Electron Gun

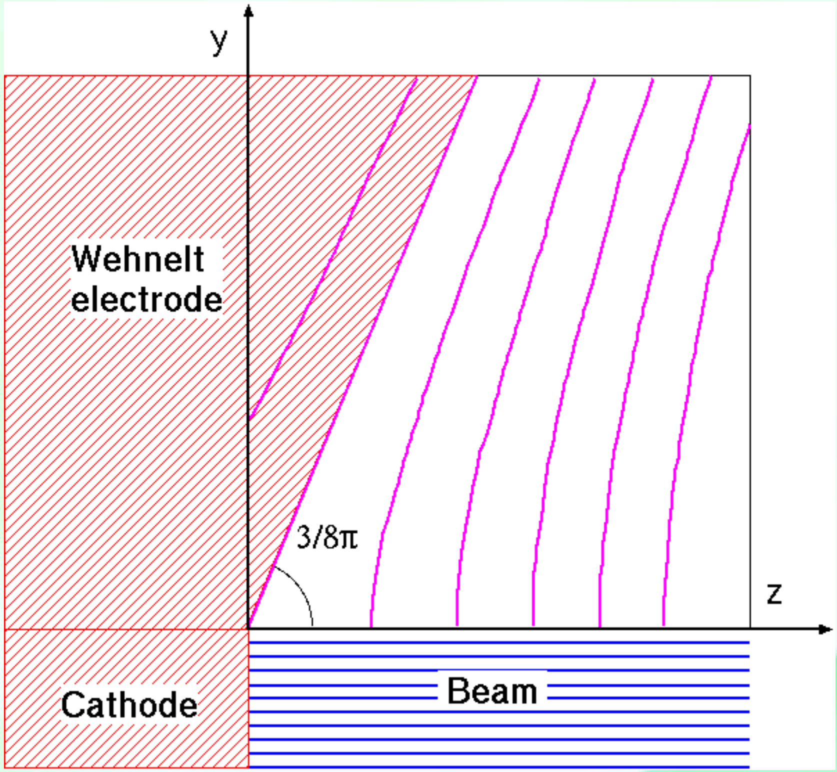
Electron Gun

	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 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 DC Gun

- Emission from a thermionic cathode is purely continuous.
- For primary bunch forming,
  - Grid control by triode structure
  - Pre-bunching by RF cavity (Pre-Buncher cavity)
- Sub Harmonic Buncher and/or Buncher are employed to shorten the bunch-length further.
- Any thermionic cathodes can not generate polarized electron.



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 melting point and vapor pressure. T_e is temperature, where the vapor pressure of the material is 1E-5 Torr and 10 atomic layers are lost per second.
- Figure of merit of thermionic cathode is

$$\eta = \frac{\phi}{T_e} \qquad (3-1)$$

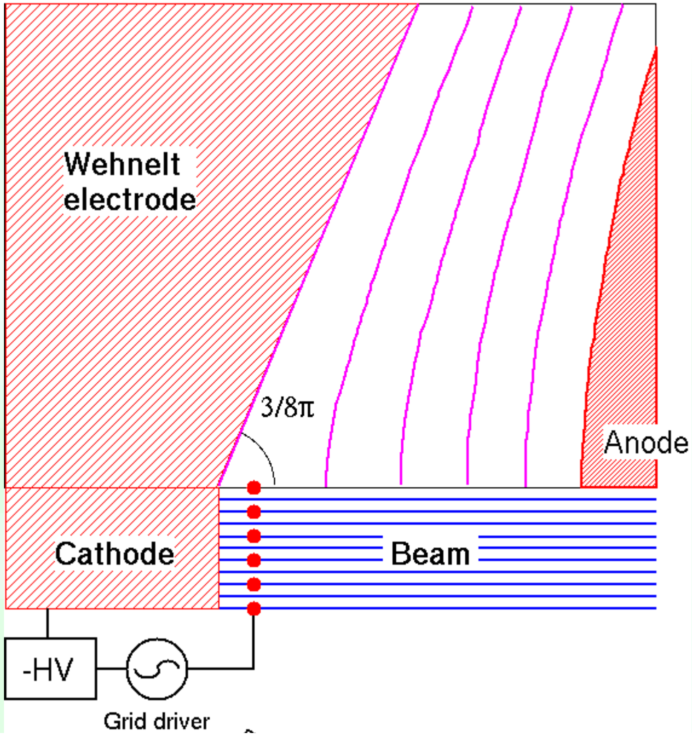
Thermionic Cathode

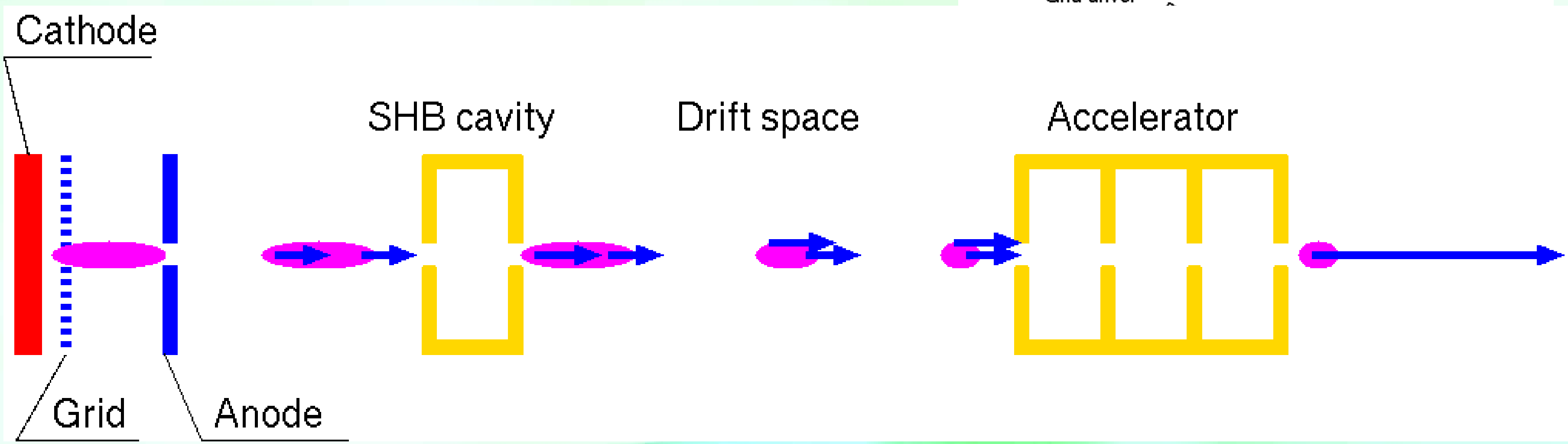
Material	ϕ (ev)	T_e (K)	ϕ/T_e(x1E+3)
W	4.5	2860	1.57
Ta	4.1	2680	1.53
Mo	4.2	2230	1.88
Cs	1.9	320	5.94
Th-W	2.6	1800	1.44
BaO	1.0	1400	0.71
CeB_6	2.5	1400	1.79
LaB_6	2.5	1400	1.79

- $\varphi/T_e<2.0$ 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.

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.





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 by the velocity modulation. The bunch repetition is determined by Pre-Buncher frequency.
- Further bunching is made by SHB and Buncher.

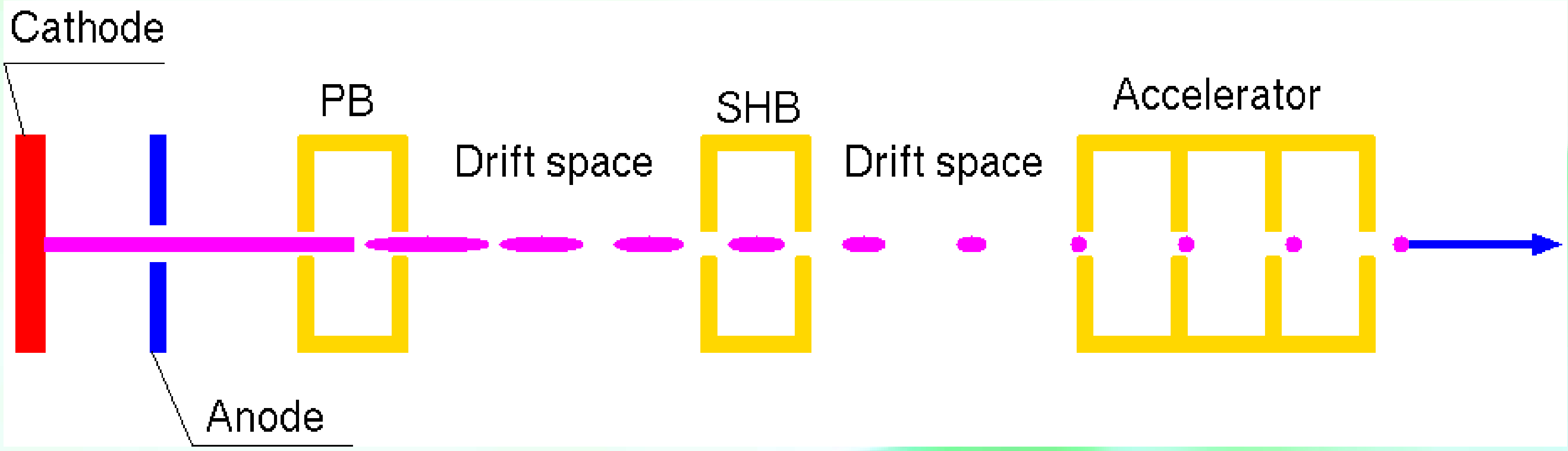
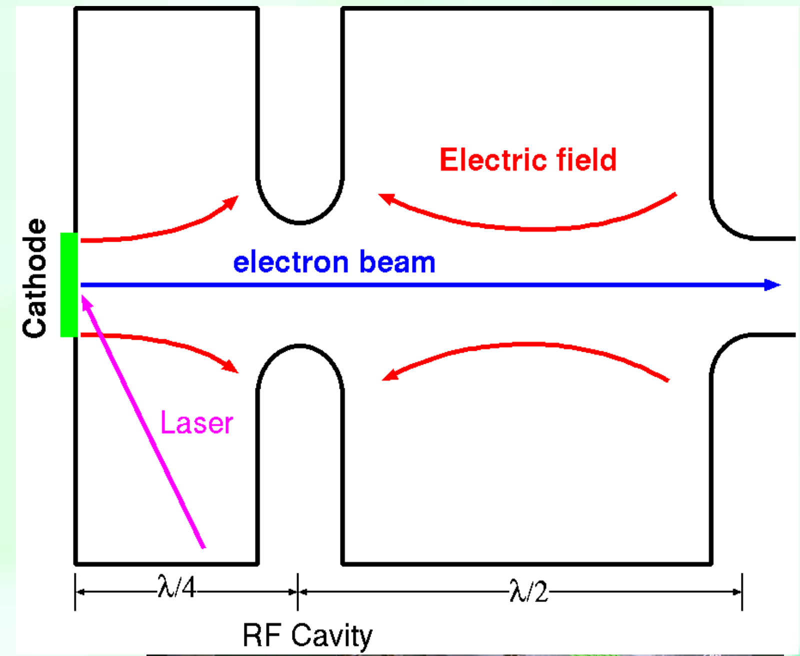
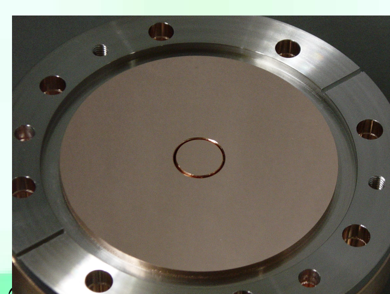


Photo-Cathode RF Gun (1)

- Short bunch electron beam is generated by ps 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.





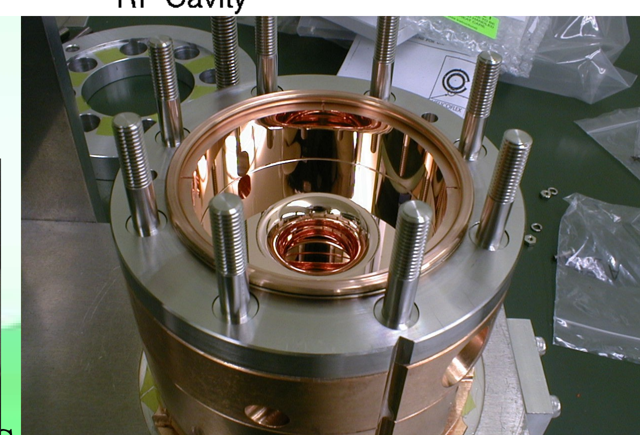
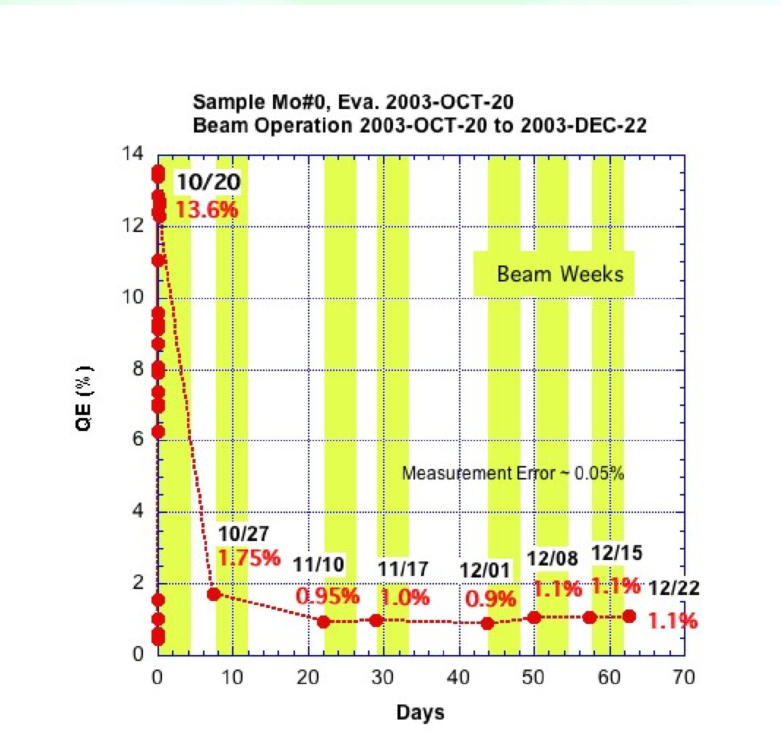


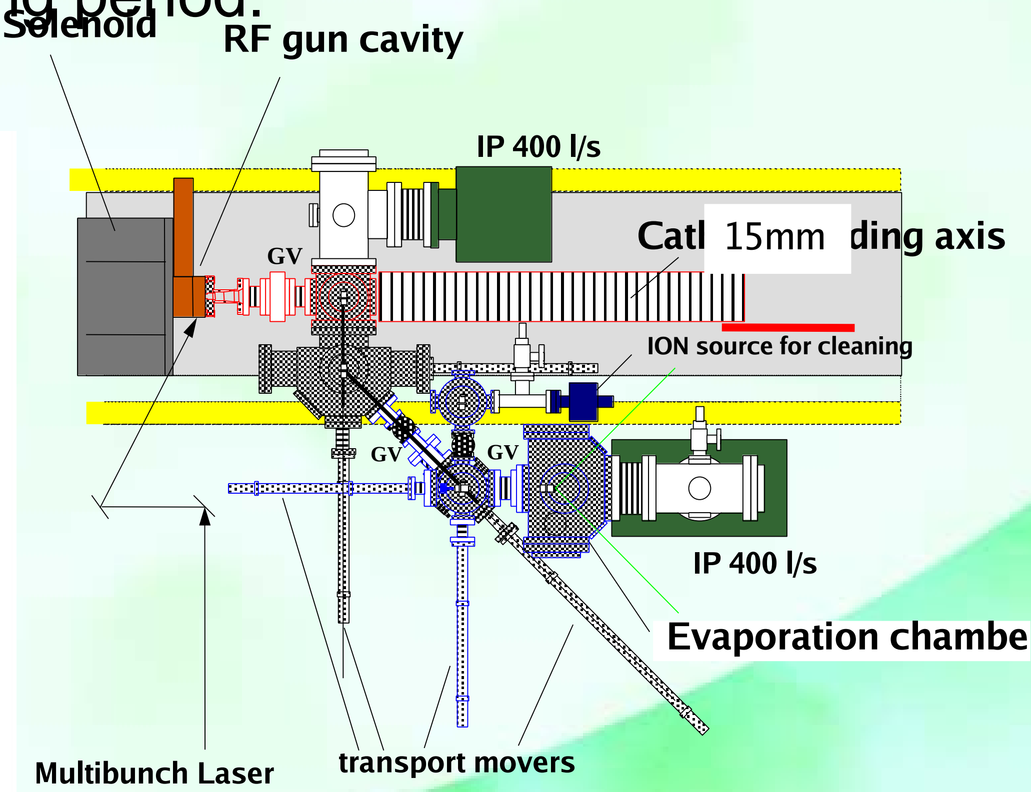
Photo-cathode RF Gun (2)

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

Photo-cathode RF Gun (3)

- CsTe cathode is made on Mo base plug by evaporation in a vacuum chamber.
- Load-lock transfer system in vacuum.
- 1% QE is kept for a long period.





N. Terunuma

Photo-cathode RF Gun (4)

Pockels cell
KD*P crystal
7kV maximum
Rise&Fall time <3nsec

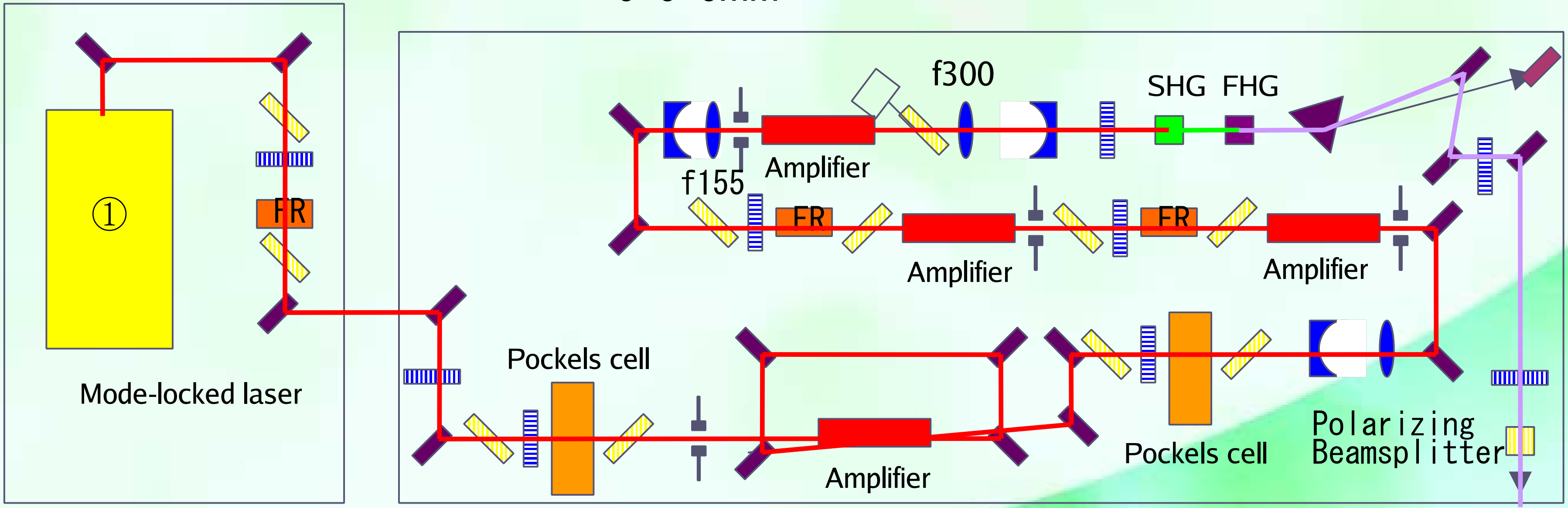
Fast Pockels cell
3.4kV maximum
Rise time : < 1nsec
Double Pockels Cell

Nd:YVO_4
357MHz mode-locked,
1064nm, 410mW(CW),
7.2ps(FWHM)

SHG
CASIX, β -BBO
6×6×6mm

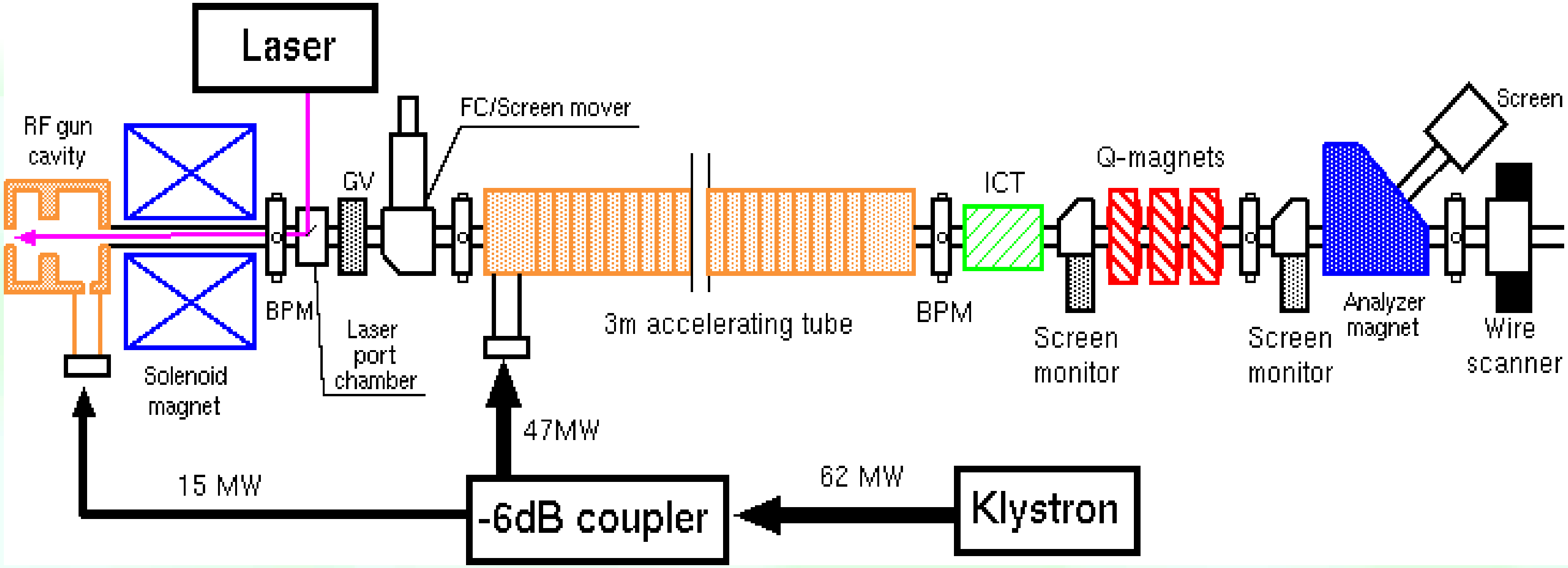
FHG
CASIX,β -BBO
6×6×6mm

UV light:
12ps(FWHM)
10μJ/pulse



to RF gun

RF Gun: A Typical configuration



- Multi-bunch laser: 1-20, 2.8ns spacing
- Bunch charge : 1-3nC/bunch
- $\varepsilon_{nx,y}$: 5μm
- Energy :80±0.8~2.4 MeV

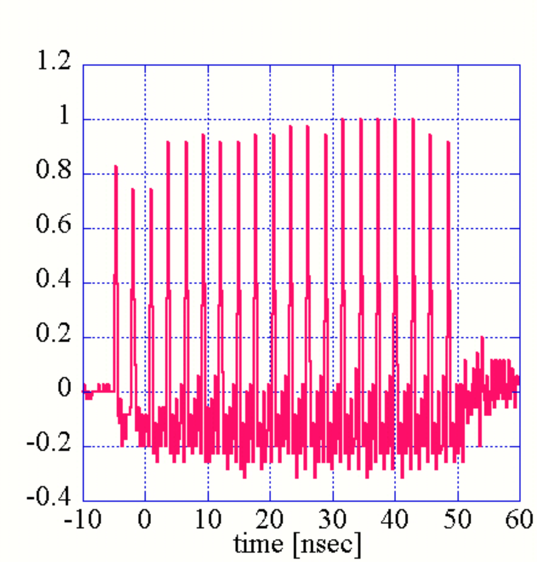


Photo-Cathode DC Gun (1)

- 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 the candidate for ILC and CLIC.
- The bunch structure (repetition and duration) is determined by the laser.

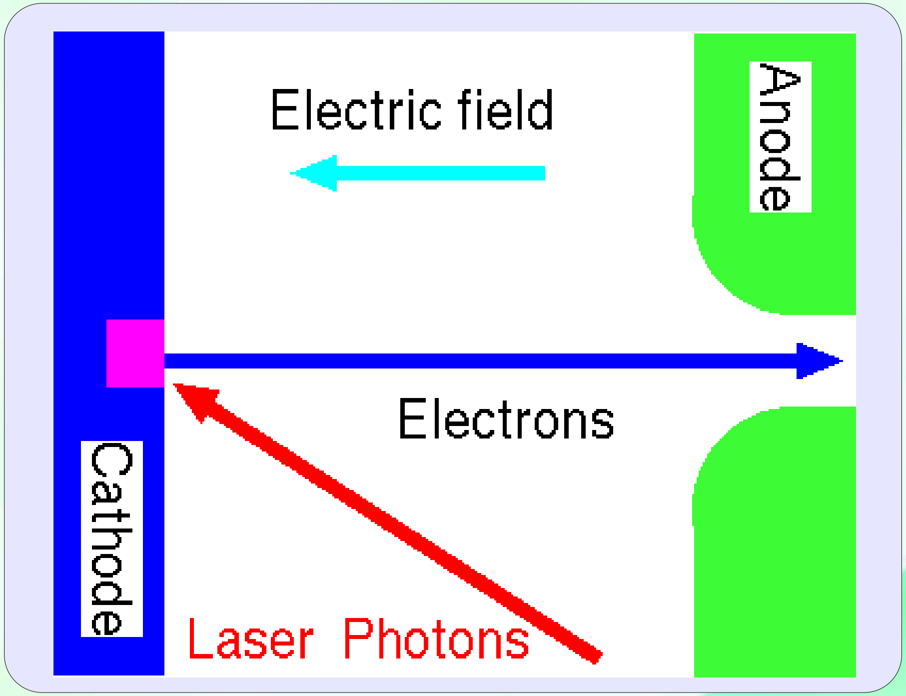
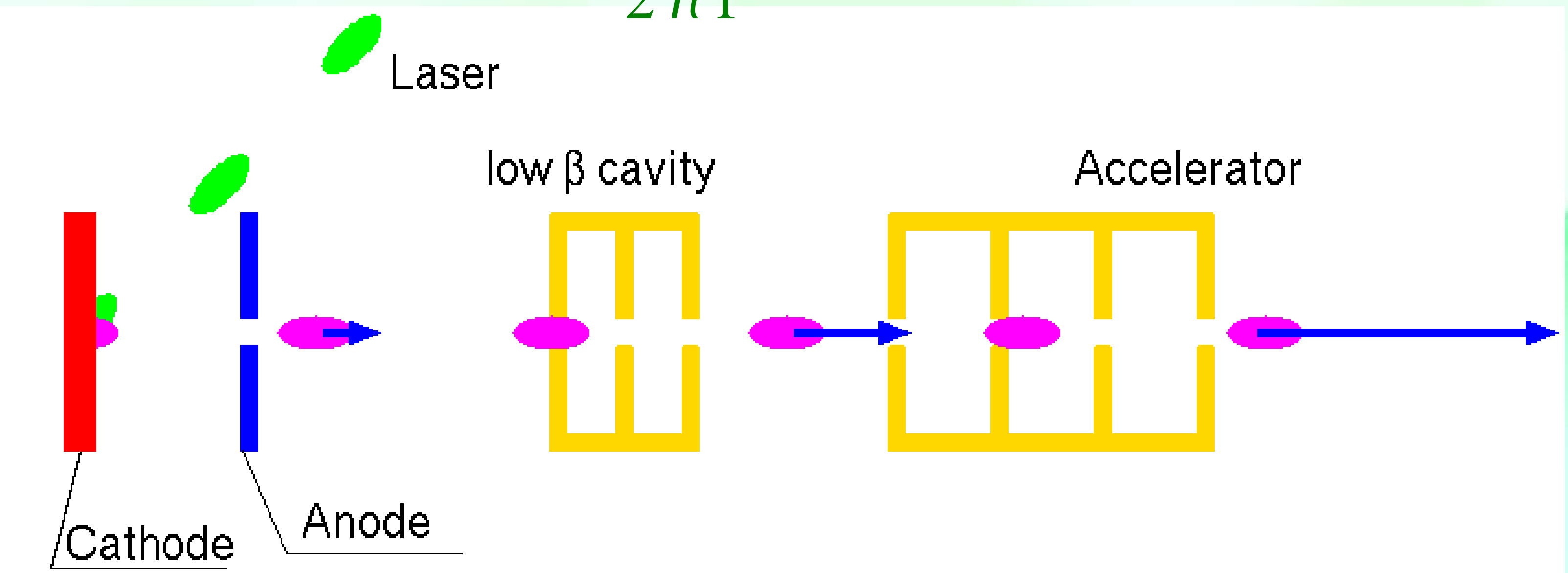


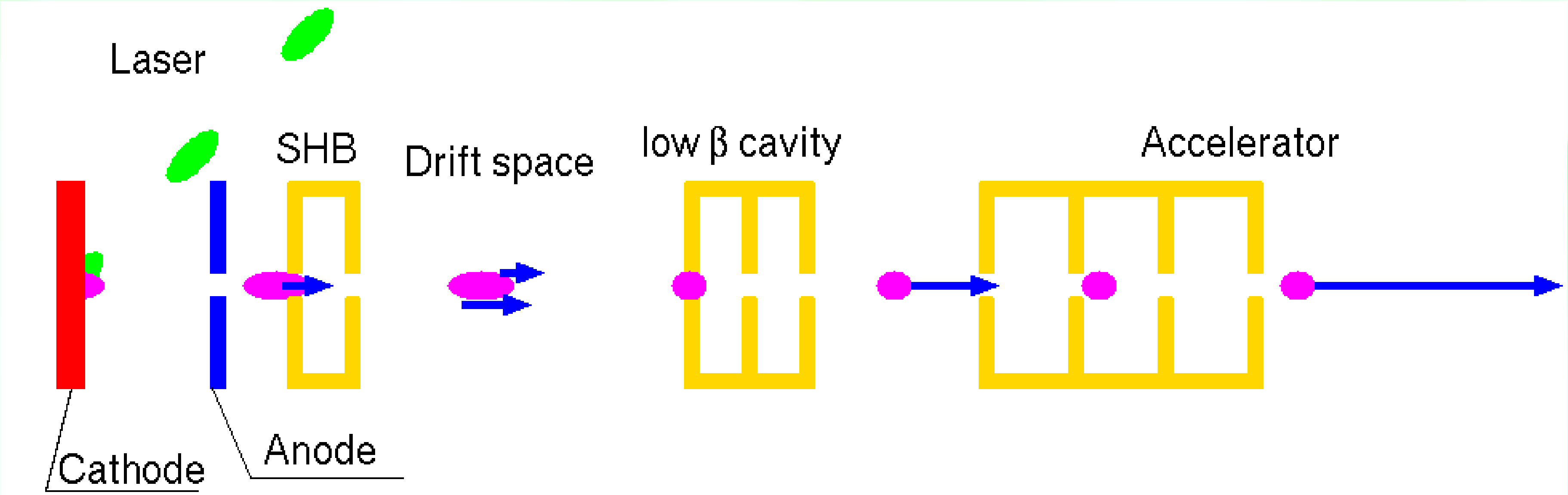
Photo-Cathode DC Gun (2)

- The bunch structure (repetition and duration) is determined by the laser.
- 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.

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



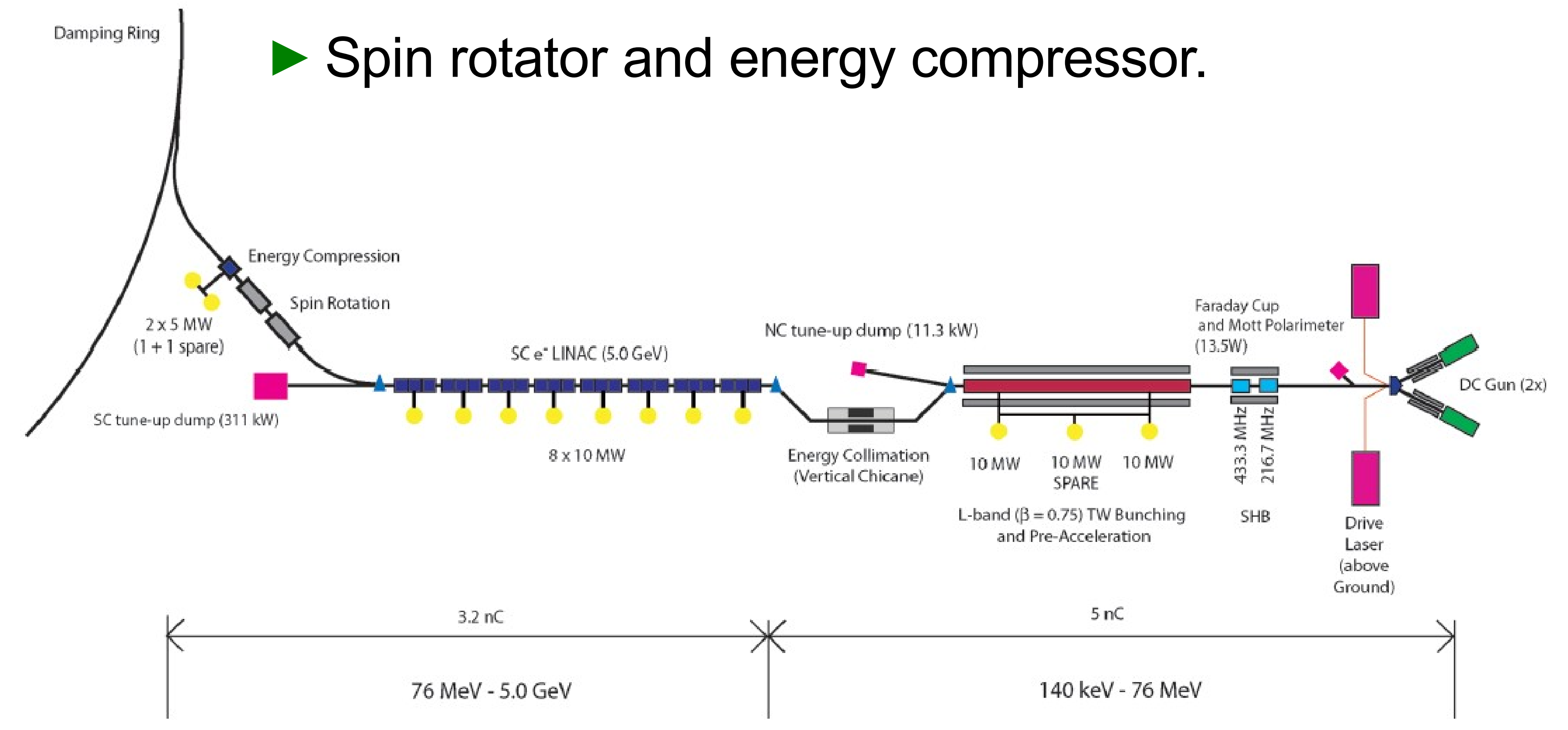
- ► In some case, SHB is placed for bunching.
- ► Low-beta cavity followed by accelerator.



Electron Source for Linear Colliders

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.



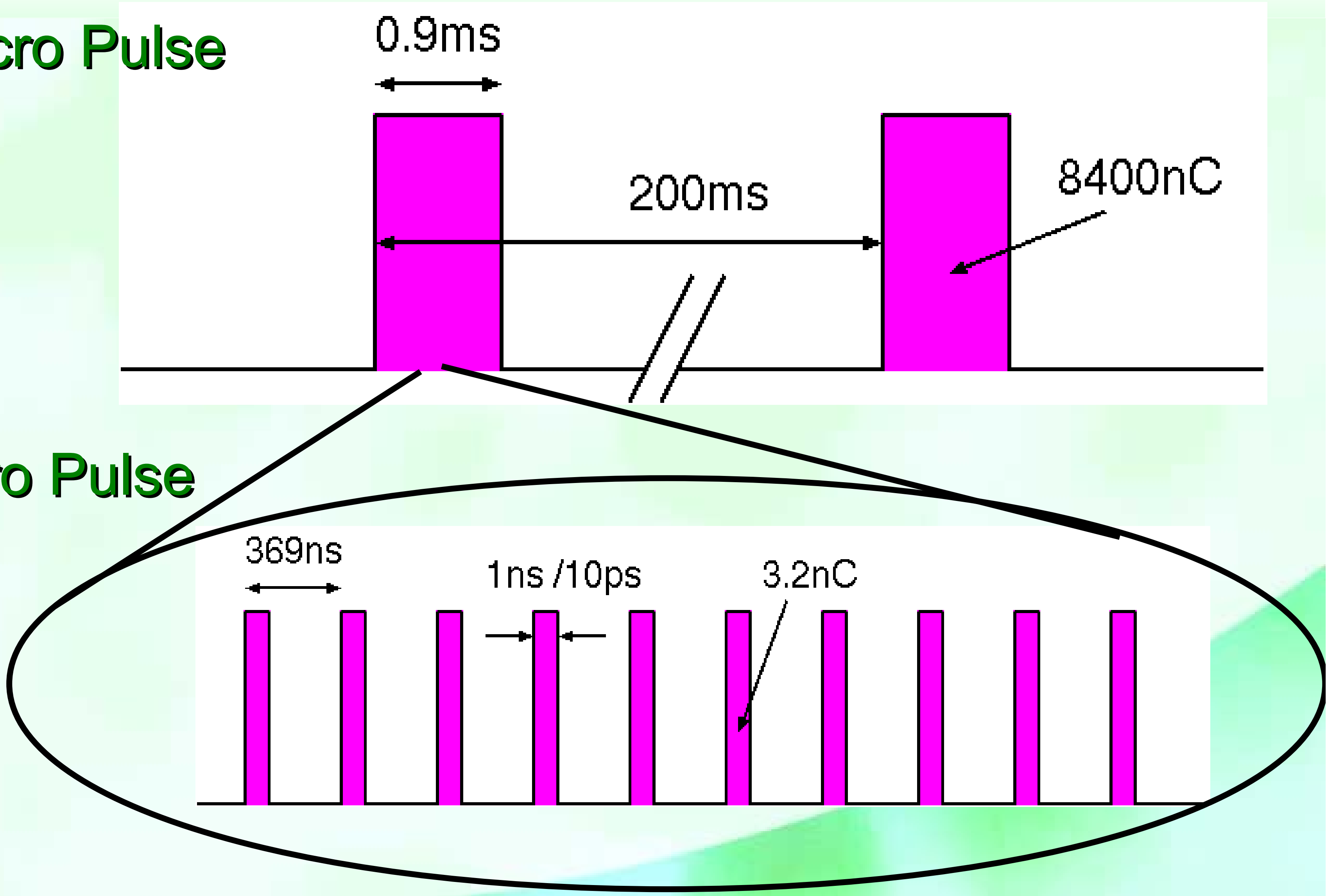
ILC Requirements

Parameters	
Pulse length	0.9ms
Pulse reputation	5Hz
# of micro bunches in a pulse	2625 (1310)
Bunch separation	369(670)ns
Bunch charge	3.2nC
Micro bunch length at source	1ns
Peak current	3.2A
Electron Polarization	80%

Pulse structure

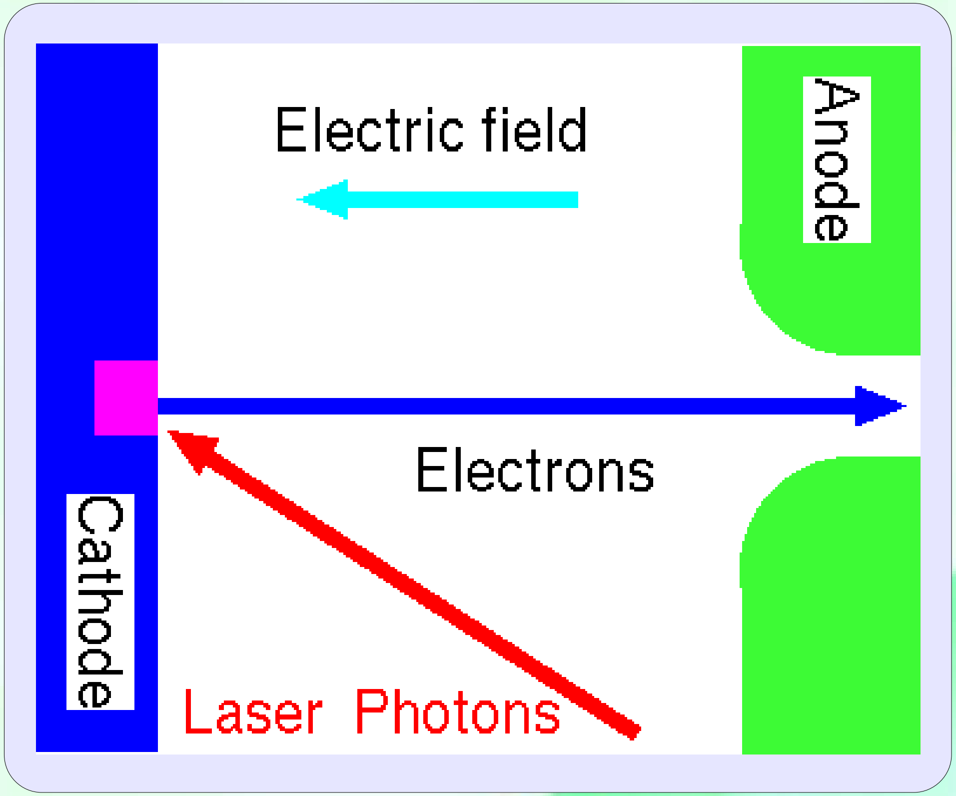
Macro Pulse

Micro Pulse



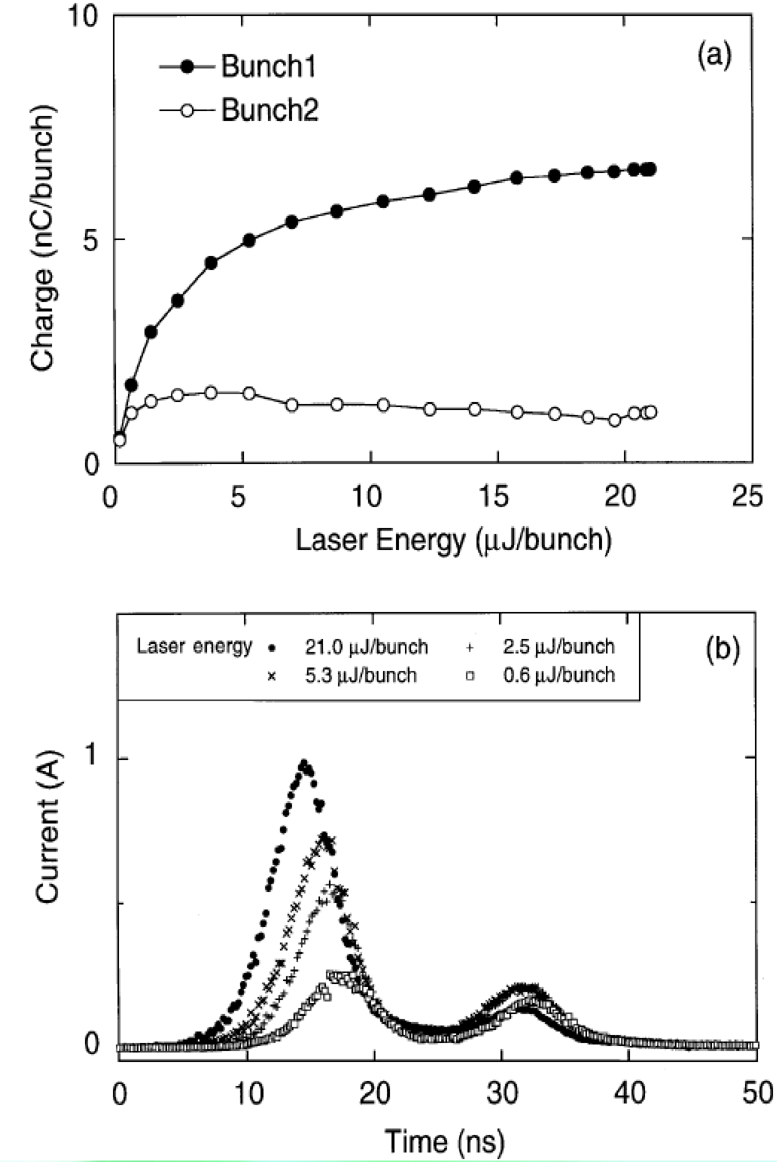
Basic Concept

- Circularly polarized photons are injected to NEA GaAS cathode; polarized electrons are generated.
- Beam extraction by a static electric field, 120-200kV.
- The extraction current is limited up to 3.1A by space charge, 1.1ns for 3.2nC.



Surface Charge Limit (1)

- For Linear colliders, multi-bunch electron beam should be generated.
- Anomalous charge limit phenomena is observed (Surface Charge Limit) for high intensity beam generation.
  - The emission current is limited with high-intensity laser.
  - This suppression is more serious on multi-bunch generation, because this effect looks "additive".

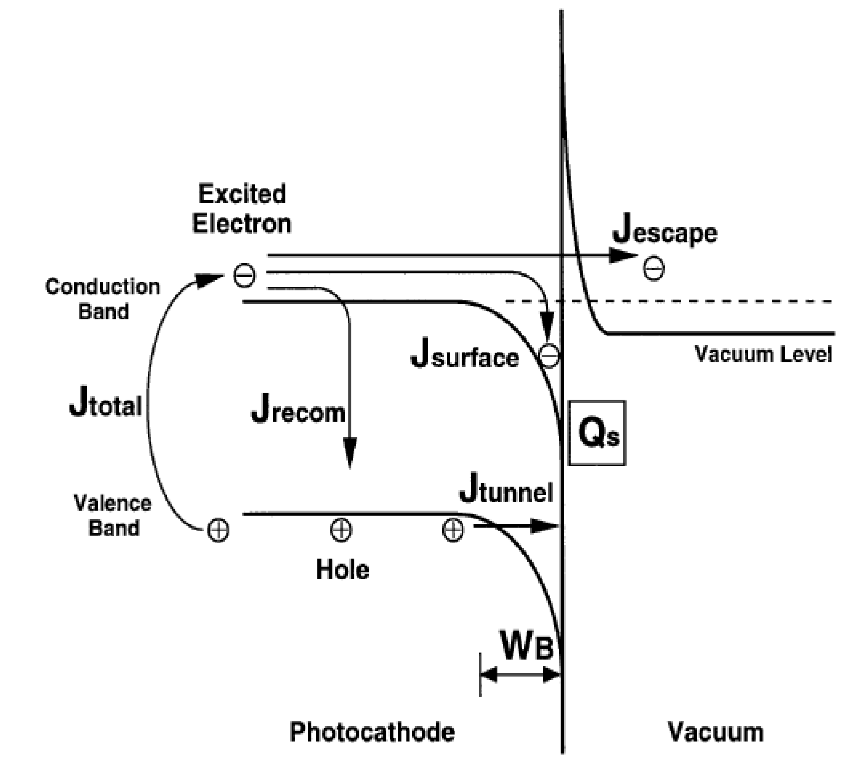


K. Togawa, NIM A 414 (1998) 431-445

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

Surface Charge Limit (2)

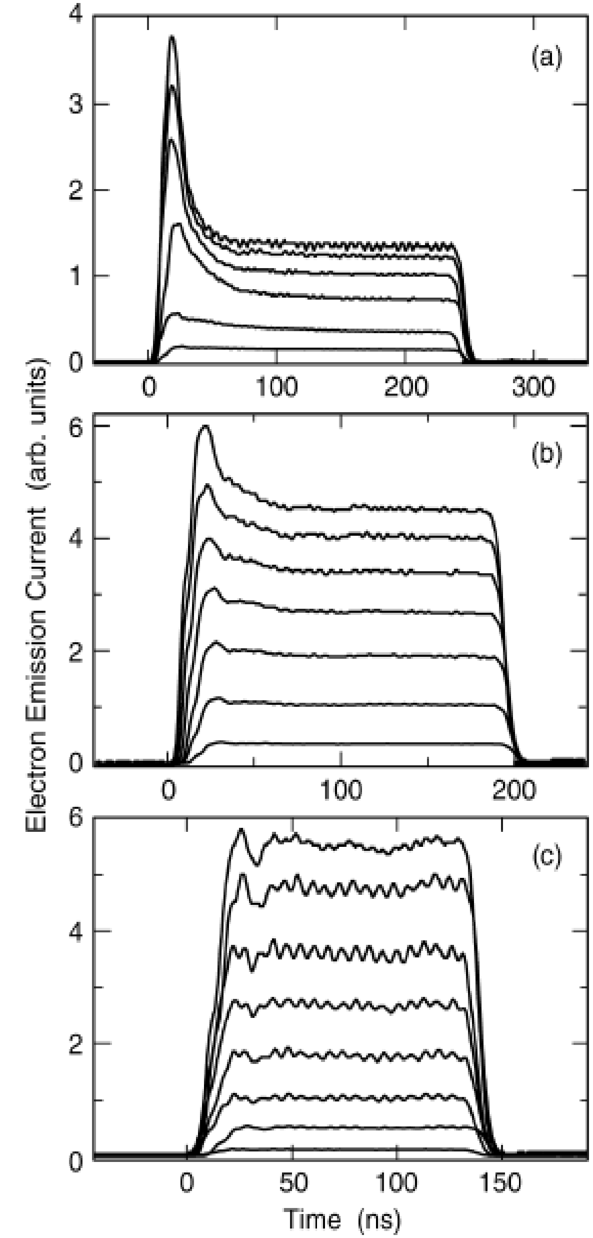
- The surface charge limit is caused by Photo-voltage effects;
  - Some part of emitted electron, $J_{surface}$ is captured at BBR(Band Bending Region).
  - Due to the potential by the captured electron, the effective vacuum level is increased.
- Emission probability, J_{escape}/J_{total} is proportional to size of EA; Photo-voltage effects decrease size of EA and limit the current.



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

Surface Charge Limit (3)

- SCL can be compensated by enhancement of the recombination between the captured electron and hole in VB.
- It is realized by increasing the positive carrier density in VB with high p-doping density.
  - P-doped (Be) GaAs demonstrates that SCL is overcome.
- Finally, 5.0A/cm² is achieved. It is more than the requirement of ILC gun.

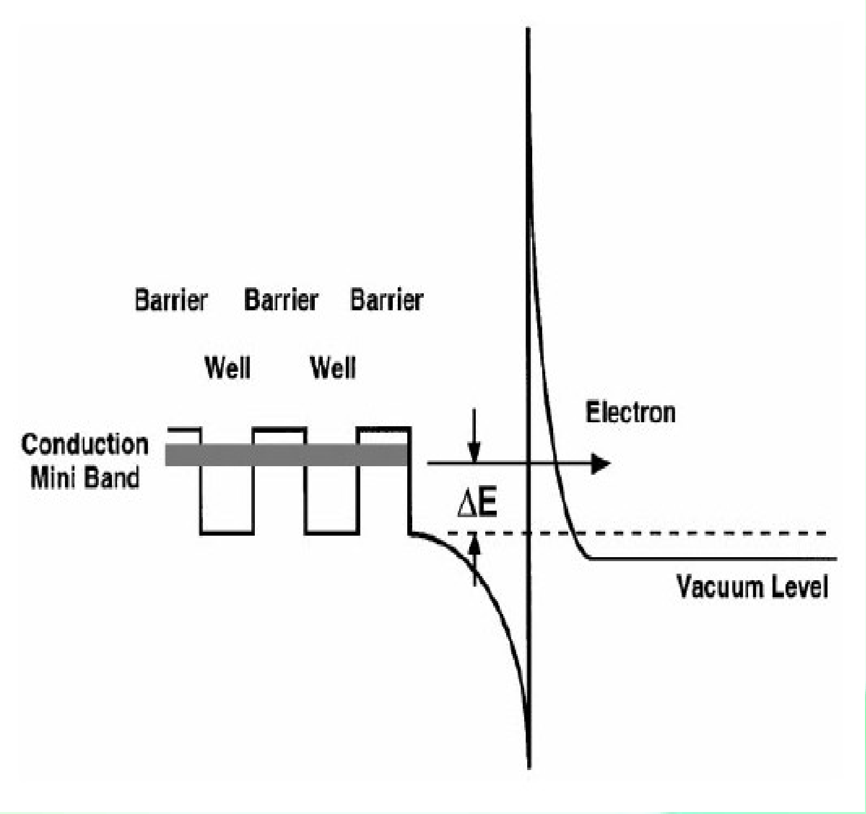


(a) sample 1b(Na=0.5), (b) sample 2a(Na=1.0), and (c) sample 3(Na=2.0). The laser intensity is 1 to 150 W/cm2.

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

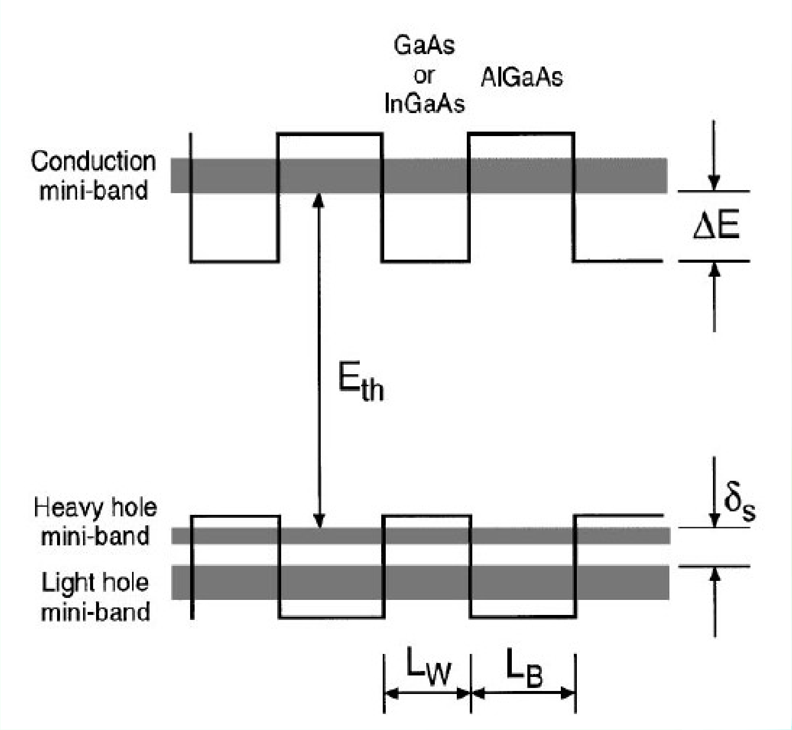
Surface Charge Limit (4)

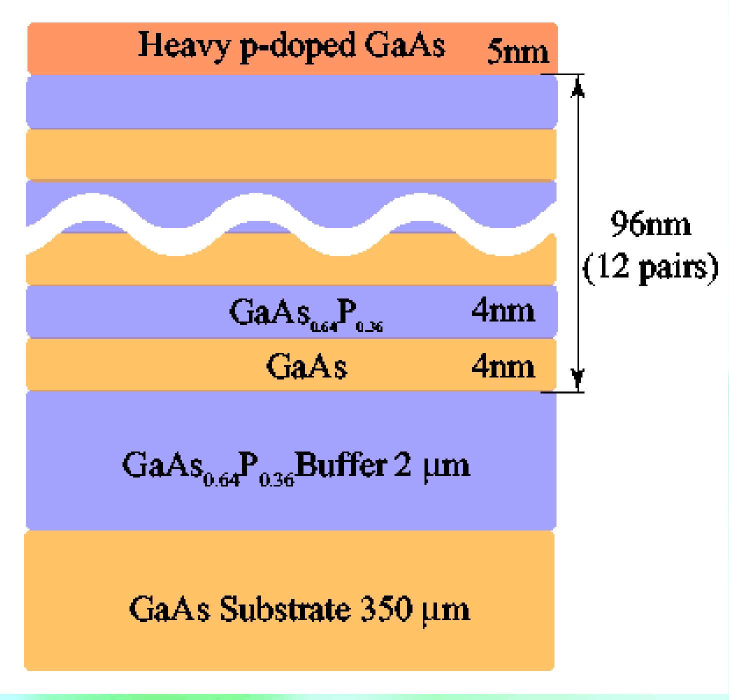
- Super-lattice Cathode has an advantage against SCL.
  - J_{escape} is proportional to the size of NEA.
  - The effective size of NEA in Super-lattice cathode is larger than that of bulk-GaAs.
  - The escape probability, $J_{esacape}/J_{total}$ is larger for Super-lattice cathode. SCL current should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



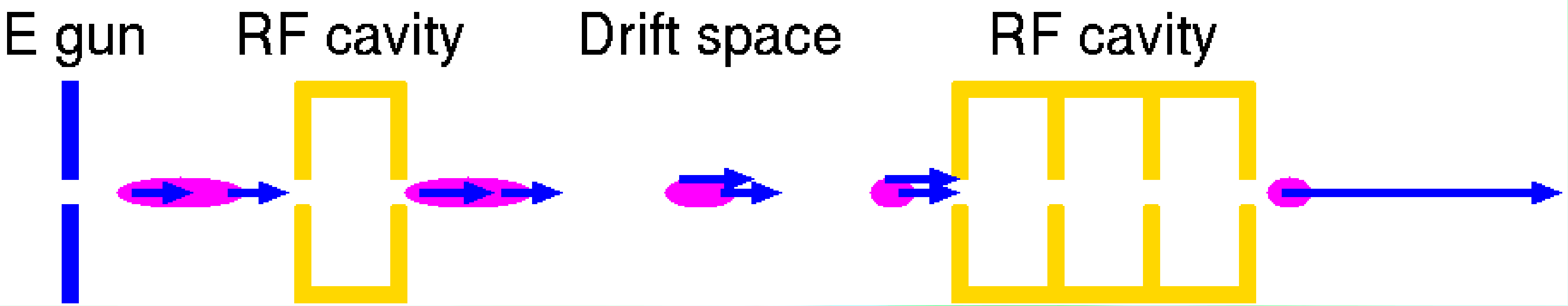


Bunching(1)

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

Bunching (2)

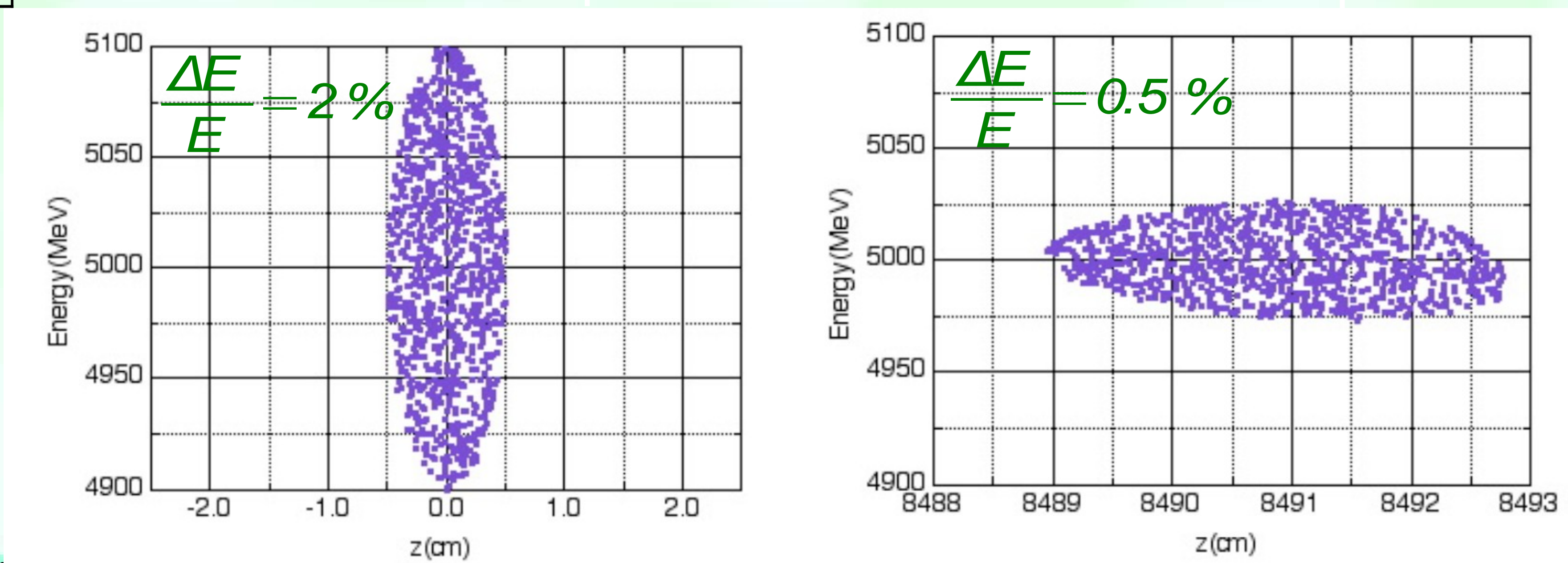
- Bunch length is 1ns at the exit of Electron gun.
- Velocity bunching to shorten the bunch length for RF acceleration.
- Acceleration by high gradient RF cavity for the whole bunch, compensates the velocity modulation and the beam becomes rigid.



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



Energy Compression (2)

Introduction
Electron Emission
Related Physics
Electron Gun
e- Source for LCs
Laser
Summary

Energy compression is almost a reverse process of the bunch compression. Dispersive section rotates the bunch by angle determined by R_{56}. Energy modulation by RF is characterized with R_{65}. Total transfer matrix is

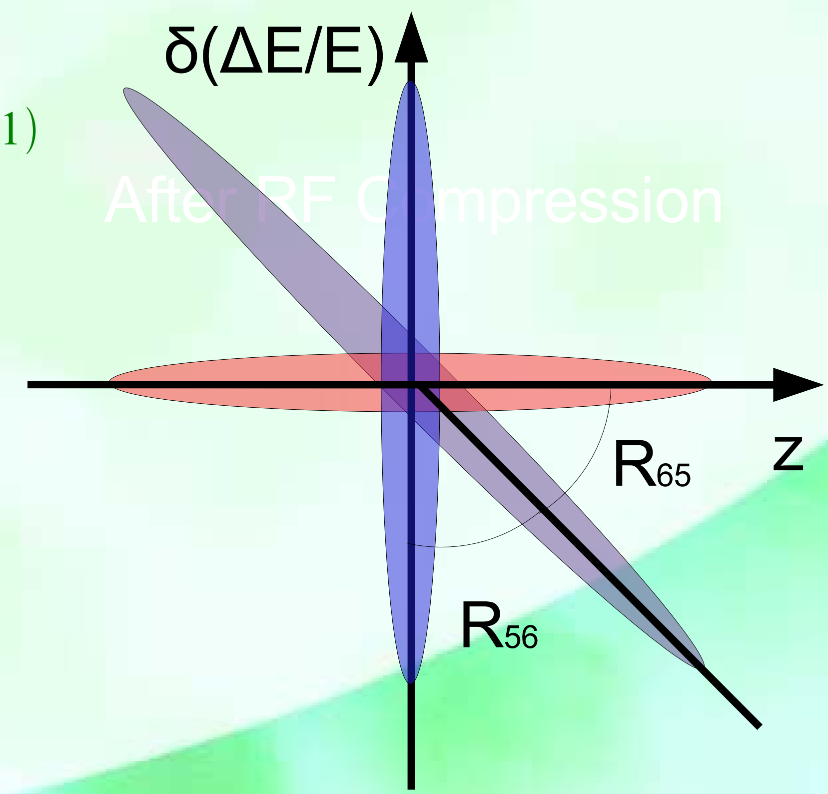
$$\begin{bmatrix} z(s_2) \\ \delta(s_2) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} 1 & R_{56} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} z(s_0) \\ \delta(s_0) \end{bmatrix} = \begin{bmatrix} 1 & R_{56} \\ R_{65} & 1+R_{56}R_{65} \end{bmatrix} \begin{bmatrix} z(s_0) \\ \delta(s_0) \end{bmatrix} \quad (4-1)$$

Matching condition for energy compression is

$$1+R_{56}R_{65}=0 \quad (4-2)$$

The final energy spread is

$$\delta(s_2)=z(s_0)R_{65} \quad (4-3)$$



HV Operation (1)

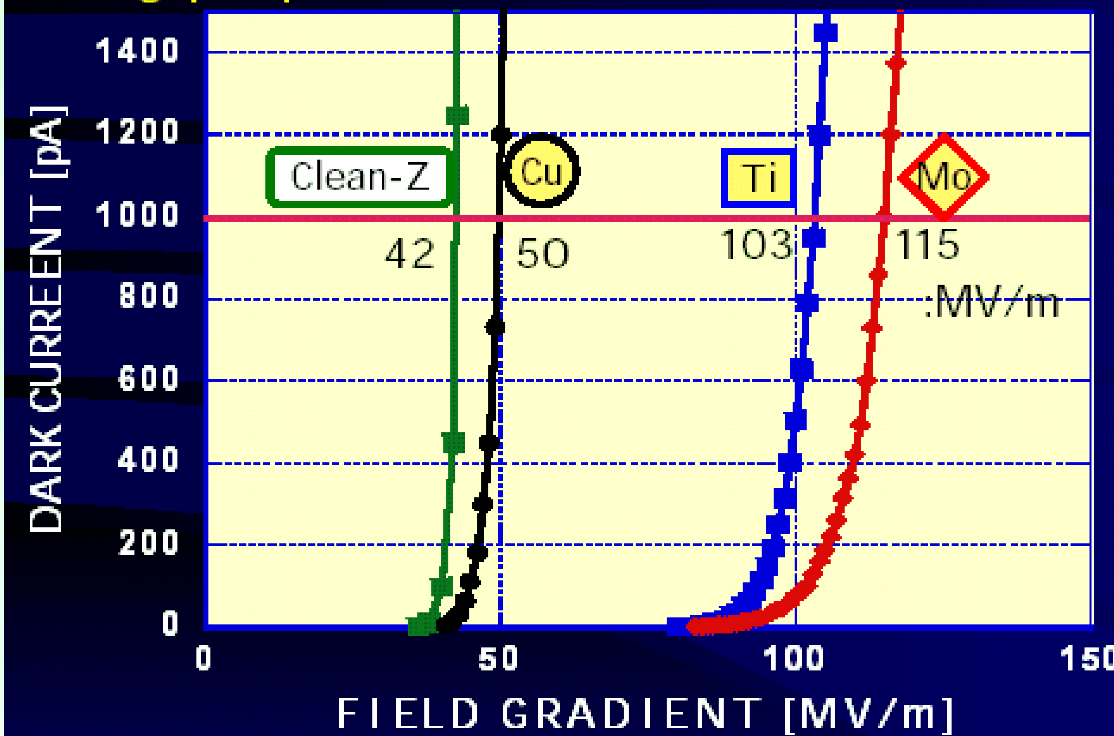
- Instead of the energy compressor, shorter bunch length in accelerator make the energy spread after acceleration smaller.
- Since the bunch length at the gun exit is determined by the space charge limit, higher voltage operation makes a higher peak current and bunch length can be shorter.
- Short bunch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

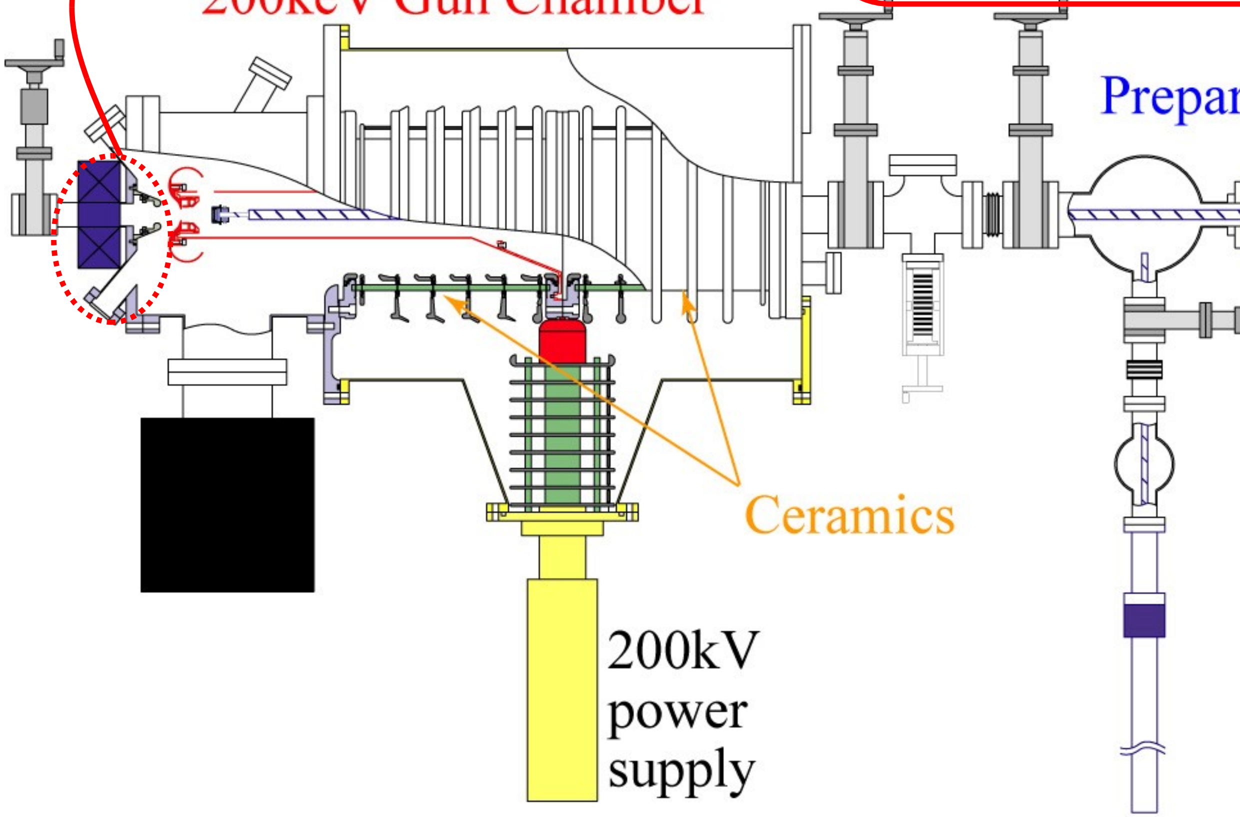
A point to note ...

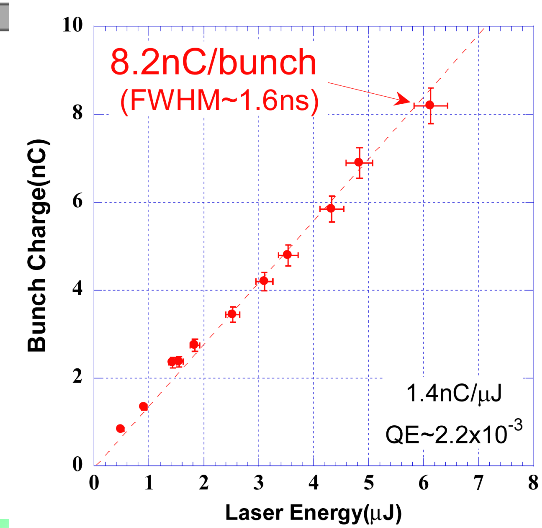
Only 7mm^2 area exposed maximum field gradient.

ILCWS2005, Snowmass

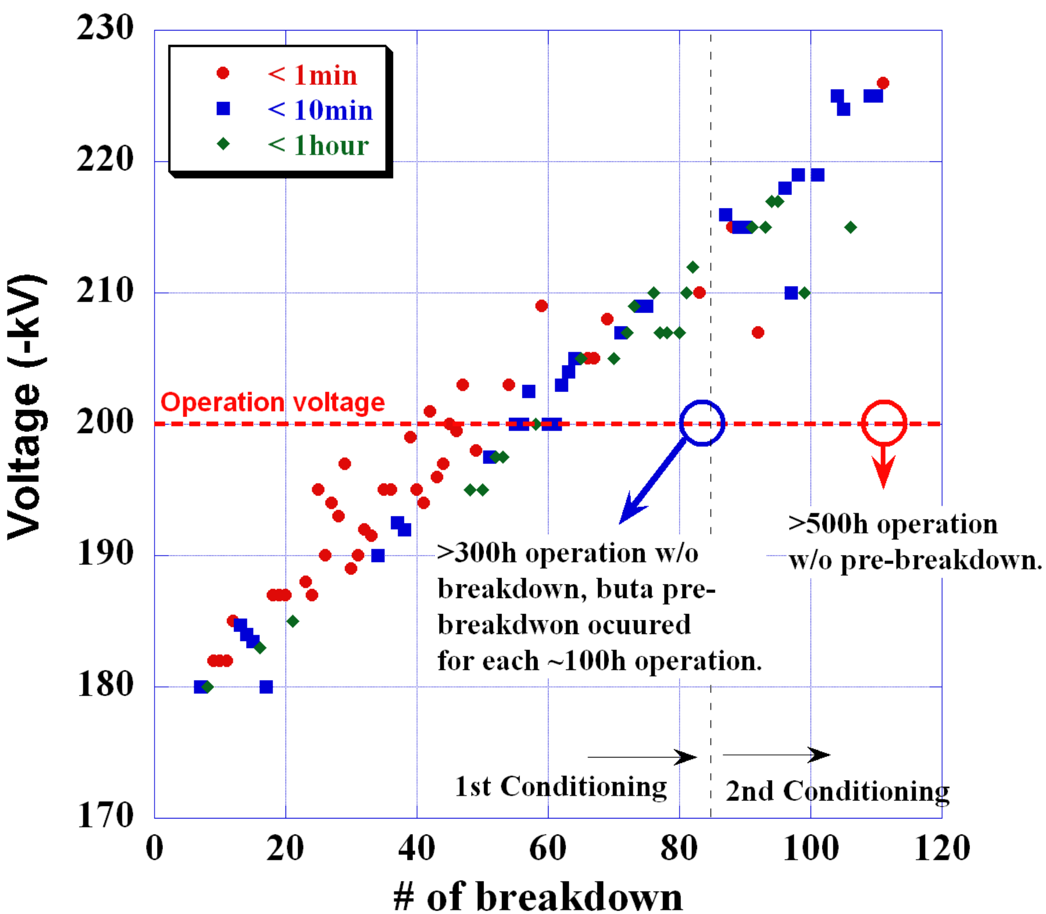
HV Operation (3)

High field DC Polarized Electron Gun@Nagoya





200kV gun Mo-Ti Electrode conditioning



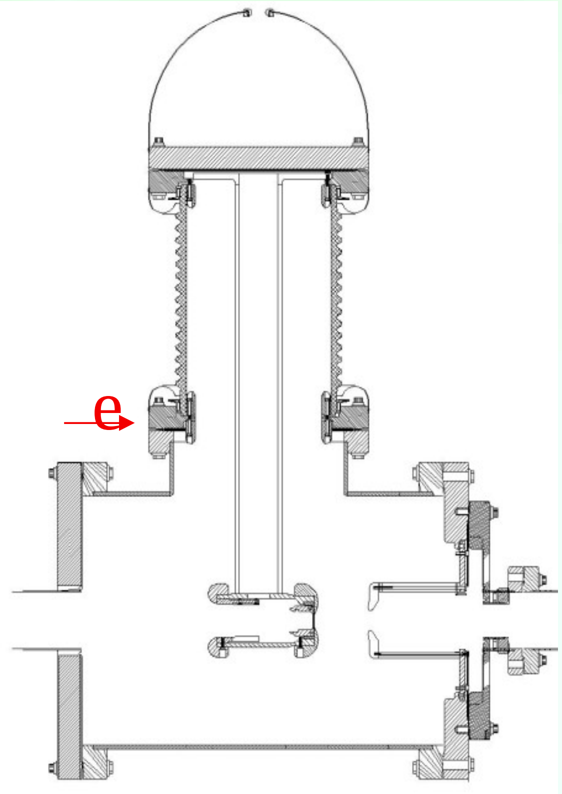
- Electrode conditioning was done in UHV condition.
- 215kVconditioning: No breakdowns occurred for >300 hrs, but pre-breakdown gives a crucial damage on cathode.
- 225kV conditioning: No pre-breakdown occurred > 500 hrs. Stable operation.

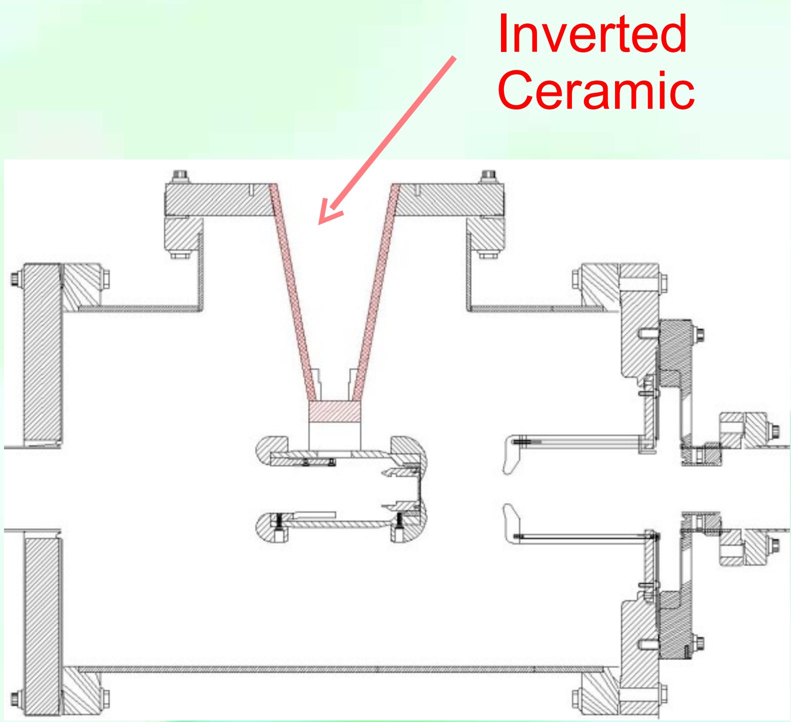
ILC08, M. Yamamoto

HV Operation (4)

Currently developing a 200kV gun (J-Lab)

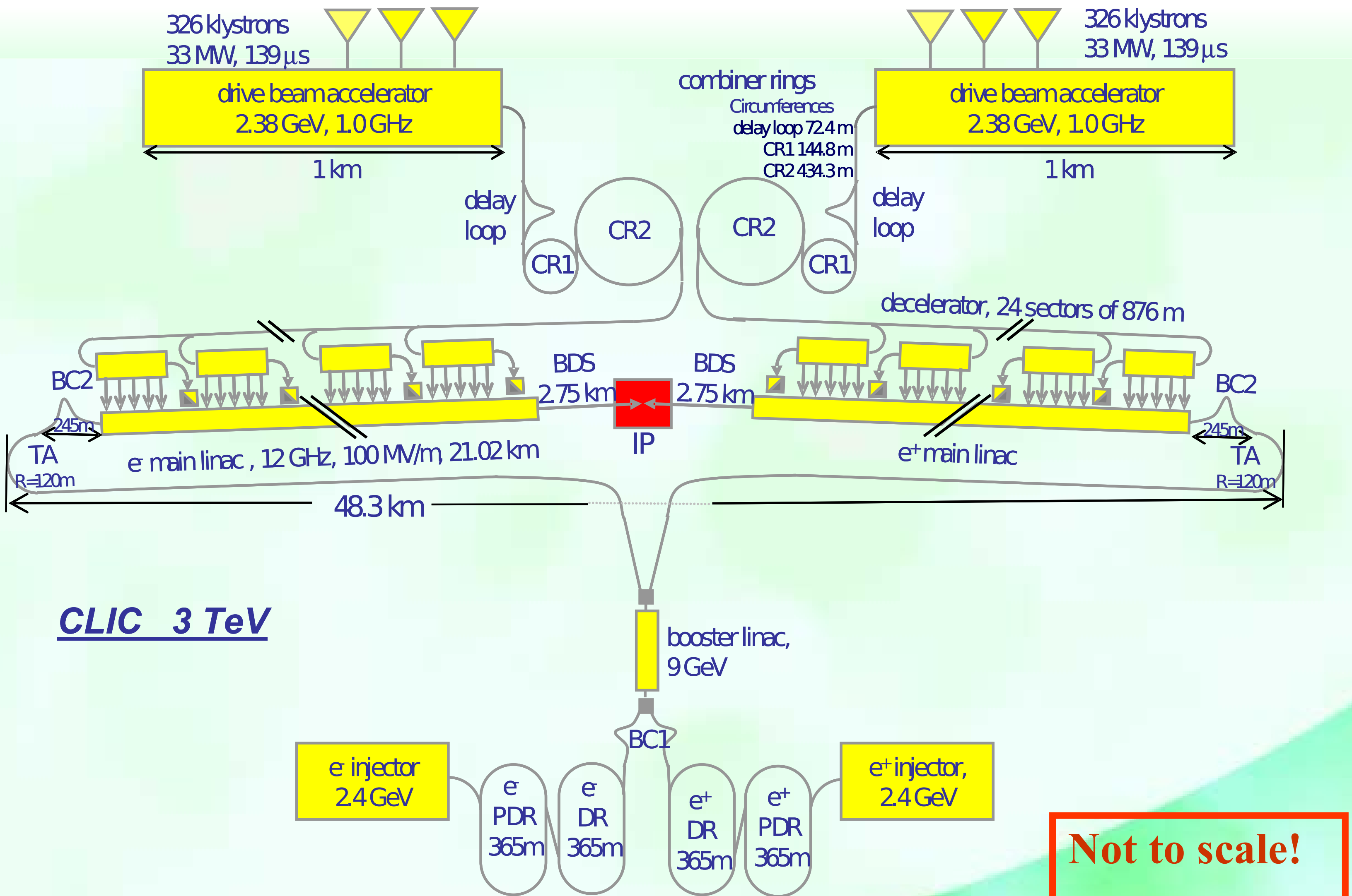
- **Joint with ILC (CEBAF synergy)**
- **Inverted ceramic insulator**
  - **medical x-ray technology, no exposed HV, no SF6, field emission not likely to accumulate on insulator**





A. Brachmann

The full CLIC scheme



G. Geschonke , EPAC08

The CLIC Two Beam Scheme

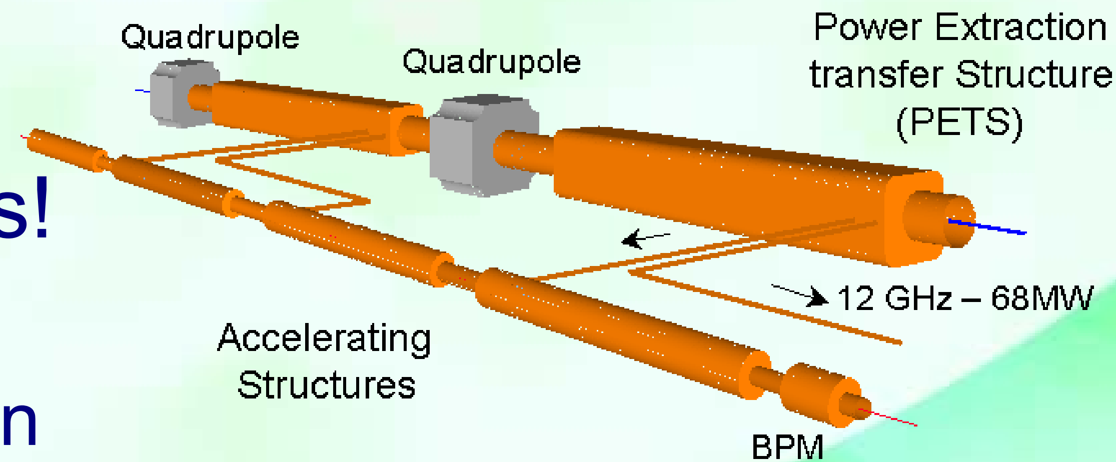
Two Beam Scheme:
Drive Beam supplies RF power

- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

We need two beams!

- Drive beam for RF
- Main beam for collision

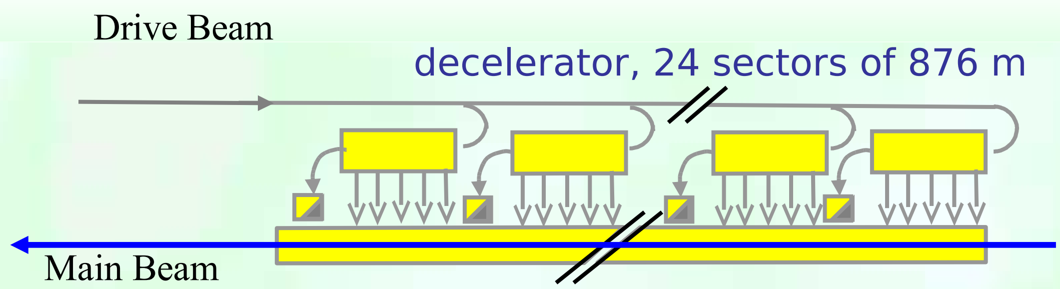
Drive beam – 100 A, 240 ns
from 2.4 GeV to 240 MeV



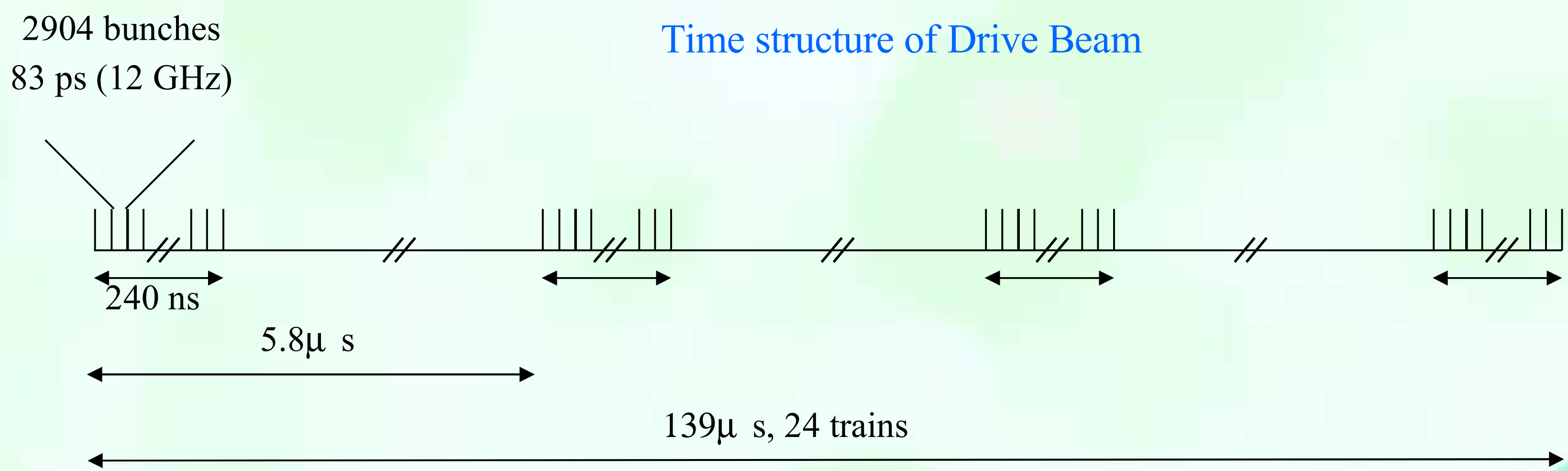
Main beam – 1.2 A, 156 ns
from 9 GeV to 1.5 TeV

G. Geschonke , EPAC08

Drive Beam for CLIC



Time structure of Drive Beam



Bunch charge: 8.4 nC, Current in train: 100 A

G. Geschonke , EPAC08

Drive Beam generation: Delay Loop

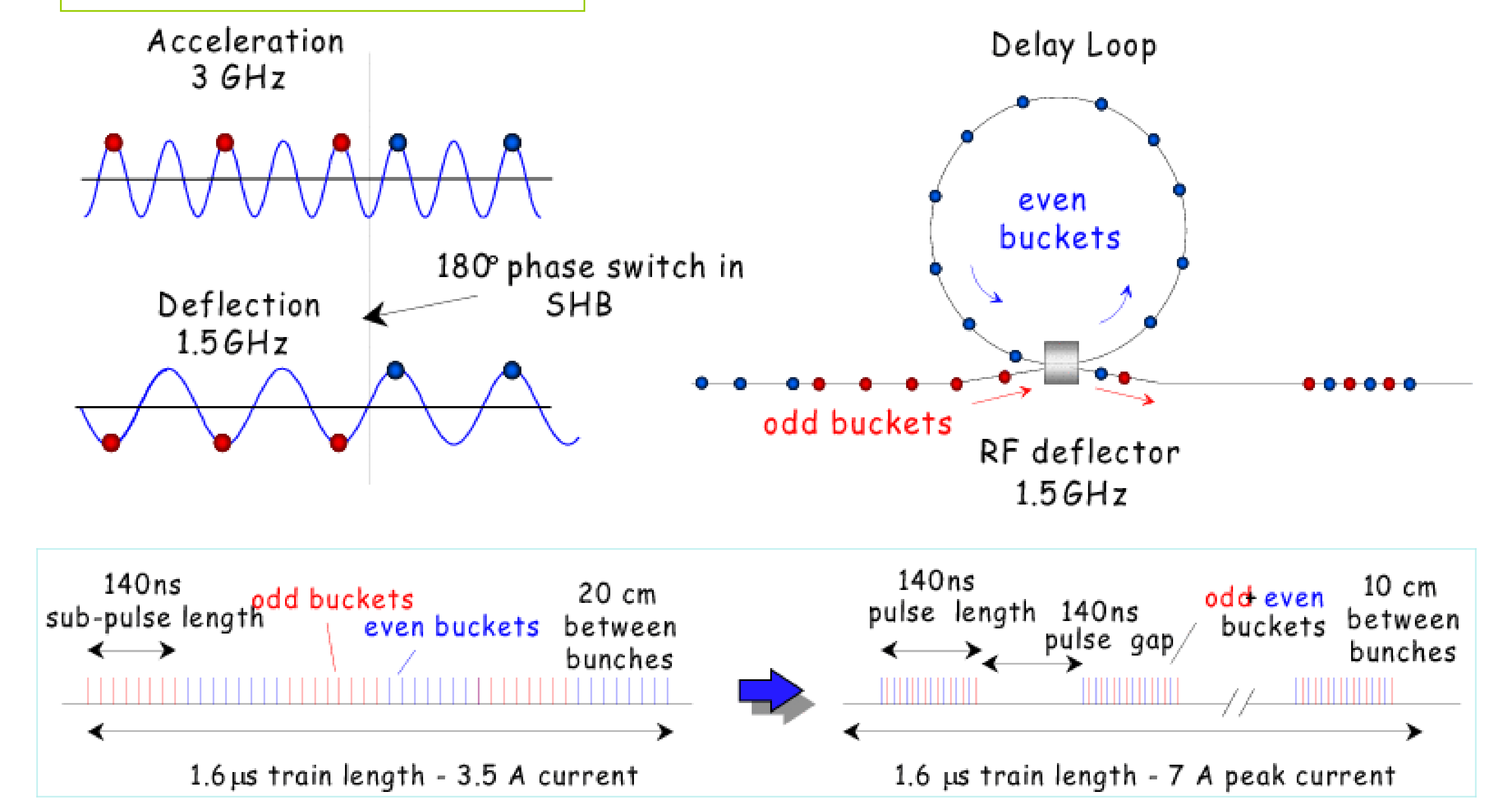
Principle: A long high intensity bunch train (1.4 μ s) is accelerated with 3 GHz

Bunch manipulations increase bunch repetition frequency

and increase peak current

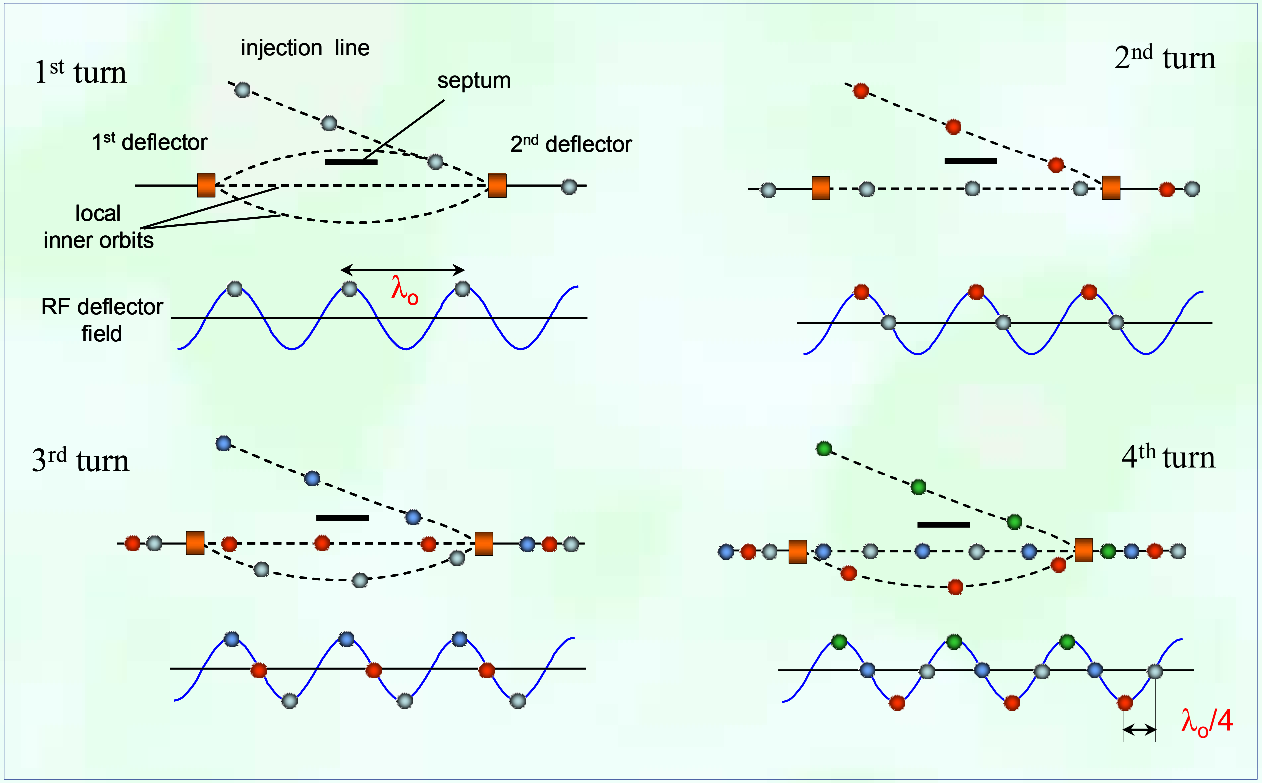
"Phase-coding" of bunches

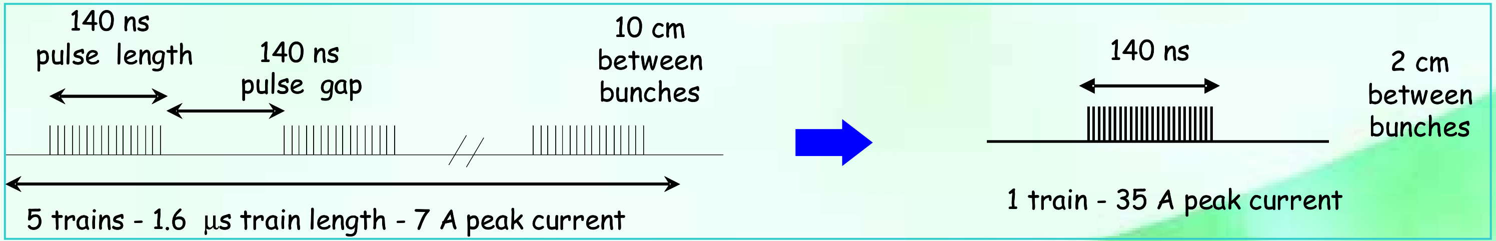
bunch interleaving with **Delay Loop**



Drive Beam generation: Combiner Ring

successive injection of 4 bunch trains into **Combiner Ring**





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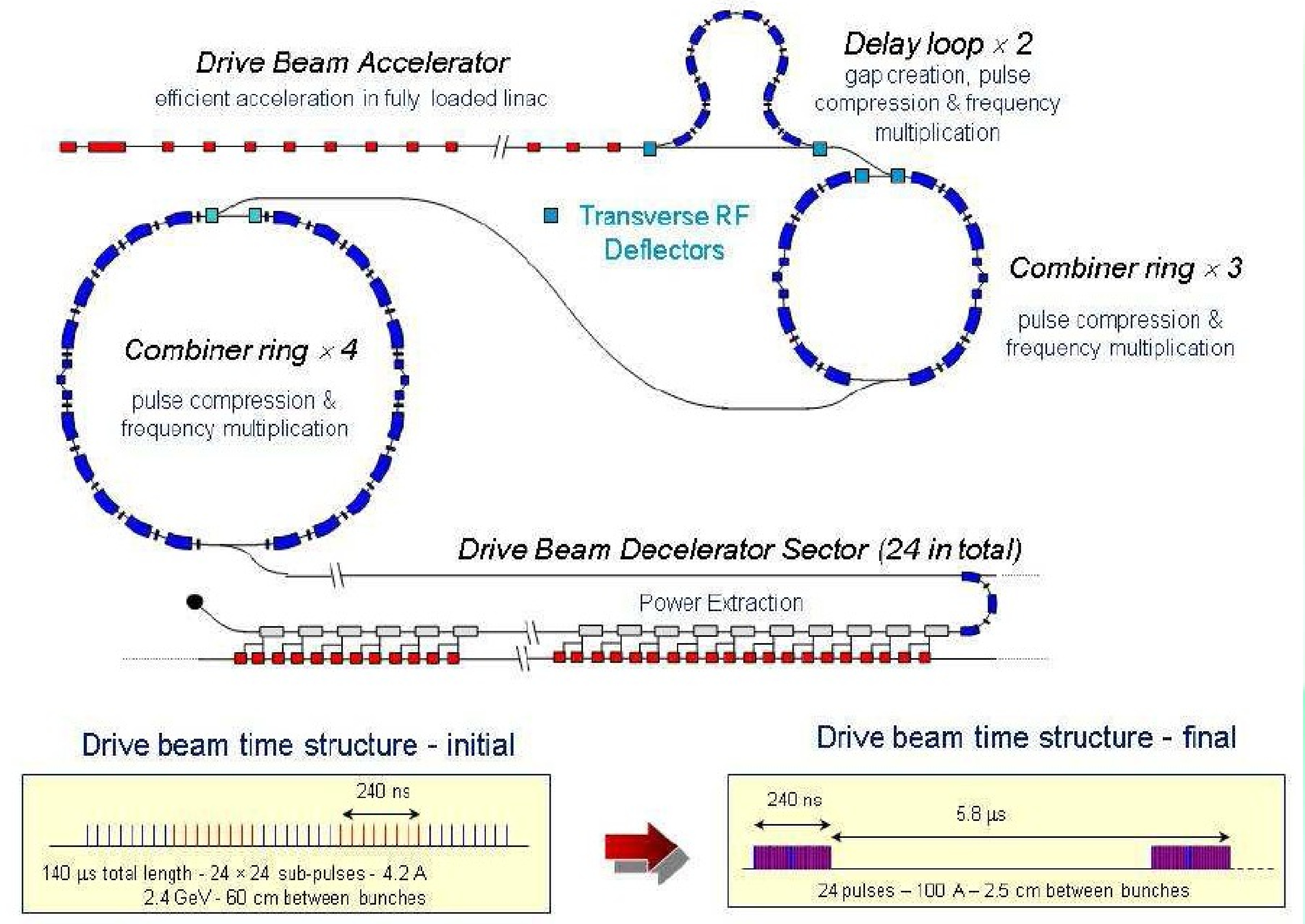
Drive Beam generation: Injector complex



CLIC requirements

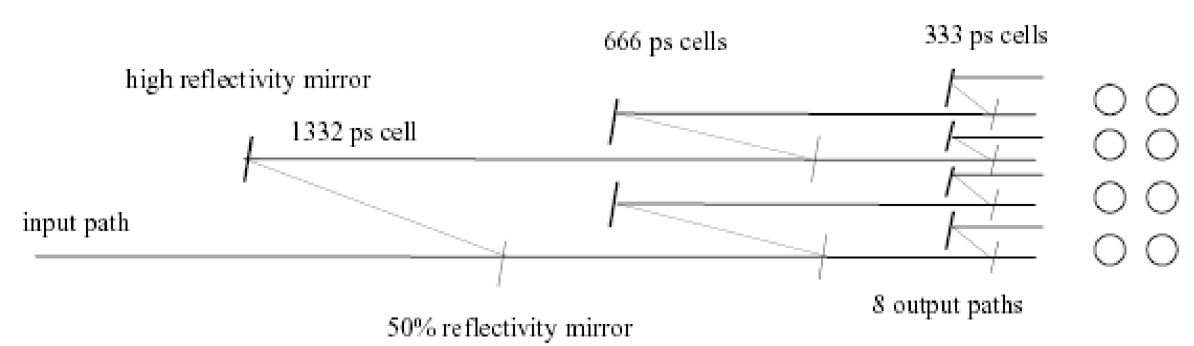
Drive Beam Parameters (at gun)	
Pulse length	140 us
Pulse reputation	50Hz
# of micro bunches in a pulse	2904x24
Bunch separation	2.00ns
Bunch charge	8.6nC
Beam current	4.2A
After Combiner Rings	
Mini-train length	240ns
# of mini-train	24
# of micro bunches in a mini-train	2904
Bunch separation	83ps
Bunch charge	8.6nC
Beam current	100 A

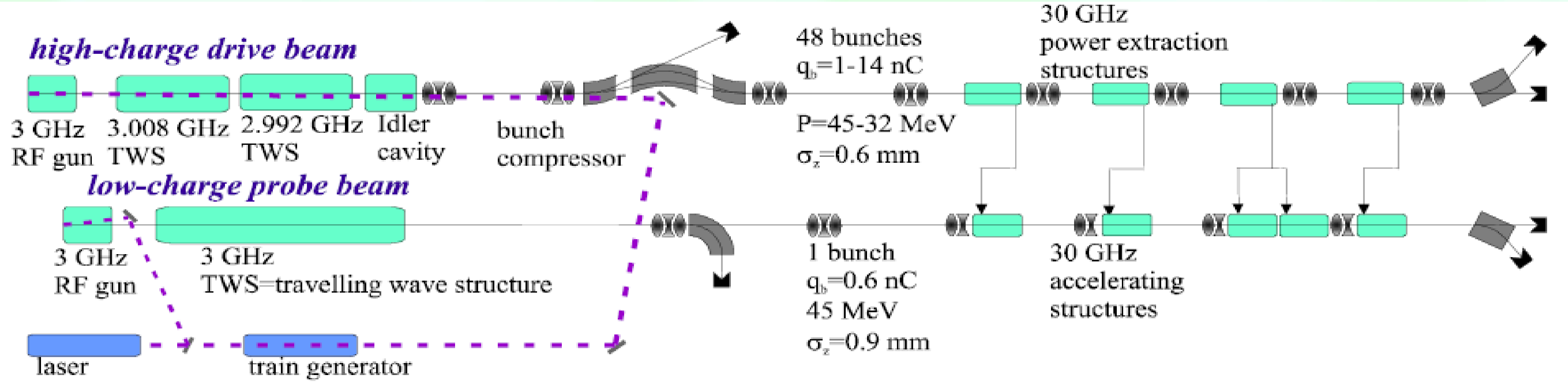
CLIC Drive Beam Source

- Two options for CLIC drive beam source
  - Thermionic gun.
  - PC RF gun.
- CTF2 (CLIC Test Facility 2) employ a PC RF gun.
- CTF3 (CLIC Test Facility 3) employ a thermionic gun.
- For real CLIC, both options are in consideration.

CERN-CTF2

- ► Photo-cathode RF gun for drive and probe beams.
- ► High repetition (333ps spacing) bunch train for drive beam by train generator.





CLIC requirements

Accelerator Beam parameter	
Pulse length	156ns
Pulse reputation	50Hz
# of micro bunches in a pulse	312
Bunch separation	500ps
Bunch charge	0.9nC
Polarization	80%
Bunch length at gun	100ps
Peak current	9A

- 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 is surely challenging.

Laser for Photo-cathode

Laser for Photo-Cathode

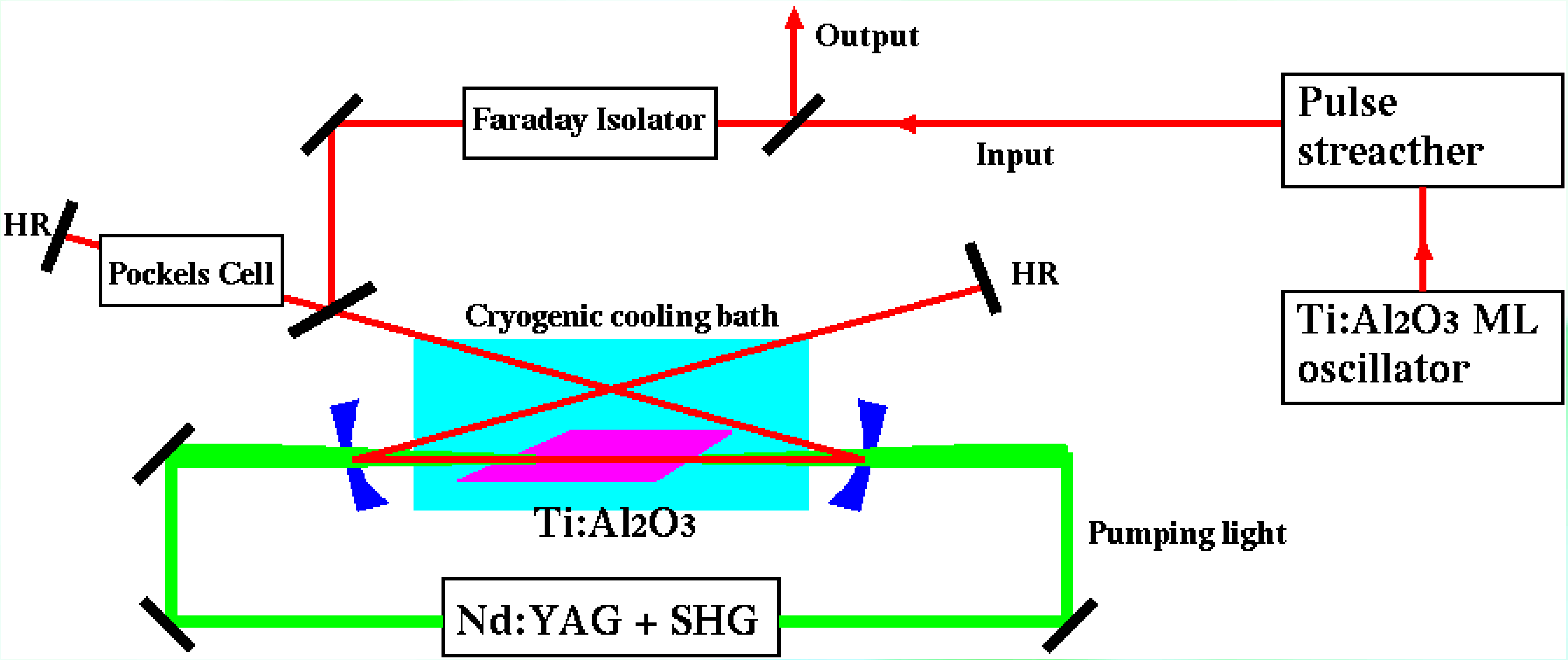
- Laser is one of the most important element of the photo-cathode gun, especially, the LC electron gun.
- Beam properties are mostly determined by the laser.
  - Temporal structure : 1ns bunch length, 3MHz repetition, 0.9 ms macro pulse.
  - Beam emittance : 10 μrad.
  - Polarization :circular polarization and wave length optimization around 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.

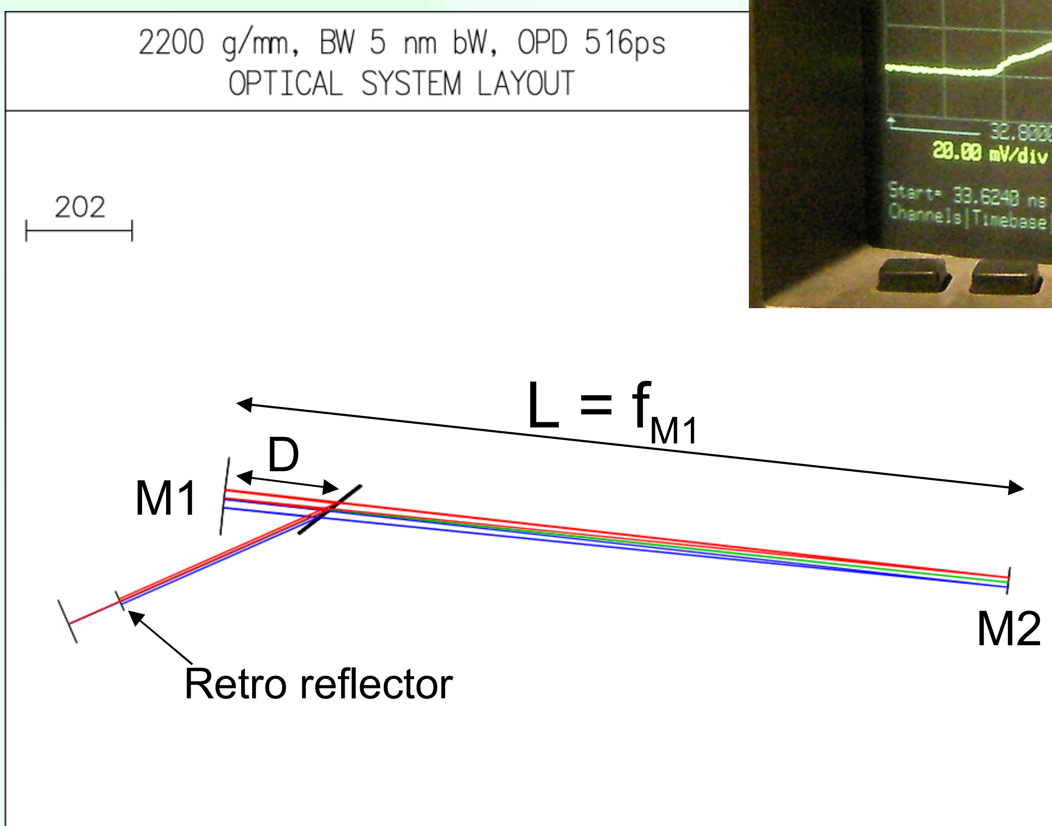
ILC Baseline Design

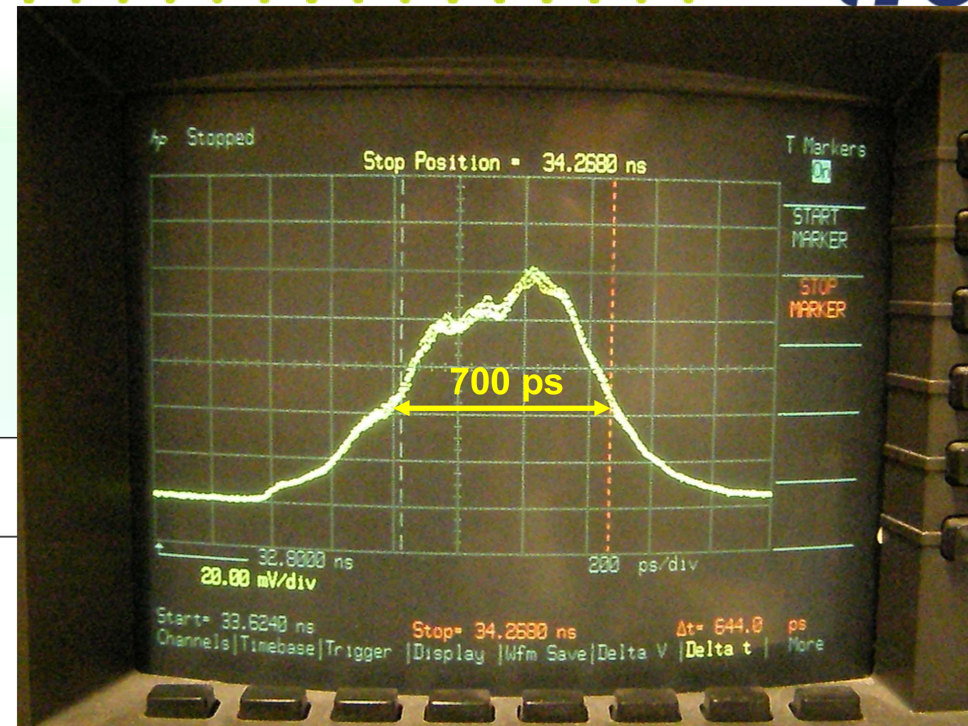
- Ti:Al_2O_3 mode lock + 3MHz pulse picker by Pockels cell makes a pulse train.
- Macro-pulse amplification by Ti:Al_2O_3 regenerative amplifier pumped by SH of Nd:YAG.
- Wave length is tunable. It is an extension of the existing technology, but the stability is a challenging issue.



Pulse stretcher

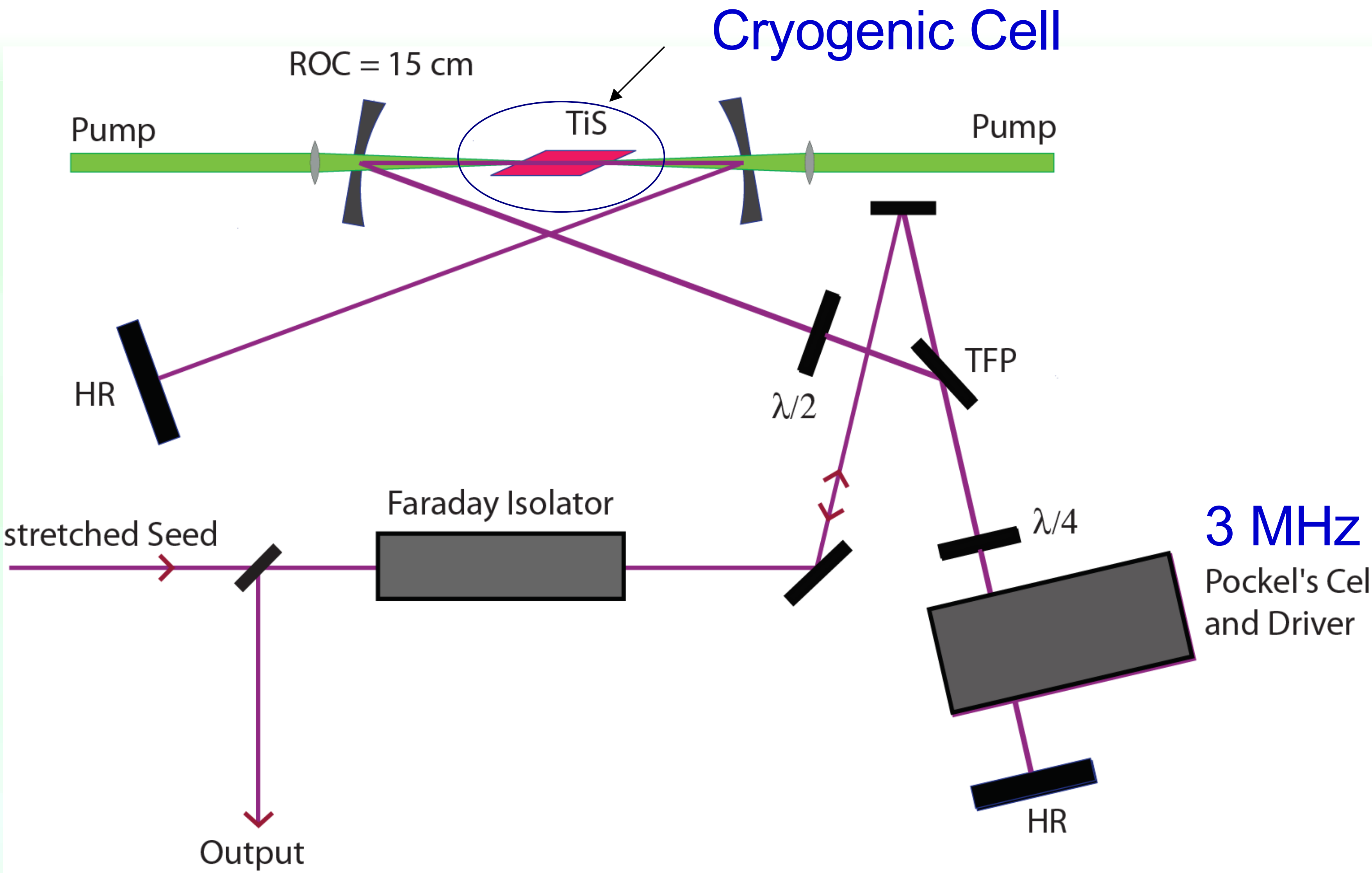
Pulse from Model-lock laser (200fs) is stretched to 1ns for ILC Bunch.





A. Brachmann

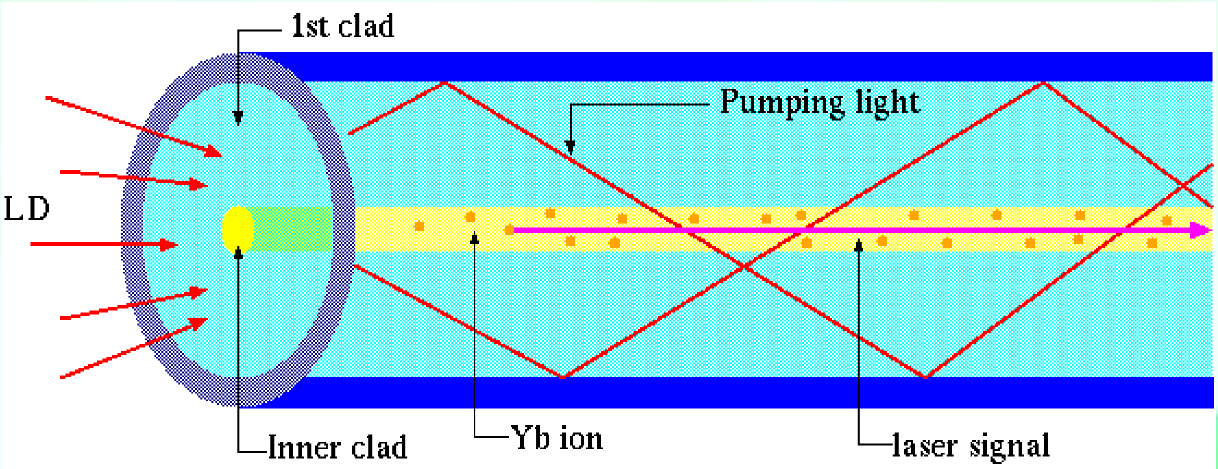
Regenerative Amplifier

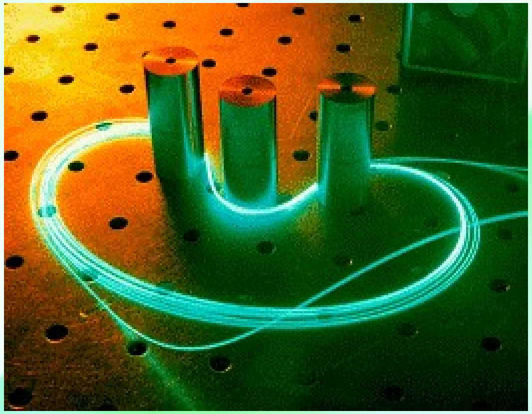


A. Brachmann

Yb 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"

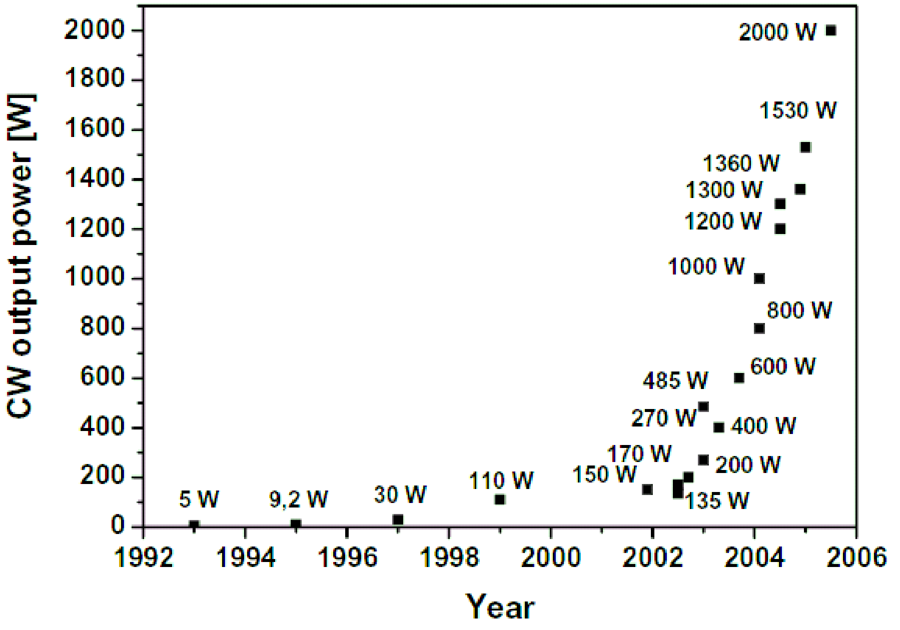


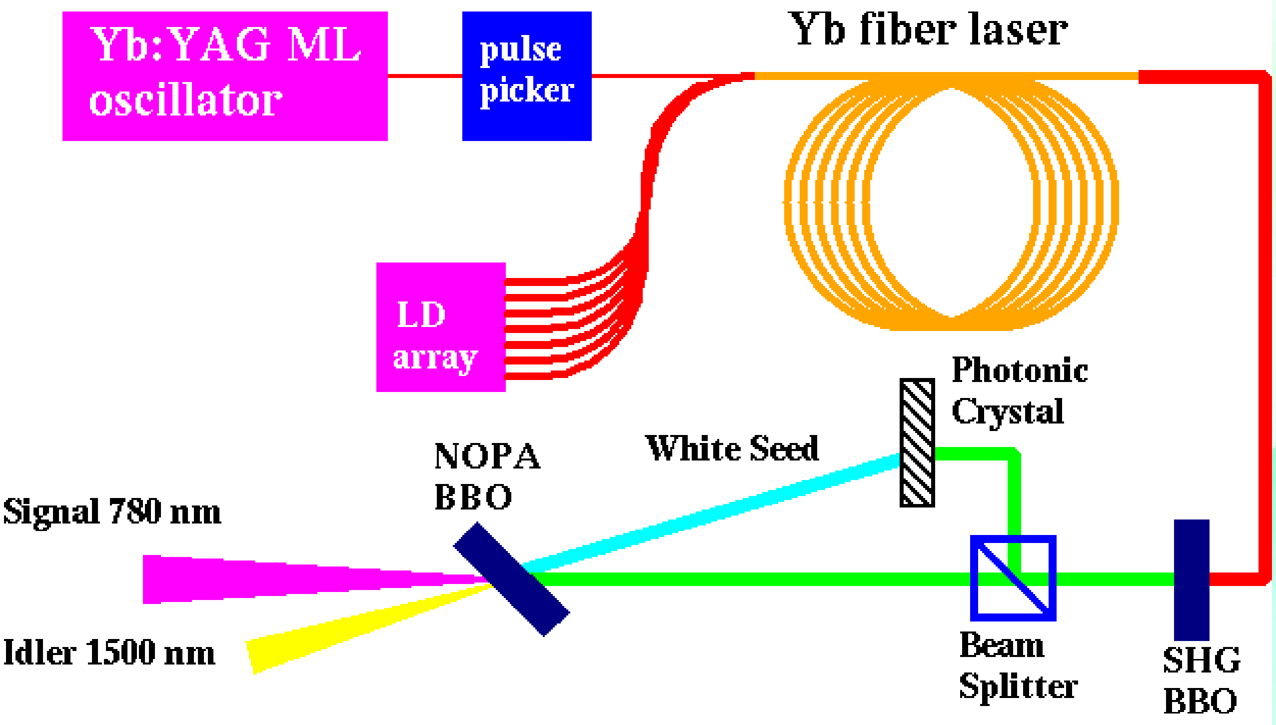
Fig. 4: Power evolution of cw double-clad fiber lasers with diffraction-limited beam quality over the last decade

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.

Yb:YAG fiber laser + OPA

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



Nonlinear Optics (1)

By intense laser field, non-linear polarization is induced in a 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

By the non-linear effect, second harmonics (2ω) and 0 frequency mode are induced. That can be understood that the square of the fundamental mode is separated to be 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

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

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

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

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.

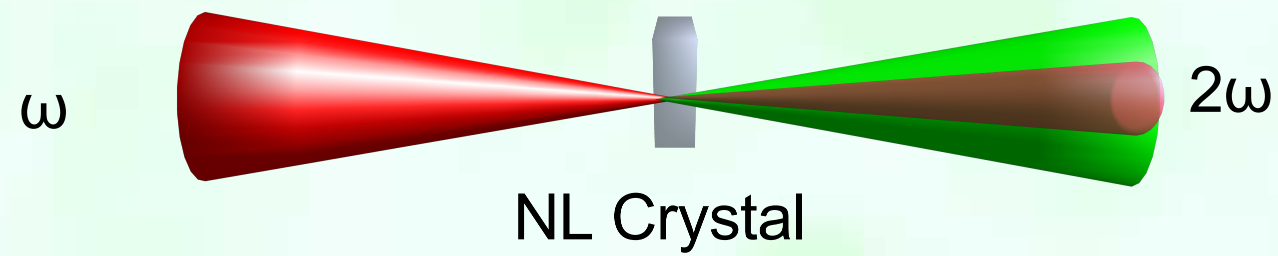
SHG: Second Harmonic Generation

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 an 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)

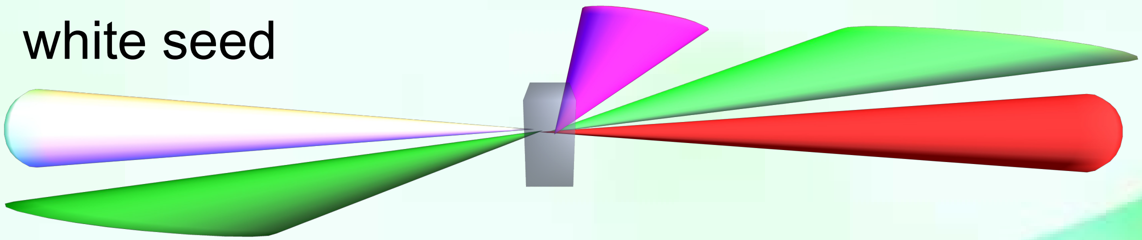
► Yb fiber amplifier generate powerful pulse train in 1030nm.

► 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 tune-ability is achieved.

► OPA make the wave length tune-ability possible with the powerful Yb fiber laser system.



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.
- Surface charge and space charge limitation should be solved by cathode R&D and HV operation.
- Drive laser for LC is a challenging task.

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