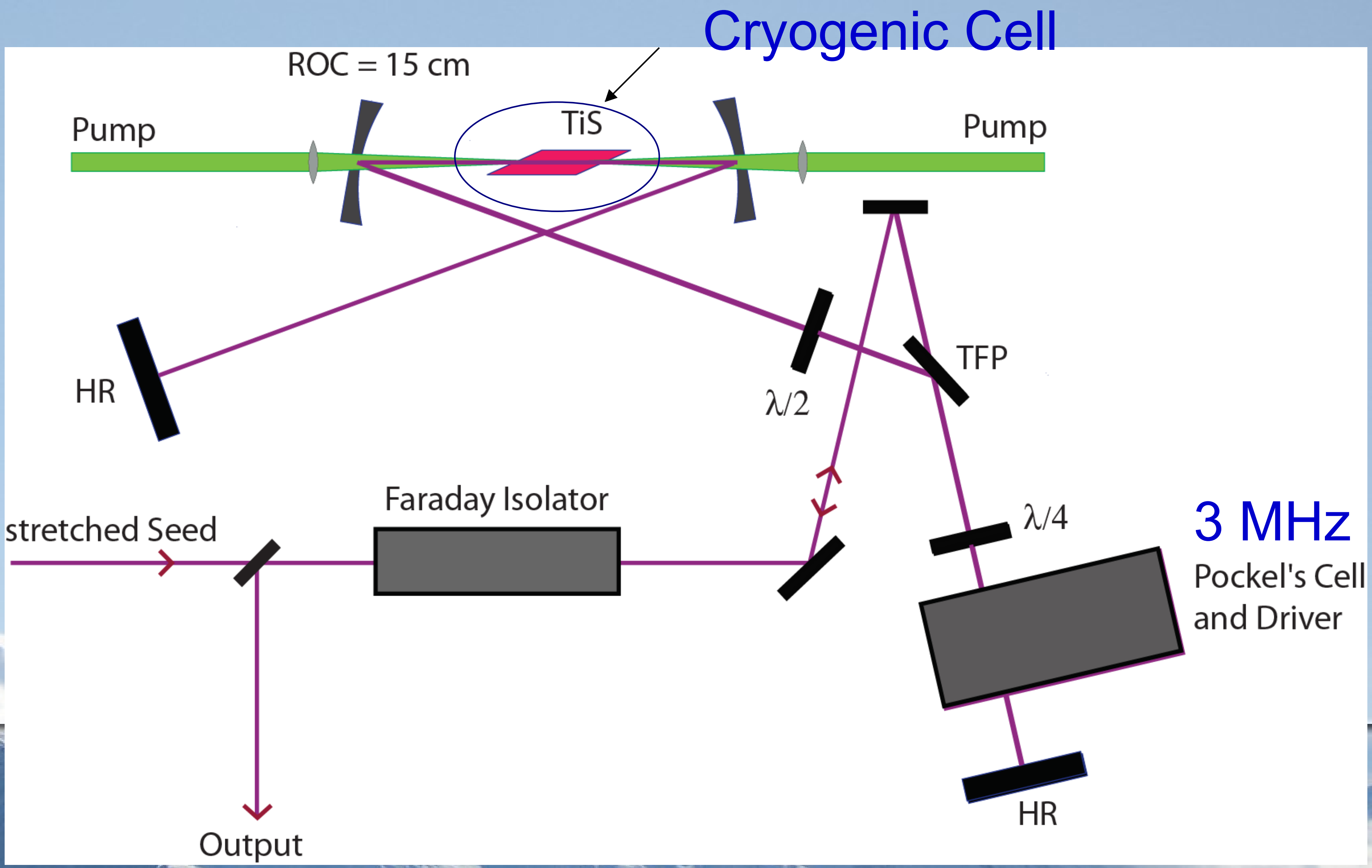
Pulse from Model-lock laser (200fs) is stretched to 1ns for ILC Bunch.





A. Brachmann

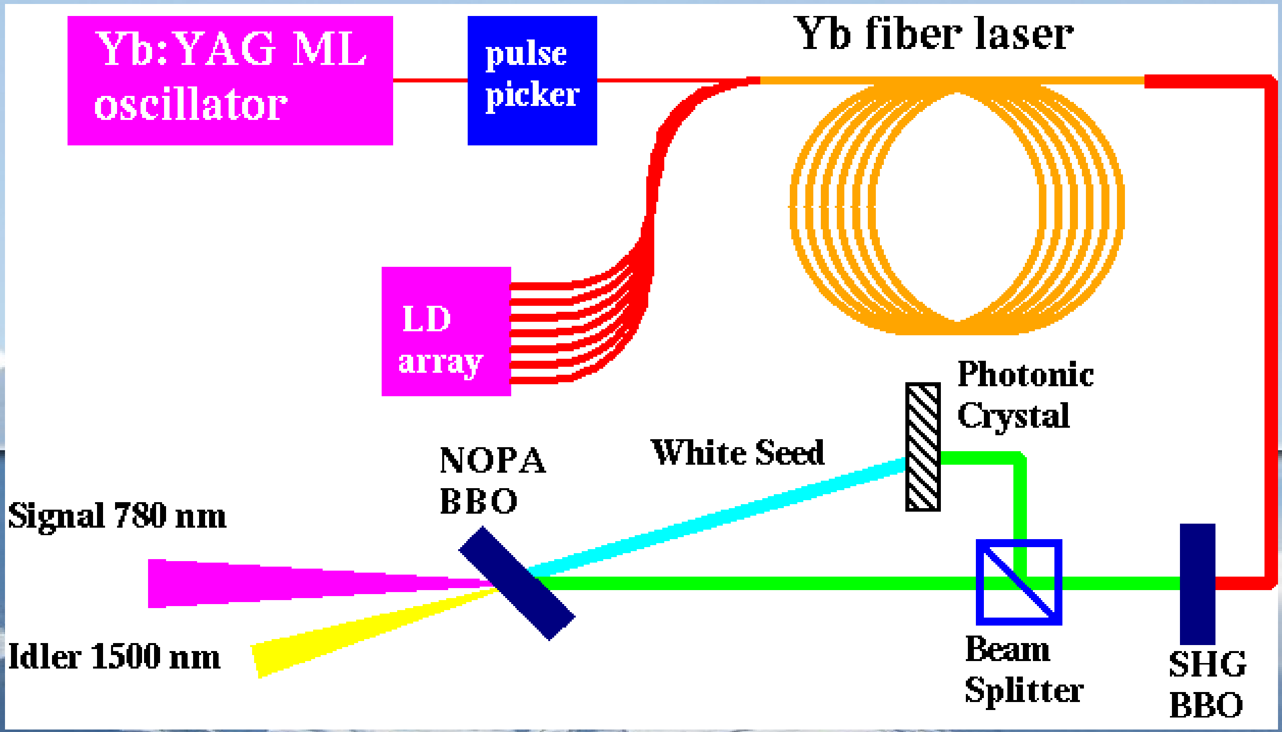
Regenerative Amplifier



A. Brachmann

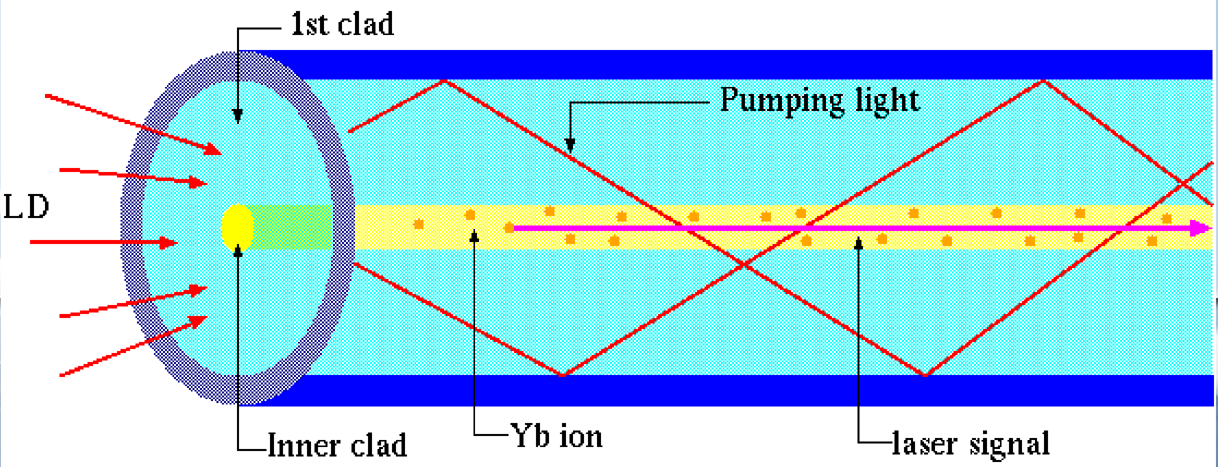
Yb:YAG fiber laser + OPA

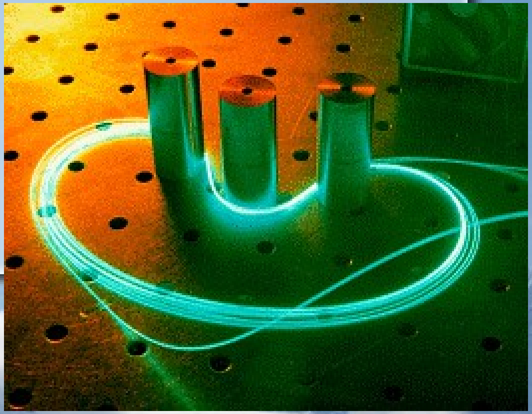
- Yb:YAG mode lock and Pockels cell Pulse Picker generate 3MHz pulse train.
- Yb: fiber laser amplifies the pulse train.
- NOPA (Non-collinear Optical Parametric Amplification) realize the wavelength tune-ability around 700nm.
- It could be LD pumped-full solid stable laser.



Yb fiber laser (1)

- Double clad-core optical fiber.
- Light from InGaAs LD (940nm) is introduce to 1st clad for pumping. Direct pumping by LD is very efficient and stable.
- Signal propagates in the inner core, where Yb ion is doped, and is amplified by stimulated emission.
- Due to the long structure, power density can be low and large limit on the high power operation.





J. Limpert

Yb fiber laser (2)

- The gain per length is low, but the propagation is quite efficient and the total gain can be quite high.
- High efficiency, low-loss, high-power, very stable.
- 2kW CW amplification is achieved.

J. Limpert,T. Schreiber, and A. Tünnermann, “Fiber based high power laser systems"

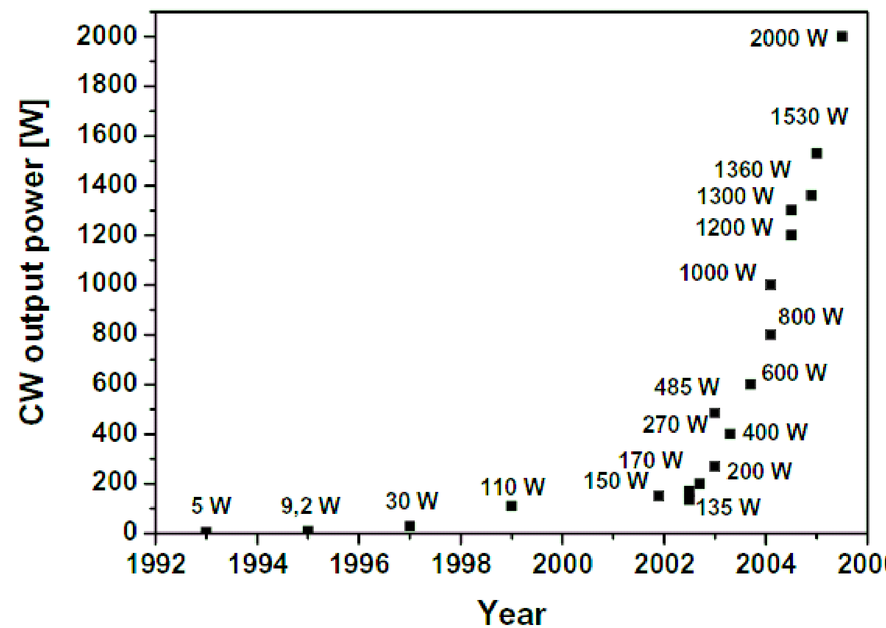


Fig. 4: Power evolution of cw double-clad fiber lasers with diffraction-limited beam quality over the last decade

Nonlinear Optics (1)

Non-linear polarization is induced by intense laser field in material. In usual linear regime, the electric polarization is

$$\mathbf{P}=\varepsilon_0\chi\,\mathbf{E} \qquad (5-1)$$

Non-linear polarization (up to second order) is

$$\mathbf{P}=\varepsilon_0\chi^{(1)}\mathbf{E}+\epsilon_0\left[\chi^{(2)}(2\omega=\omega+\omega)+\chi^{(2)}(0=\omega-\omega)\right]\mathbf{E}^2 \qquad (5-2)$$

Sum frequency   0 frequency

Second harmonics (2ω) and 0 frequency mode are induced. That corresponds to that second order of the fundamental mode is expressed with 2ω mode and 0 mode.

$$\mathbf{P}^{(2)}\propto\cos^2(\omega t)=\frac{1}{2}\cos(2\omega t)+\frac{1}{2} \qquad (5-3)$$

SH   0

Nonlinear Optics (2)

The phase velocity of polarization and SH is

$$v_1=\frac{2k_1}{2\omega}=\frac{n_1}{c} \qquad (5-4) \qquad\qquad v_2=\frac{k_2}{2\omega}=\frac{n_2}{c} \qquad (5-5)$$

k_1 and k_2 are wave number, n_1 and n_2 are refractive index. The phase velocity should be same for efficient SH generation, because the growth is expressed as

$$|E_2|^2=\frac{\omega_2^2}{4\epsilon_0^2 n_2^2 c^2}|P^{(2\omega)}|^2\frac{\sin^2\left(\frac{\Delta kz}{2}\right)}{\left(\frac{\Delta kz}{2}\right)^2}z^2 \qquad (5-6)$$

which is maximized by $\Delta k \equiv 2k_1 - k_2 = 0$, when the phase velocity is same for both modes. Usually, material shows normal dispersion, that $n_1 > n_2$ for $\omega_1 > \omega_2$ and the condition is never satisfied. It is satisfied only with birefringence material.

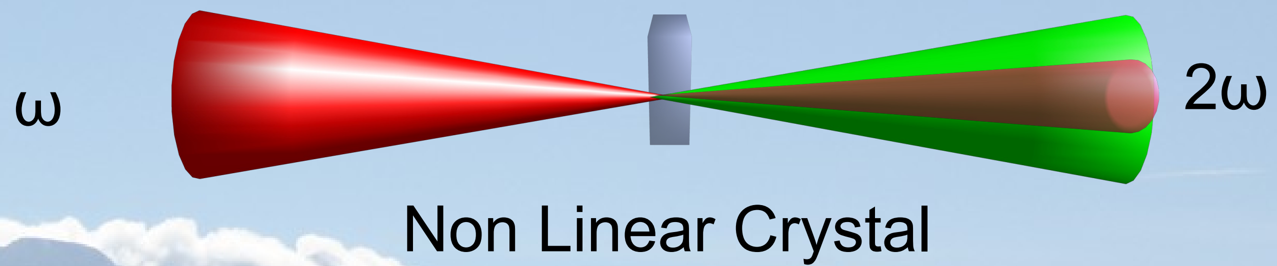
SHG: Second Harmonic Generation

By focusing laser light in birefringence material, second harmonics is generated.

$$\omega_1 + \omega_1 = \omega_2 \qquad (5-7)$$

The phase matching condition should be satisfied for efficient conversion.

$$n_1 \omega_1 + n_1 \omega_1 = n_2 \omega_2 \qquad (5-8)$$



OPA (1)

As reverse process of harmonic generation, high energy photon can be split into two low energy photons,

$$\omega_1 = \omega_2 + \omega_3 \qquad (5-9)$$

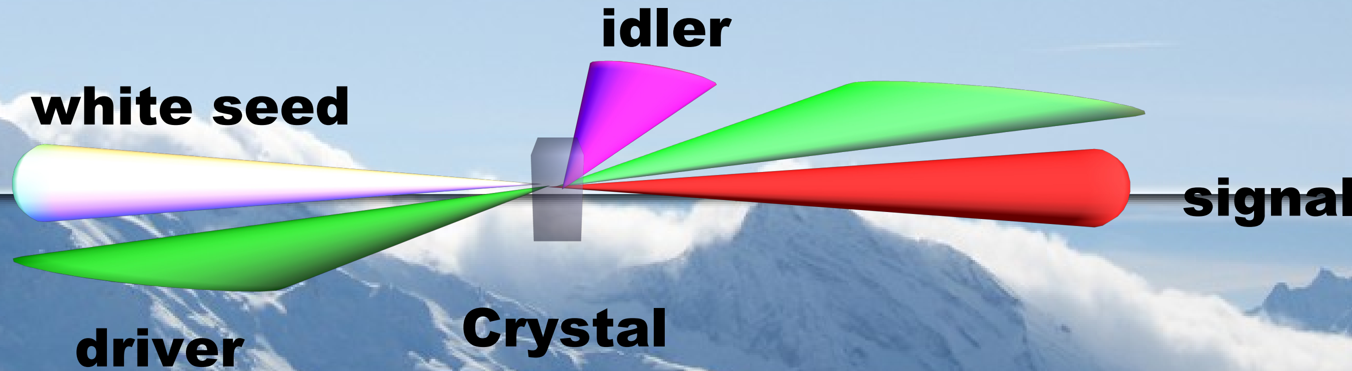
When intense ω_1 laser is given, ω_2 and ω_3 light are amplified. This is Optical Parametric Amplifier (OPA). The phase matching condition is

$$n_1 \omega_1 = n_2 \omega_2 + n_3 \omega_3 \qquad (5-10)$$

ω_1 is called as "driver" in OPA. When ω_2 is what we want (signal), ω_3 is called as "idler".

OPA (2)

- Yb fiber amplifier generate powerful pulse train in 1030nm.
- The fundamental mode is converted to SH, 515nm by SHG.
- The 515nm is driver in OPA. It can be converted to 800nm signal and 1500nm Idler.
- The phase matching condition can be modified by changing the angle between crystal axis and light direction. Wavelength is tune-abile.



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.
- The beam property depends on the emission process, external condition (surface field, etc.), beam transport and acceleration.

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