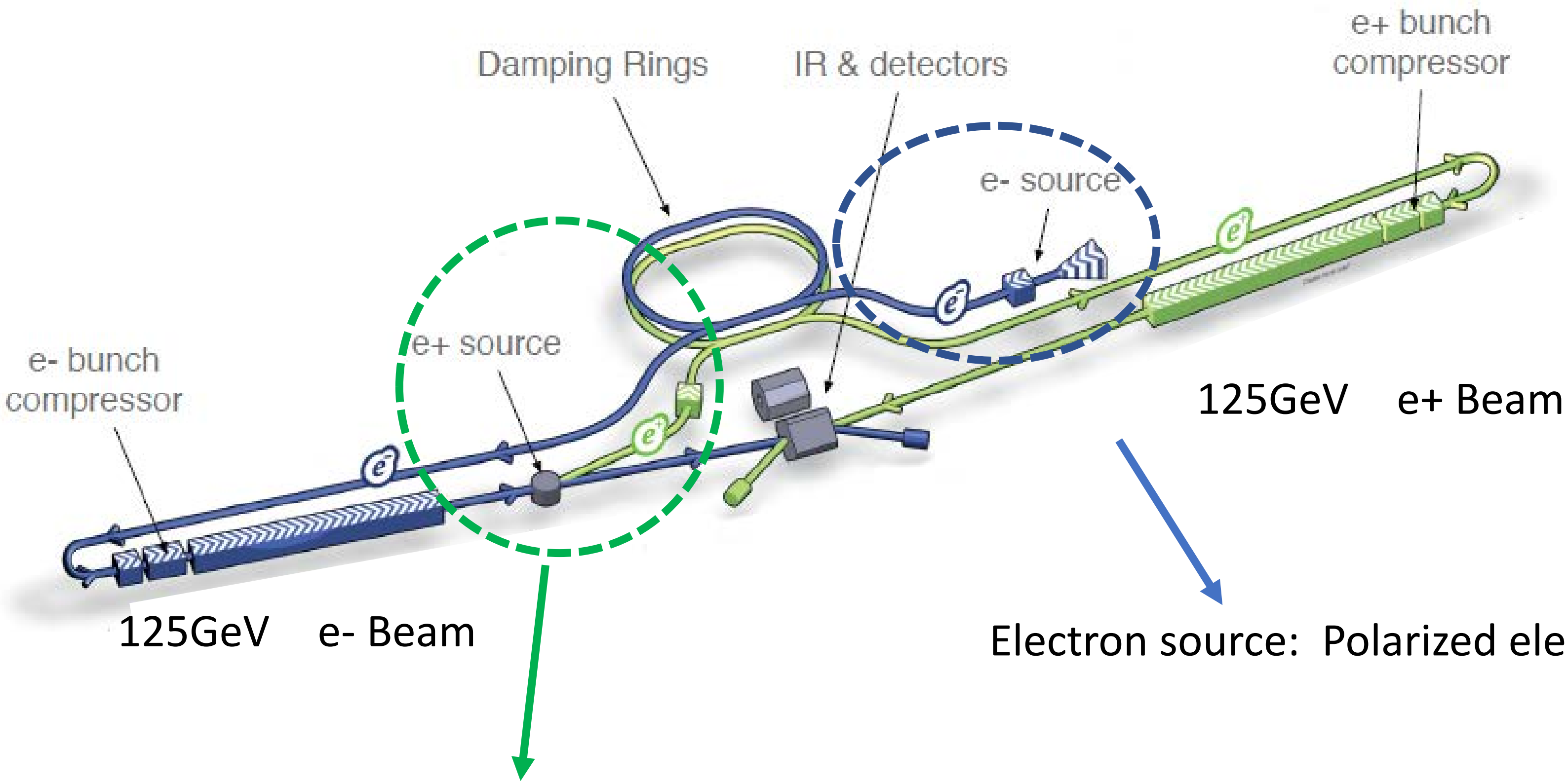
Electron and Positron source

KEK M. Fukuda

International Linear Collier (ILC)



125GeV　e+ Beam

125GeV　e- Beam

Electron source: Polarized electron

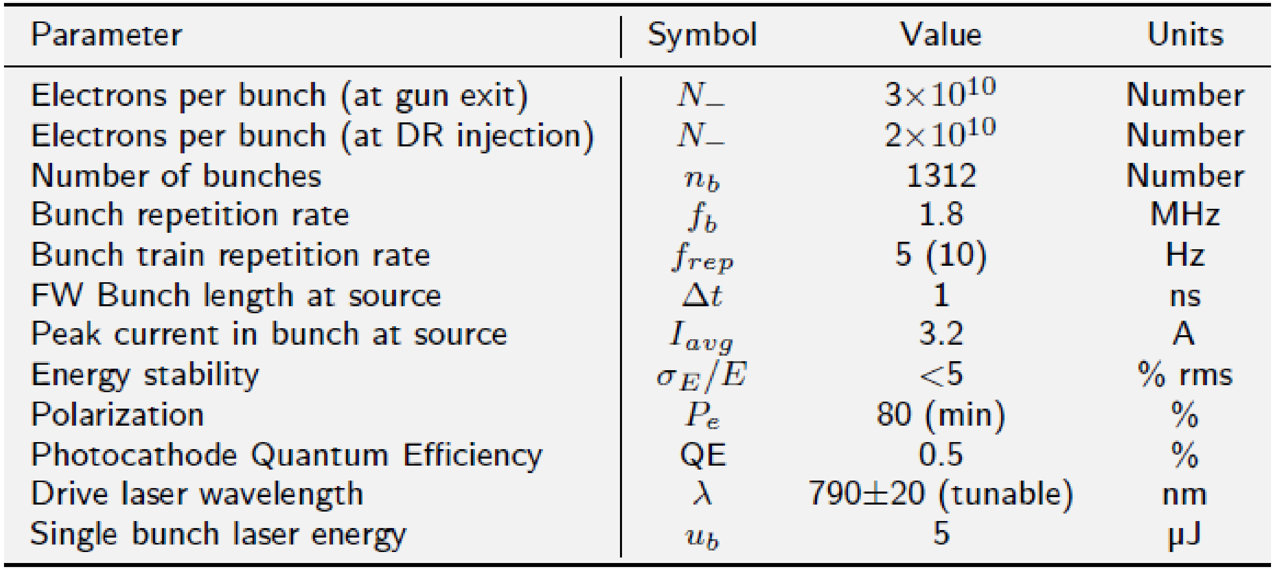
Positron source：Undulator scheme
: E-driven scheme

Electron source

Beam parameters for the electron source

ILC requires the following electron beams:

Bunch charge:	2.0×10^{10} e^-/bunch (3.2nC/bunch)
Number of bunches:	1312bunches/train
Rep. Rate:	5Hz
Polarization:	>80%

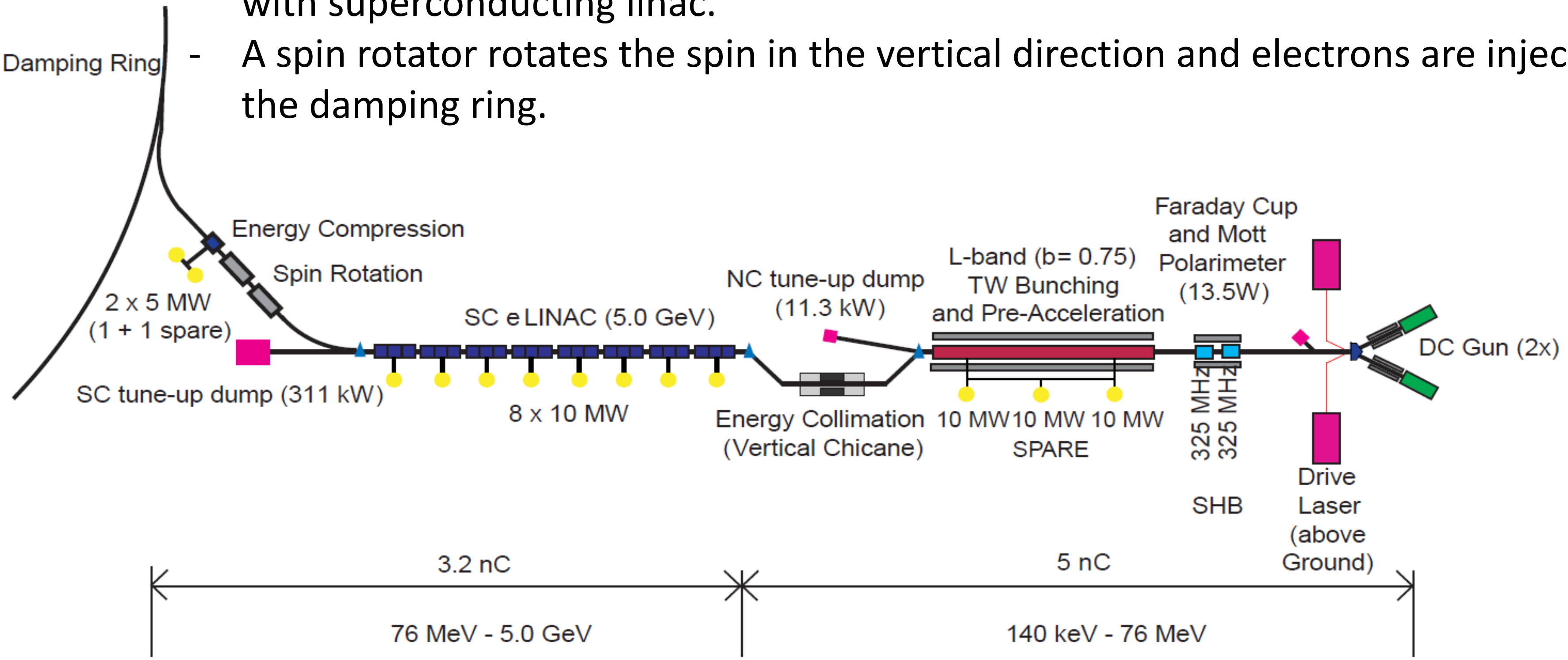


Parameter	Symbol	Value	Units
Electrons per bunch (at gun exit)	N_-	3×10^{10}	Number
Electrons per bunch (at DR injection)	N_-	2×10^{10}	Number
Number of bunches	n_b	1312	Number
Bunch repetition rate	f_b	1.8	MHz
Bunch train repetition rate	f_{rep}	5 (10)	Hz
FW Bunch length at source	Δt	1	ns
Peak current in bunch at source	I_{avg}	3.2	A
Energy stability	σ_E/E	<5	% rms
Polarization	P_e	80 (min)	%
Photocathode Quantum Efficiency	QE	0.5	%
Drive laser wavelength	λ	790$\pm$20 (tunable)	nm
Single bunch laser energy	u_b	5	μJ

ILC-TDR

Layout of the polarized electron source

- Electrons are generated by using a 200 kV DC gun with a NEA-GaAs cathode.
- The 325MHz subharmonic buncher (SHB) compresses the bunch length.(1ns→20ps)
- Electrons are accelerated to 76 MeV with an L-band TW accelerator in a solenoid magnetic field.
- After passing chicane for energy collimation, electrons are accelerated to 5GeV with superconducting linac.
- A spin rotator rotates the spin in the vertical direction and electrons are injected to the damping ring.

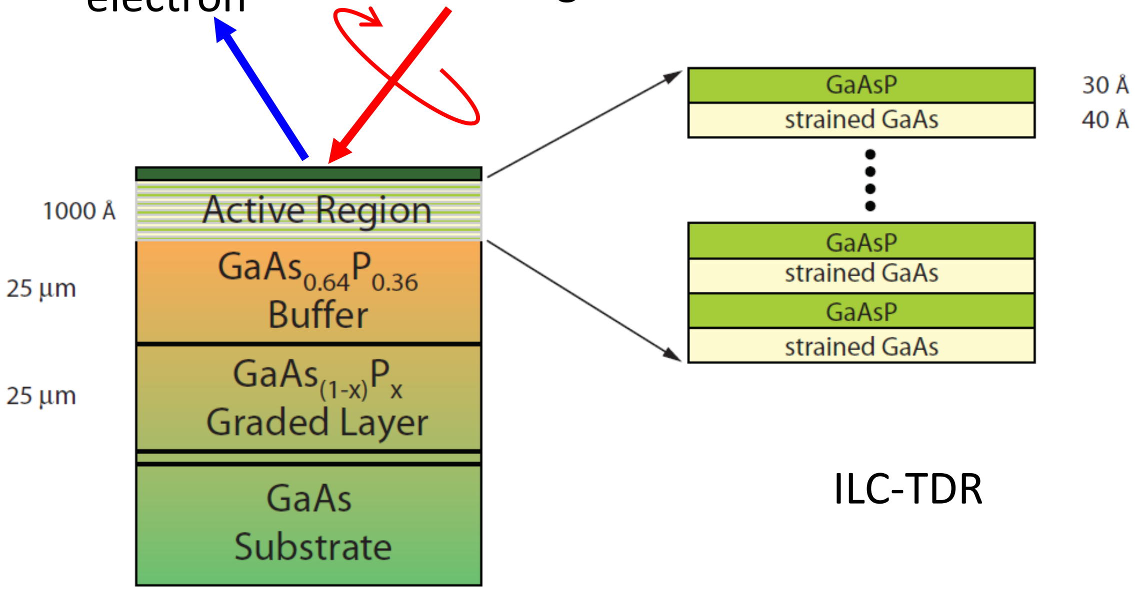


-TDR

Polarized electron generation

Strained GaAs/GaAsP superlattice photocathode
Quantum efficiency (QE): 0.3~0.5% (max. 1%)
Polarization: > 85%
QE: 0.5% , Polarization: 92% : T. Nakanishi: Proceeding of LINAC2002, 813 (2002).

Figure 4.2
Structure of a strained GaAs/GaAsP superlattice photocathode for polarized electrons.

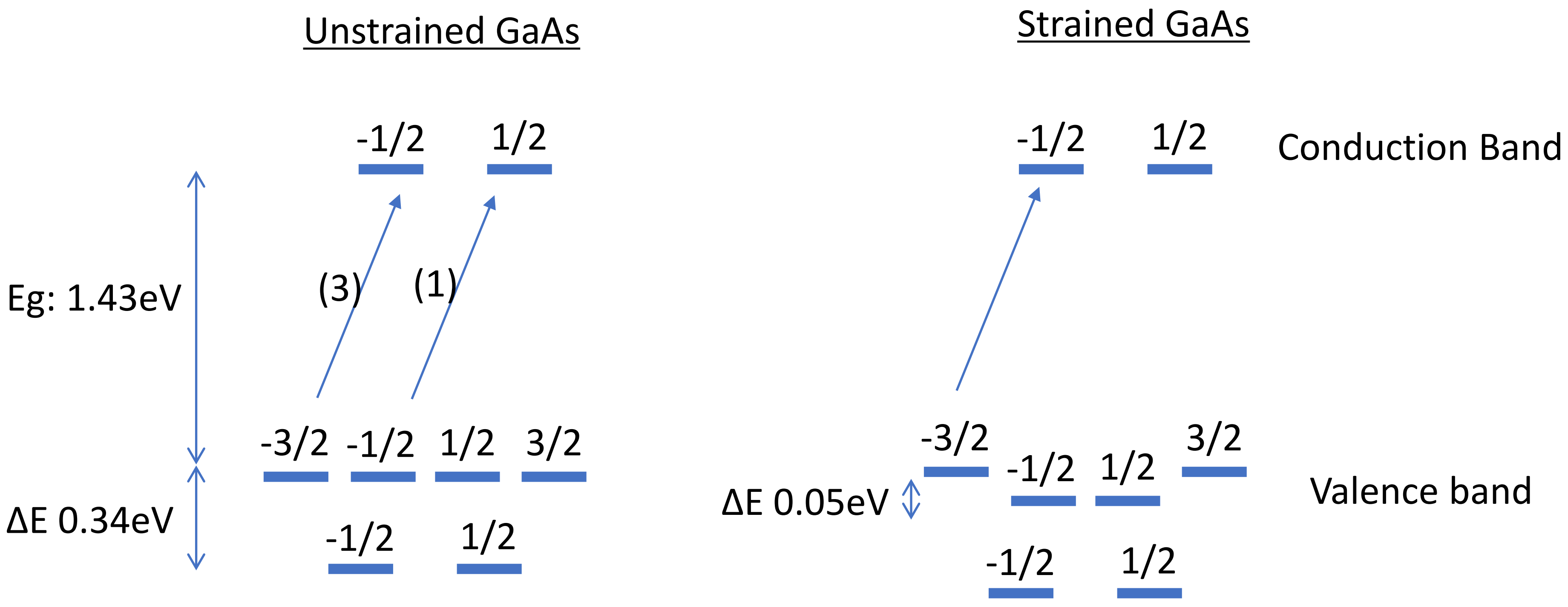

Polarized electron

Circular polarized laser light

ILC-TDR

Polarized electron generation

Unstrained GaAs →Strained GaAs: Polarization is increased.



Unstrained GaAs

Strained GaAs

Conduction Band

-1/2 1/2

-1/2 1/2

Eg: 1.43eV

(3) (1)

-3/2 -1/2 1/2 3/2

-3/2 -1/2 1/2 3/2

Valence band

ΔE 0.34eV

ΔE 0.05eV

-1/2 1/2

-1/2 1/2

Polarization 50%(Max)

Polarization > 90%

Polarization = $(N_+ - N_-) / (N_+ + N_-)$

NEA(Negative Electron Affinity)

NEA surface is made by deposition of Cs and O on GaAs surface.
→ Quantum efficiency (QE) is increased.

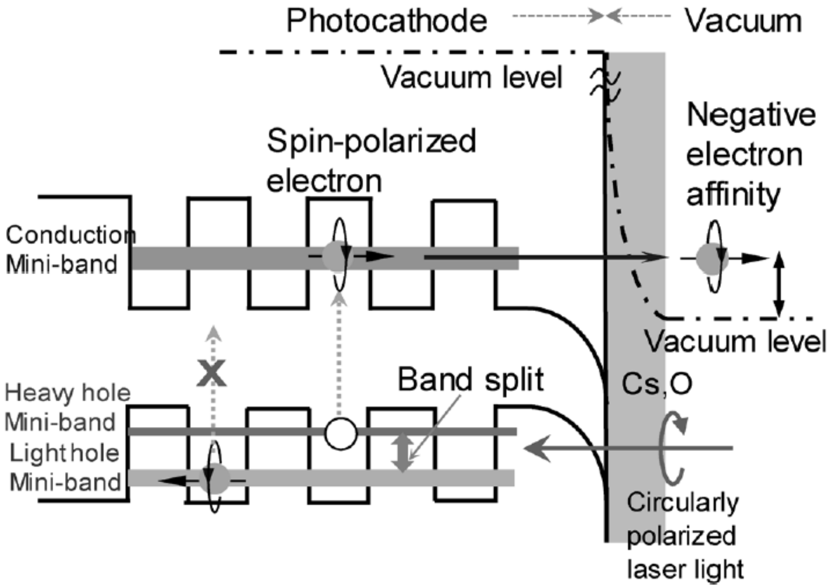


Figure 1: Concept of spin-polarized electron source using semiconductor photocathode with NEA surface.

Xiuguang JIN,「加速器」Vol. 16, No. 1, 2019（22–27）

GaAs/GaAsP strain-compensated superlattice

Strained Superlattice: Polarization 92%, QE: 0.5%
Thickness ~100nm → Absorption of the laser light: 4-5%

Strain-compensated superlattice:
→ Thickness : 720nm
→ Polarization 92%, QE: 1.6%

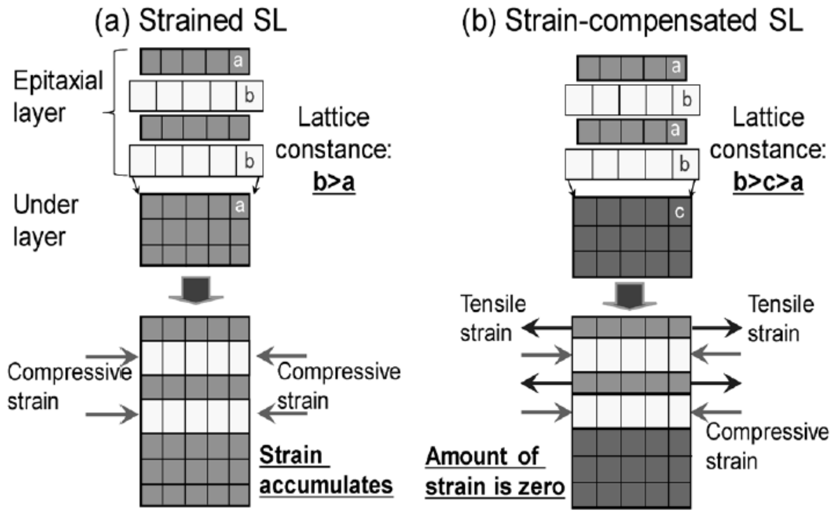


Figure 2: Detailed structures of (a) strained SL and strain-compensated SL.

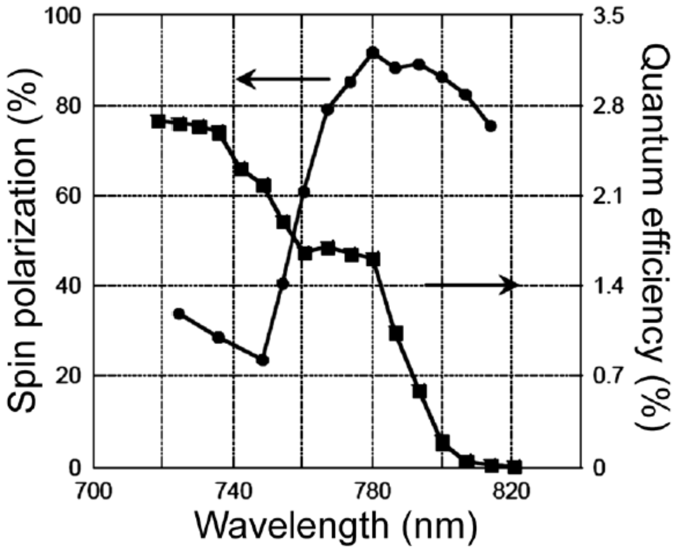


Figure 5: Spin polarization and quantum efficiency spectra for 24-pair strain-compensated SL.

Xiuguang Jin, et.al., “Effect of crystal quality on performance of spin-polarized photocathode”, Appl. Phys. Lett, Applied Physics Letters, 105(20):203509, 2014.

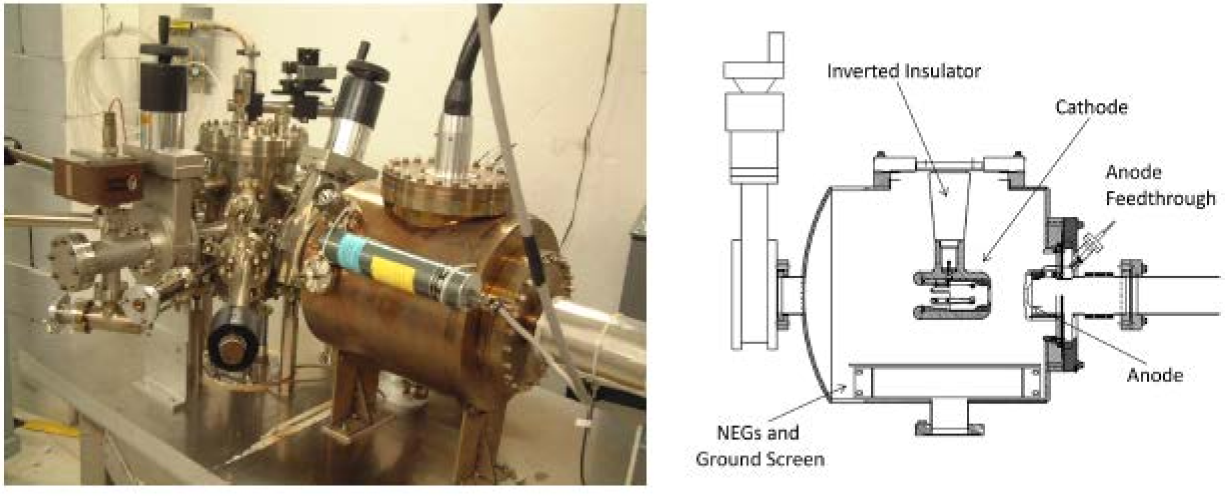
Xiuguang JIN,「加速器」Vol. 16, No. 1, 2019（22–27）

200kV DC high voltage photogun

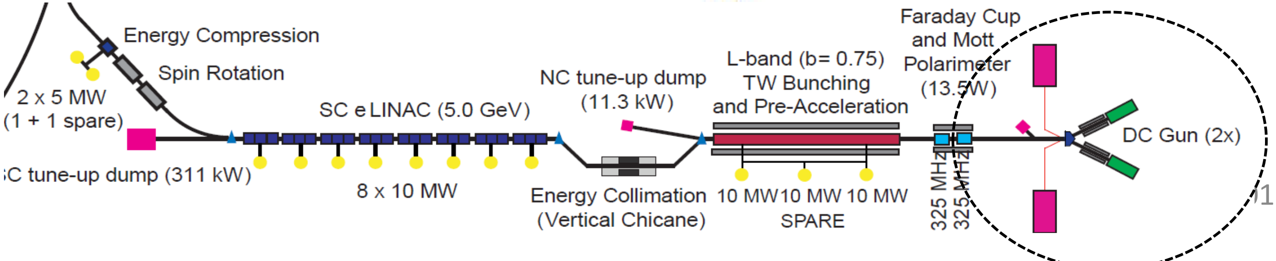
DC High voltage: 200kV
Photocathode: Strained-superlattice GaAs/GaAsP

To reduce the space charge effect which make the emittance worse, the high voltage is needed.

Figure 4.4 The chamber of the 200 kV DC high voltage photogun (a) and its schematic view (b).



(a) (b)



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Average current : 4mA

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cERL DC gun

A 500kV DC electron gun is operated in compact-ERL at KEK.

Generation of a high-current beam greater than 0.8 mA at 500 kV for approximately 2 h was demonstrated.

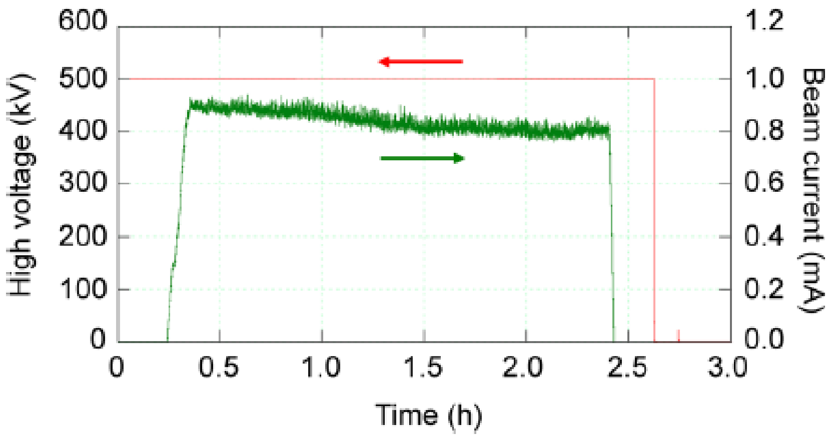


FIG. 15. Operational status of the gun during beam generation at >0.8 mA. The red and green curves show HV and the beam dump current, respectively, as a function of time.

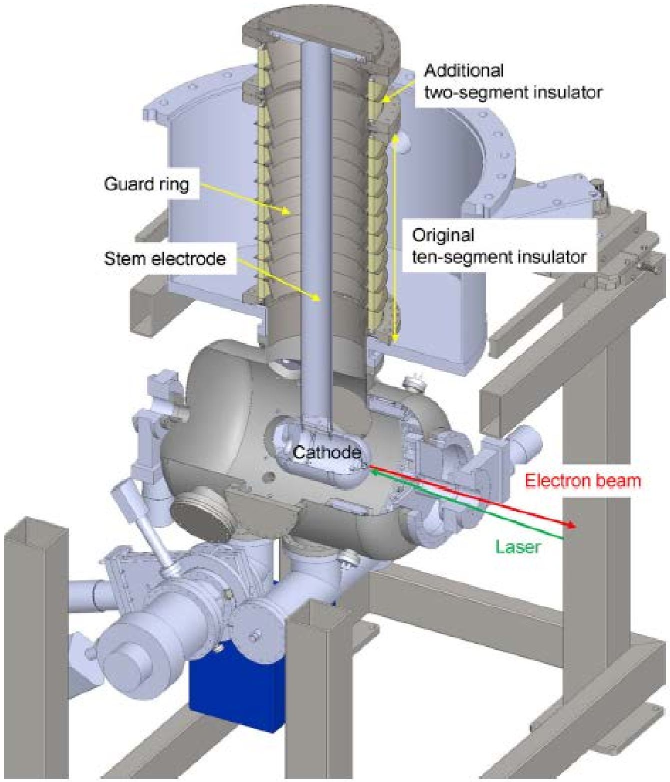
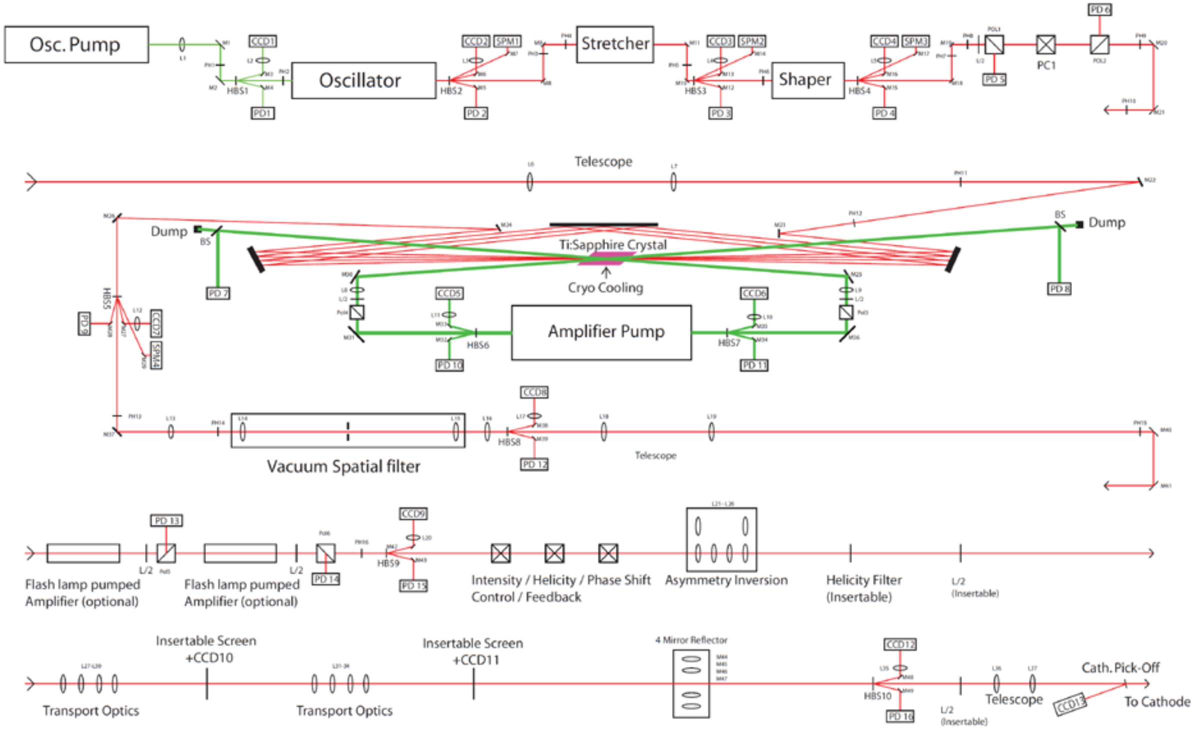


FIG. 7. Schematic illustration of the 500 kV dc photoemission gun at the cERL with additional two-segment ceramic insulator installed.

N. Nishimori et.al., “Operational experience of a 500 kV photoemission gun”, PHYS. REV. ACCEL. BEAMS 22, 053402 (2019)

Gun laser system

To match the bandgap energy of GaAs photocathodes, the wavelength of the laser system must be 790 nm and provide tunability (±20 nm) to optimize conditions for a specific photocathode. Therefore, the laser system is based on Ti:sapphire technology.



ILC-TDR

Bunching and Pre-Acceleration

The bunching system compresses the 1 ns micro-bunches generated by the gun down to 20 ps
To avoid the surface-charge-limit problem, the bunch length is 1ns at the DC gun.

- SHB(Subharmonic buncher) (325MHz) x2, 1ns → 200ps
- L-band Buncher (5cells), 200ps → 20ps

The e- beam is accelerated to 76MeV by the L-band normal conducting TW accelerator.

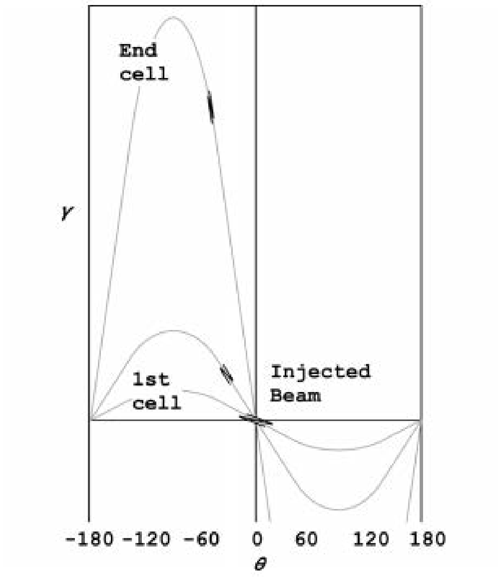
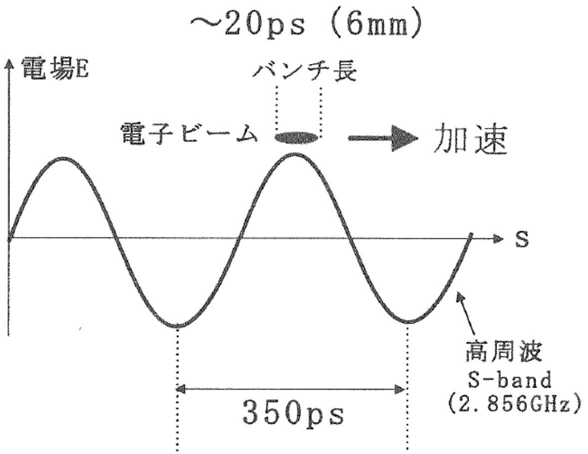
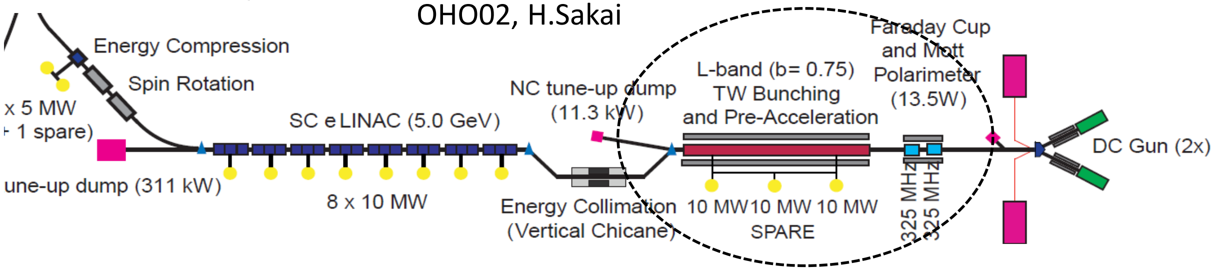


図 2.3.7 進行波型バンチャーによる電子集群の縦方向位相空間。 OHO13 T. Asaka



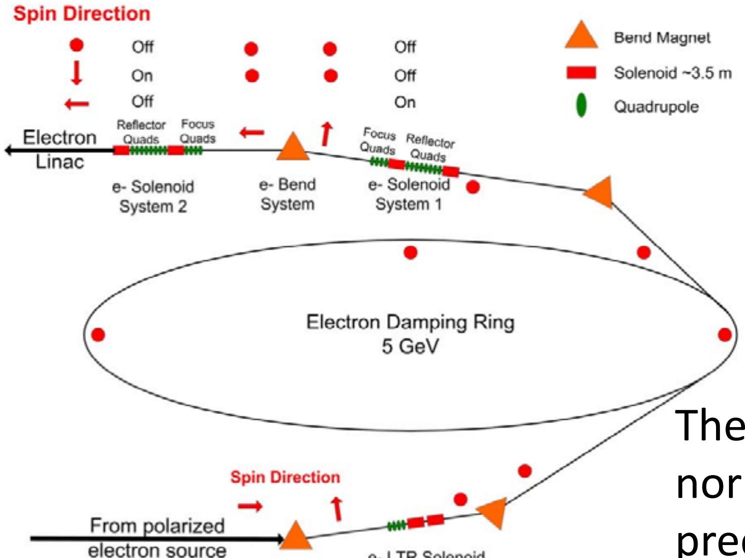
OHO02, H.Sakai



5GeV linac to Damping Ring

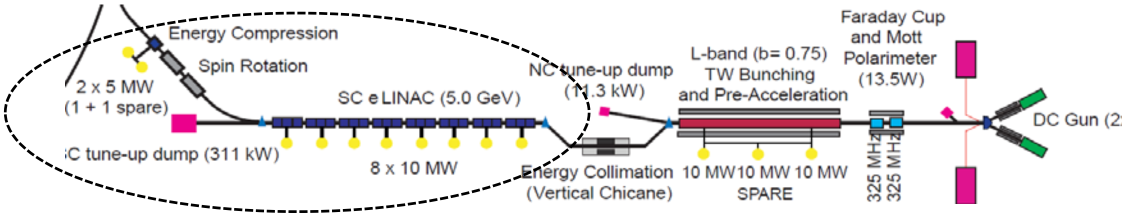
After the Pre-Acceleration、 an e- beam is accelerated to 5GeV by the Superconducting linac which consists of 24 cryomodules. That cryomodules are drived by eight 10MV klystrons .

The Linac To Ring (LTR) beam line transports the beam to the injection point of the damping ring.



K Moffeit 10 Feb 2005

Bend
7.93deg



The electron spin component in the plane normal to the applied magnetic field will precess 90deg in that plane for every 7.93deg of rotation of the momentum vector at 5GeV.

K. Moffeit, et.al. , SLAC-TN-05-045

Simulation

Simulations indicate that >95% of the electrons produced by the DC gun are captured within the **6-D damping ring acceptance:**
γ(Ax+Ay) <=0.07 m and ΔE×Δz <=(±37.5 MeV)×(±3.5 cm).
The starting beam diameter at the gun is 2 cm, which is focused to a few mm diameter before it is injected into the DR.
Simulation code: PARMELA、 MAD、 ELEGANT code [81].

Figure 4.4
Beam envelope along the 76 MeV injector.

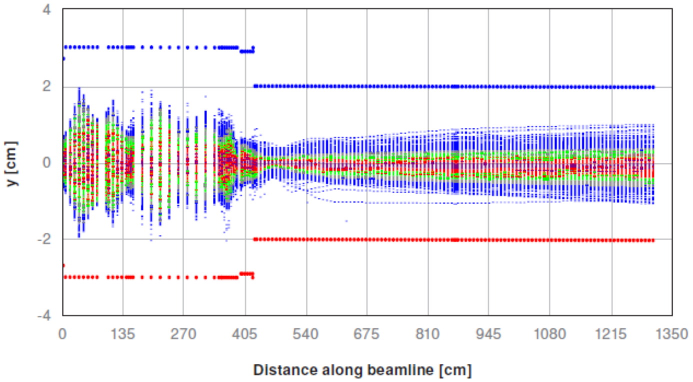
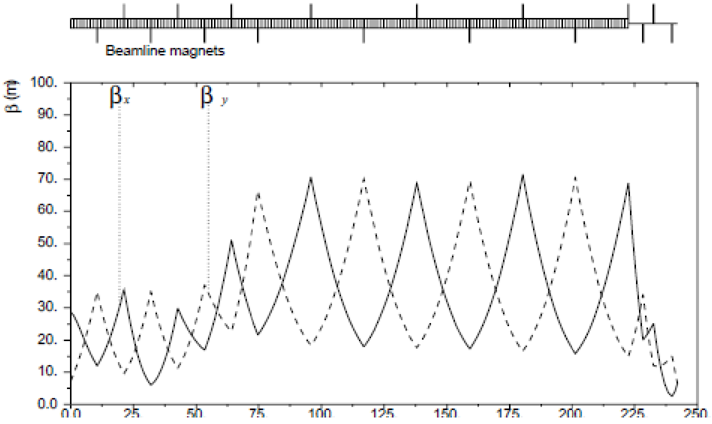


Figure 4.5
Optics of the SC electron booster linac.



ILC-TDR

Positron source

Positron production

- β+ decay

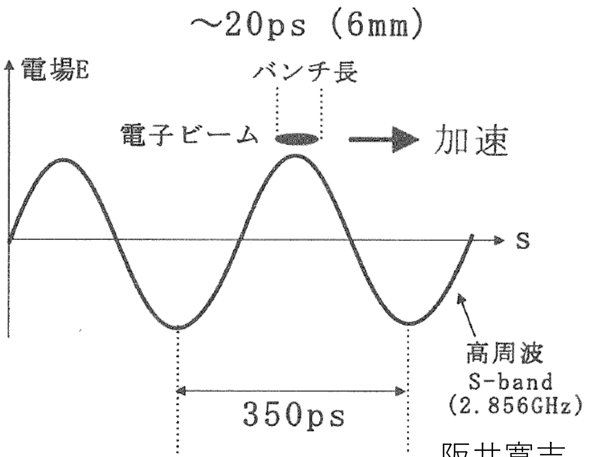
  $P^+ \rightarrow n + e^+ + \nu e$

- **Pair production**

  Photons interact with the nuclear Coulomb field and produce electron-positron pairs.

  Photons with energy of more than 1.022MeV are required.

Pair generation is used as a positron beam source. Since it accelerates by the electric field, bunched positrons are required. Bunched gamma-rays can make the bunched positrons by pair production.

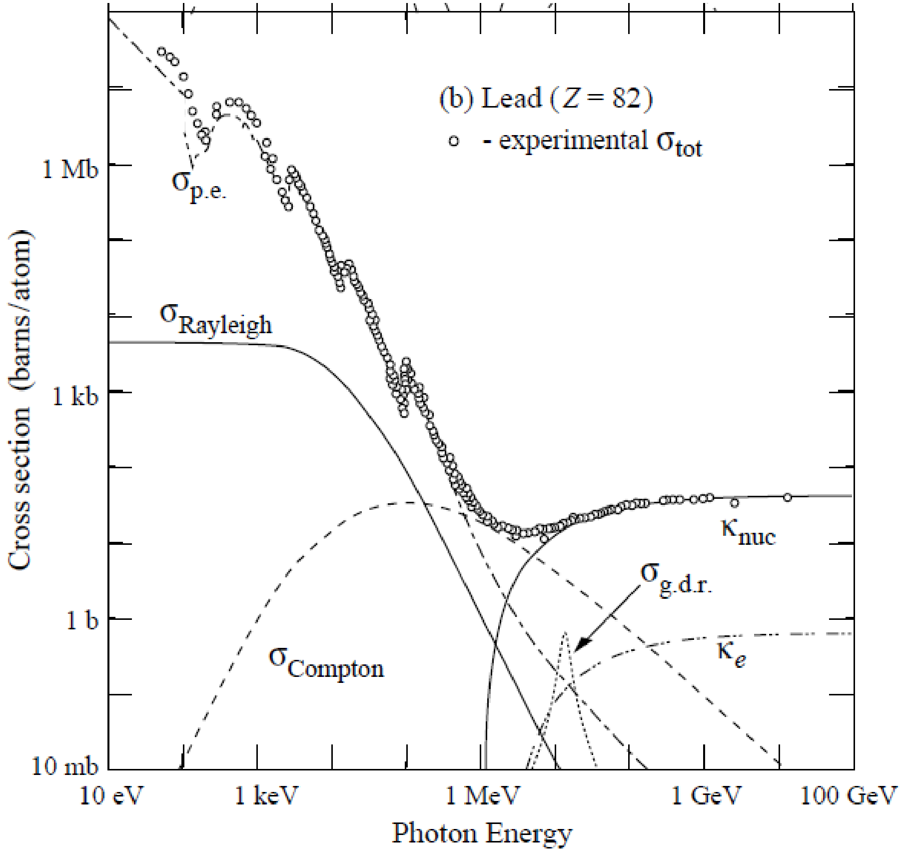


阪井寛志、OHO02

Cross section of pair production

Gamma rays of about 10 MeV or more are useful for generating positron beams.

- The cross-section rises from 1.022MeV, and the increase becomes moderate at 10-100MeV or more.
- The cross-section of pair production is proportional to the square of atomic number Z.



The Review of Particle Physics (2018)
M. Tanabashi et al. (Particle Data Group),
Phys. Rev. D 98, 030001 (2018),
http://pdg.lbl.gov/

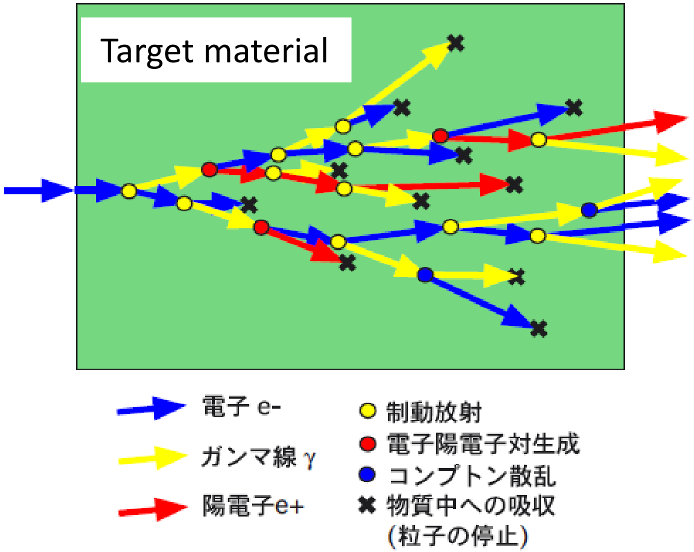
Positron beam production method

・E-driven scheme

- The electromagnetic shower is used when the electron beam is injected to the material.
- The bremsstrahlung and pair production are repeated to generate many electrons, positrons, and photons.
- Unpolarized positrons

・Undulator scheme

- Positrons are generated by pair production when gamma rays generated by a helical undulator are injected to a target material.
- Electromagnetic shower hardly occurs (a thin metal target is used.)
- Circularly polarized gamma rays can generate a polarized positron beam.



OHO’07, T. Kamitani

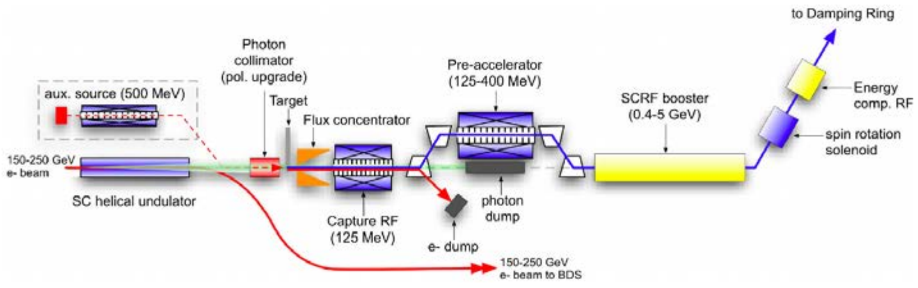
ILC positron beam

Electron beam energy	125	GeV
Number of particles in the bunch	2×10^{10}	
Number of bunches per pulse	1312	
Repetition rate	5	Hz
Main linac bunch separation	554	ns
Bunch separation in damping rings	6.15	ns
Damping ring injection acceptance		
Normalized betatron amplitude $(a_x + a_y)_{\max}$	0.07	mrad
Longitudinal emittance $(\Delta E/E \times \Delta z)_{\max}$	0.75×33	$\% \times$ mm

Report on the ILC Positron Source, Positron working group

Undulator scheme

E-driven scheme



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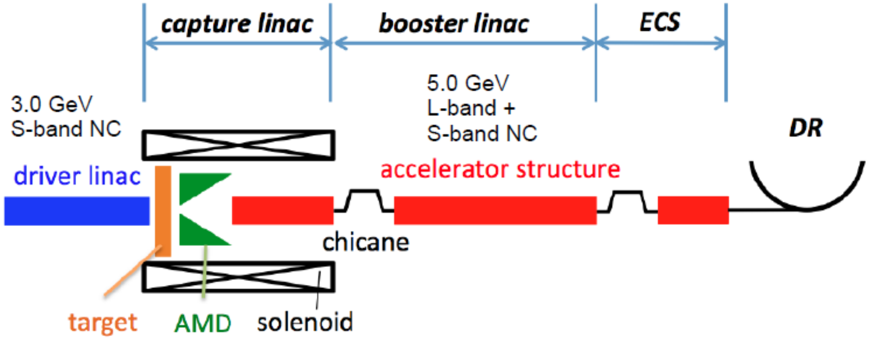
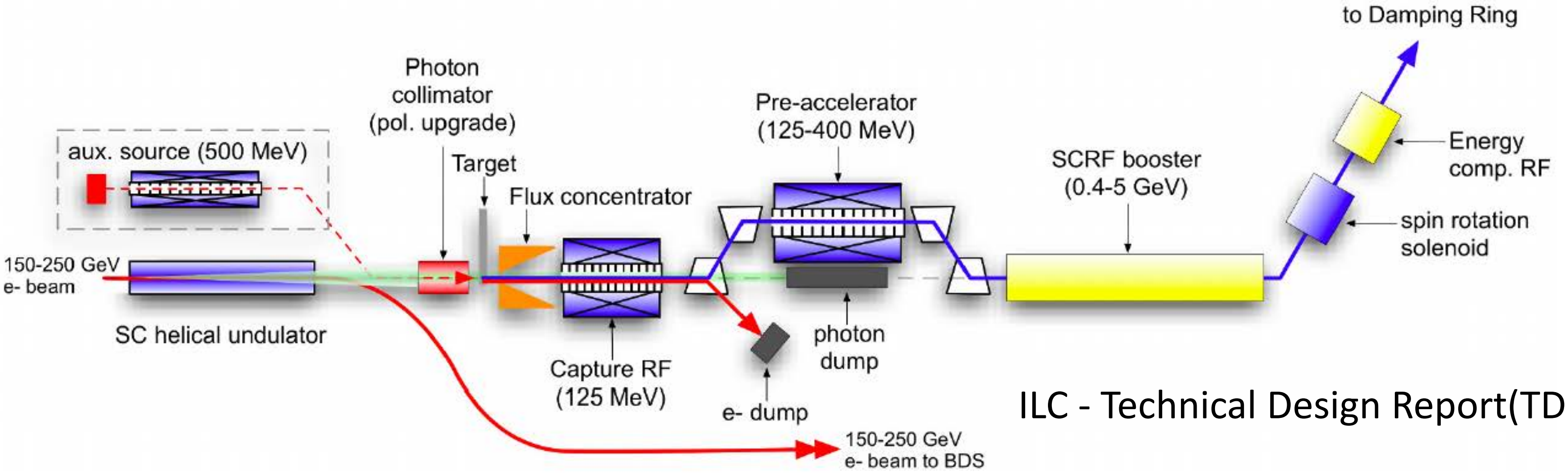


Undulator scheme

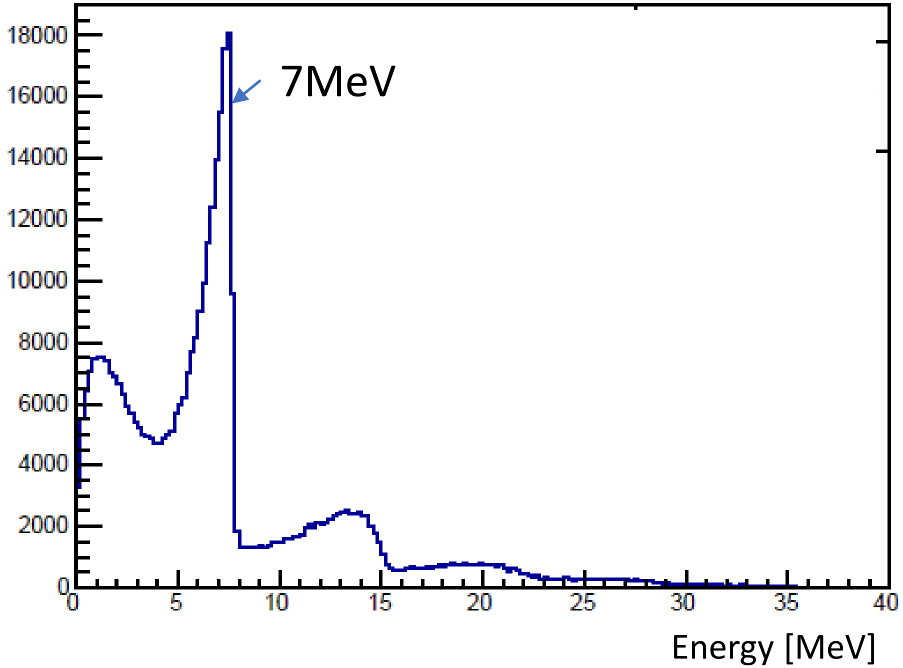


ILC - Technical Design Report(TDR)

- Gamma-rays from helical undulator drived by 125GeV e- beam is injected and positrons are generated by pair production.
- Rotating target, Material: Ti alloy
- Matching device : QWT
- Positrons are accelerated up to 400MeV in the capture linac and the pre-accelerator.
- Positrons are accelerated up to 5GeV by SC booster.
- A spin rotator rotates the spin in the vertical direction and electrons are injected to the damping ring.
- ECS reduced the energy spread for matching to DR aperture.

Gamma-ray generation using helical undulator

The electron beam energy was changed to 125 GeV.
→Gamma-rays energy is also reduced from 10 MeV to 7 MeV.
→ It causes the reduction of the intensity of gamma-rays because the cross section of pair production is decreased.
→Therefore, the length of undulator is extend from 147 m to 231m.

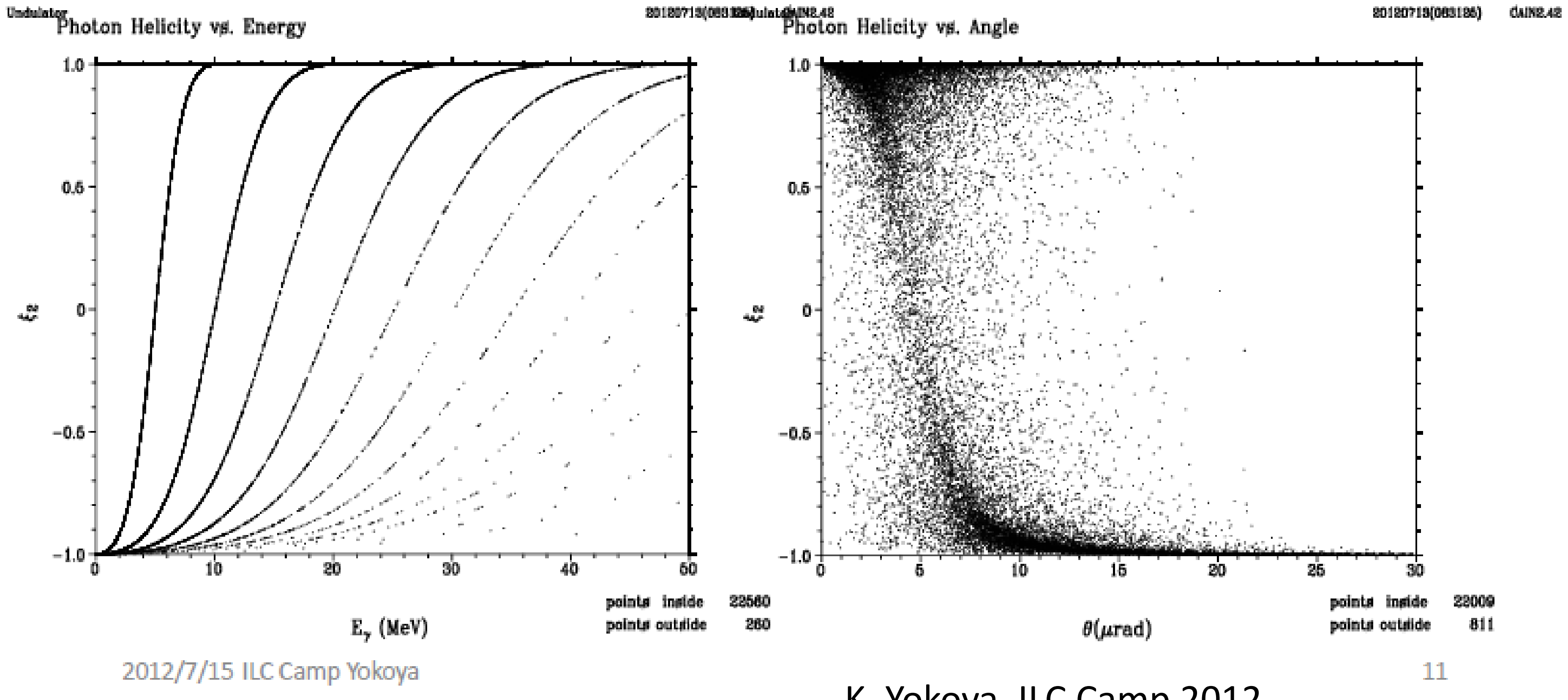

Energy distribution of gamma-rays


Undulator prototype made in Cockcroft
K=0.92 , λu 1.15cm、
Inner diameter: 5.85mm

Phys. Rev. Lett 107 (2011) 174803

Positron polarization

The polarization of gamma rays correlates with energy and scattering angle.
Higher polarization is derived by choosing higher energy gamma-rays.
Polarization : 30 – 60%



2012/7/15 ILC Camp Yokoya

11

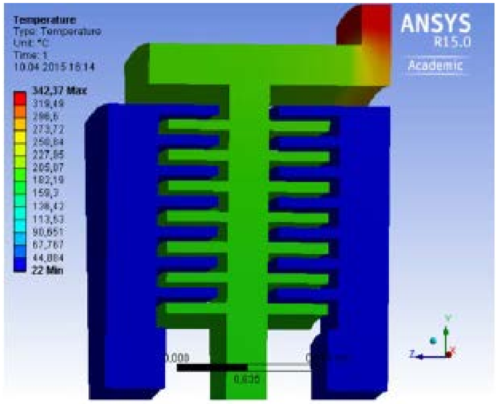
K. Yokoya, ILC Camp 2012

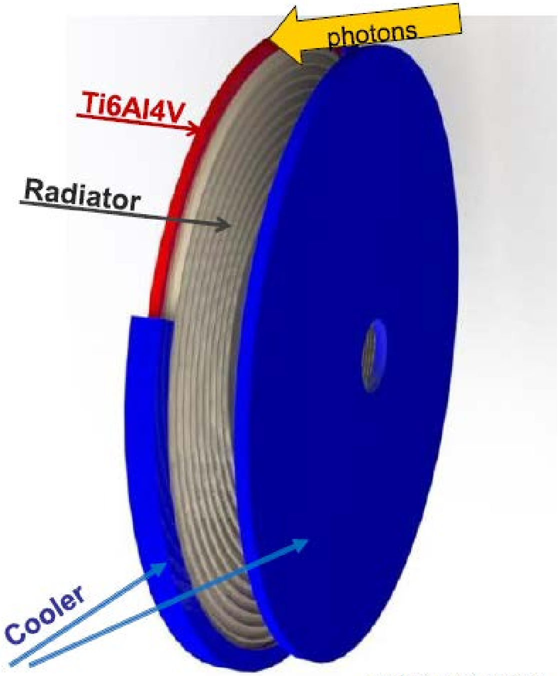
Rotating target (Undulator scheme)

A rotating target is used to reduce the thermal load on the target.

Rotating target：
  Material: Ti alloy(Ti6Al4V), thickness 7mm
  Weight: ~50kg
  Diameter: 1m
  Rotation speed: 100m/s (~2000 rpm)
  Bearing: magnetic bearing
  Cooling：Radiation cooling
  Heat load: 2kW

Average temperature < 460℃



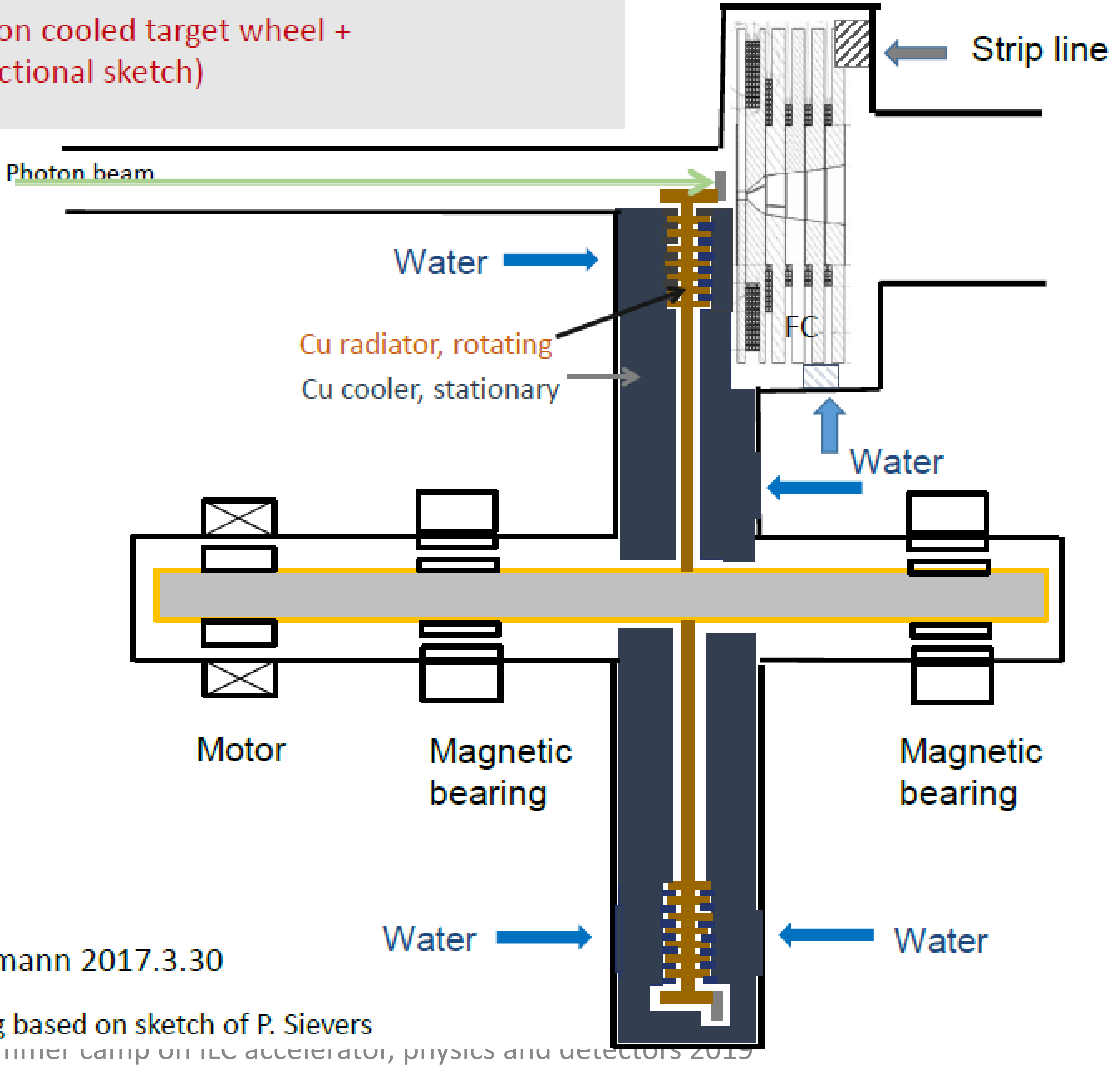


Sketch: Felix Dietrich

LCWS2017, S. Riemann

Rotating target

Radiation cooled target wheel +
FC (functional sketch)



S.Riemann 2017.3.30

Drawing based on sketch of P. Sievers

Optimization of Target thickness

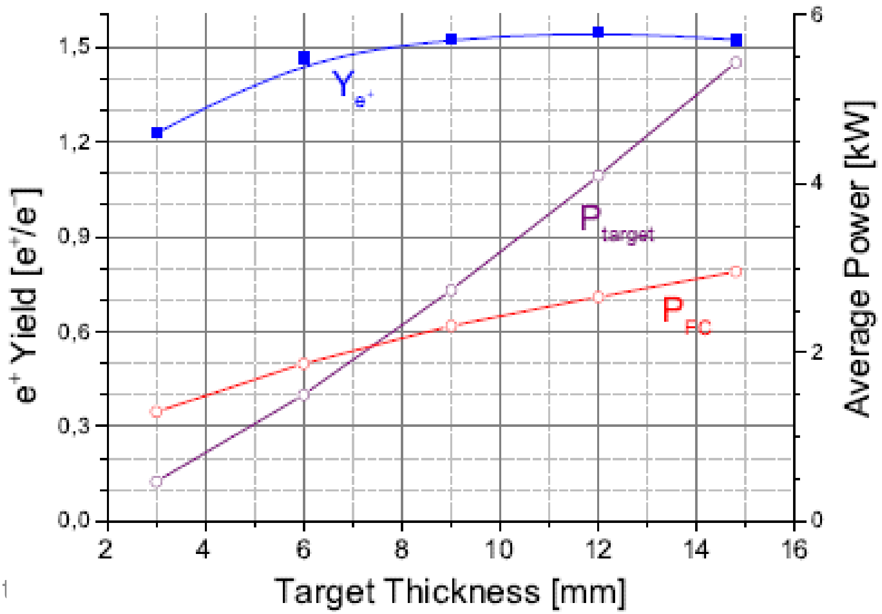
The electron beam energy was changed to 125 GeV.

- Gamma-rays energy is also reduced from 10 MeV to 7 MeV.
- Undulator length: 147 m → 231m to increase the intensity of gamma-rays.
- Heat load is increased.

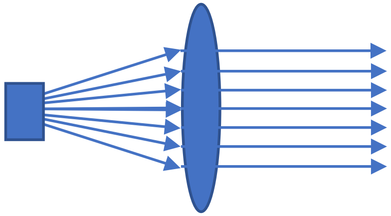
The thickness of the Ti alloy is reduced from 14 mm to 7 mm because the positron yield is almost unchanged.
The heat load is also reduced to 1/3.

e- 125GeV, 1312bunches
K = 0.85

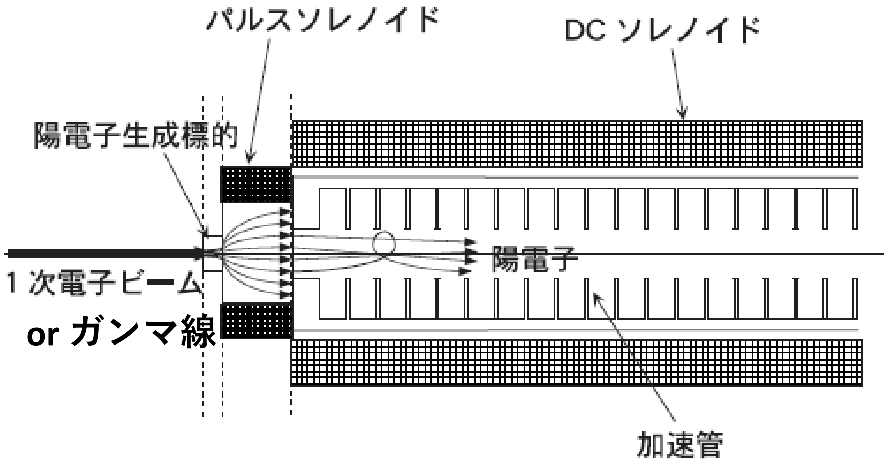
Fixed Undulator Length (231 m)



Optical matching device



The positron is captured by a strong solenoid magnetic field excited by a pulse current.



Optical matching device:

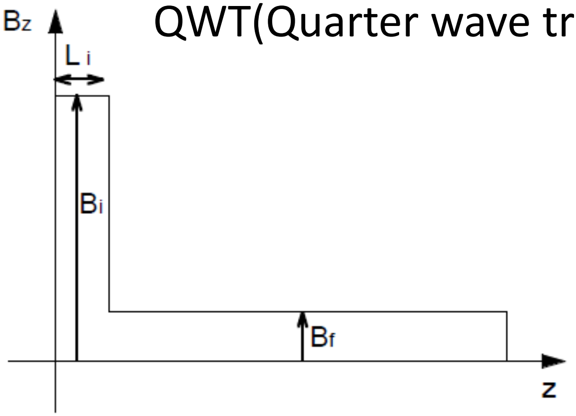
Small beam size, Large divergence

↓

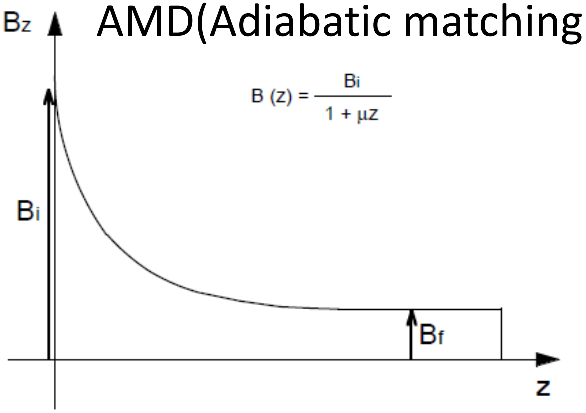
Large beam size, Small divergence

There are two method, QWT or AMD.

QWT(Quarter wave transformer)



AMD(Adiabatic matching device)



$$B\ (z) = \frac{B_i}{1 + \mu z}$$

OHO’07, T. Kamitani

Optical matching device(OMD)

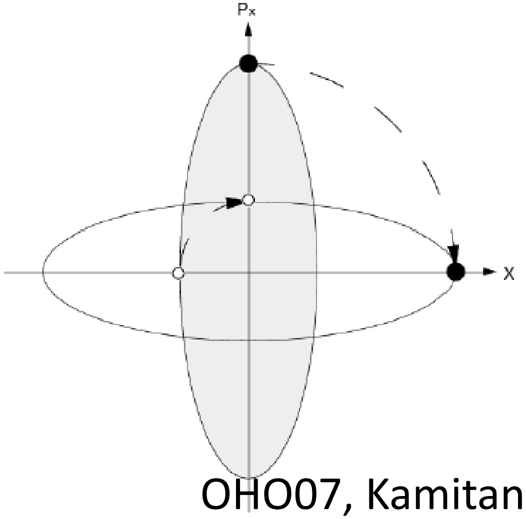
・QWT

- The QWT transforms 90deg in the phase space.
  It captures the positrons satisfying this condition.

$$p_z = \frac{eB_iL_i}{\pi}$$

Magnetic field: Bi
QWT length: Li
Momentum: pz

- Energy acceptance is narrow.



OHO07, Kamitani

・AMD

- AMD field is produced by a flux-concentrator.
- The eddy current is induced in the tapered conductor which makes the strong magnetic field.
- Energy acceptance is large.

Adiabatic invariant

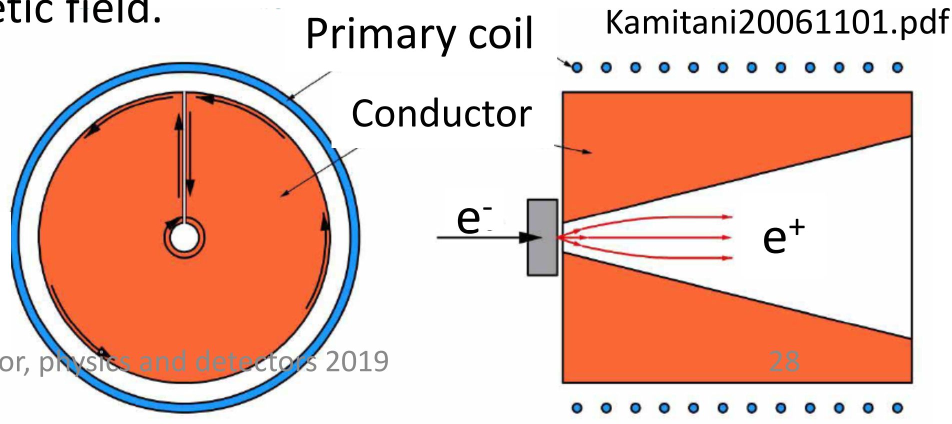
$$\int \sum_i p_i dq_i = \frac{\pi p_t^2}{eB}$$

adiabatic condition

$$\epsilon = \frac{\mu p_z}{eB_0} \le 0.5$$

CERN-94-01

Flux concentrator



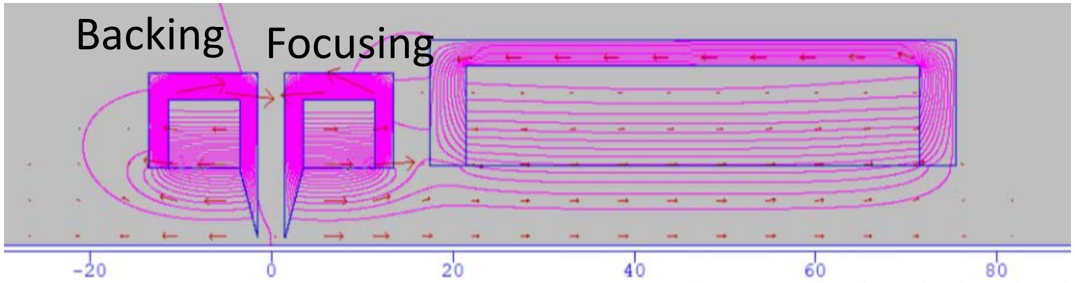
Kamitani20061101.pdf

OMD for undulator scheme

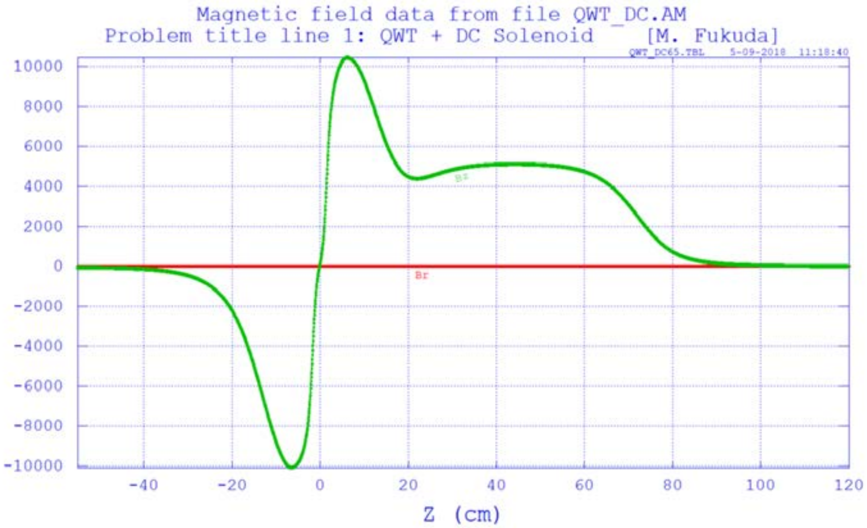
In ILC TDR, the matching device is flux concentrator.

- The strength of the magnetic field could not be maintained for 0.7 ms.
- Energy deposition is too large due to a small aperture (13mmϕ).

→ **Now we are considering using QWT.**



Designed by Wanming Liu

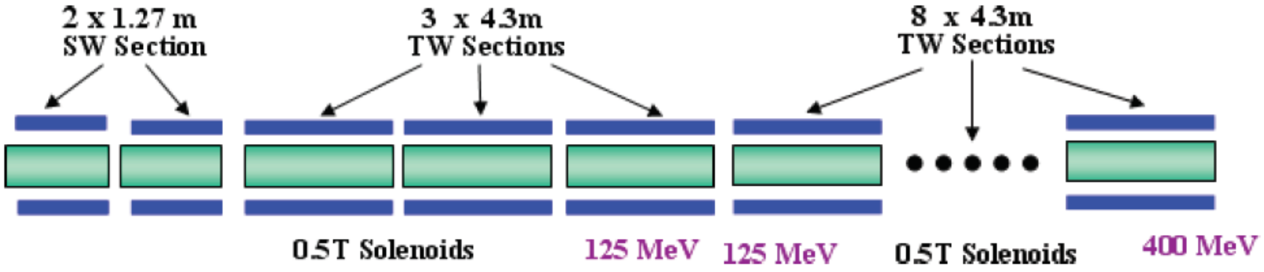


To prevent eddy currents on the rotating target, a reverse polarity backing coil is placed.
Magnetic field on the target is zero.

Capture section

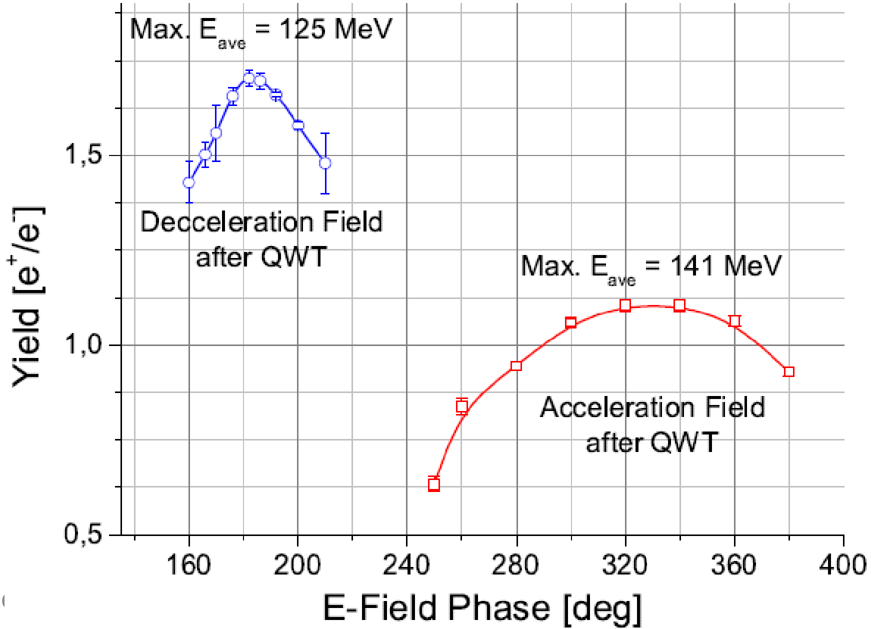
After the QWT, there is the capture section which consist of 2 SW accelerators and 11 TW accelerators.

These accelerators are put in the solenoid field.



Deceleration phase capture

When positrons are put on the deceleration phase, the number of captured positrons increases.



LCWS2017, A. Ushakov

Positron Yield for Undulator scheme

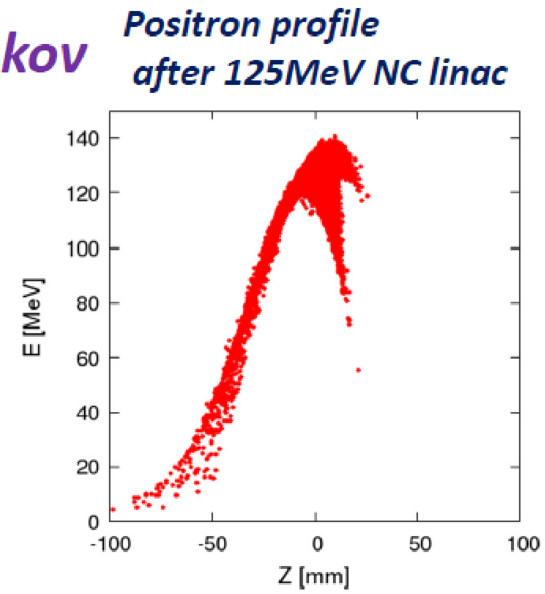
$$\text{Yield (e+/e-)} = \frac{\text{Number of positron in DR}}{\text{Number of primary electrons}}$$

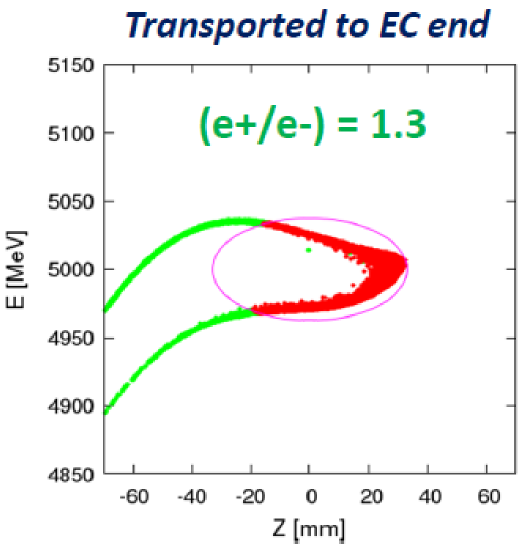
Tracking Simulations

simulated by Andriy Ushakov

Used parameters are:

- **126.5 GeV e- beam*
- ** 231 m undulator with K = 0.85*
- ** 401 m distance between the middle of undulator and the target*
- ** 7 mm target thickness (Ti6Al4V)*
- ** QWT with 1.04 T field solenoid downstream the target*
- ** Deceleation E-field downstream QWT*

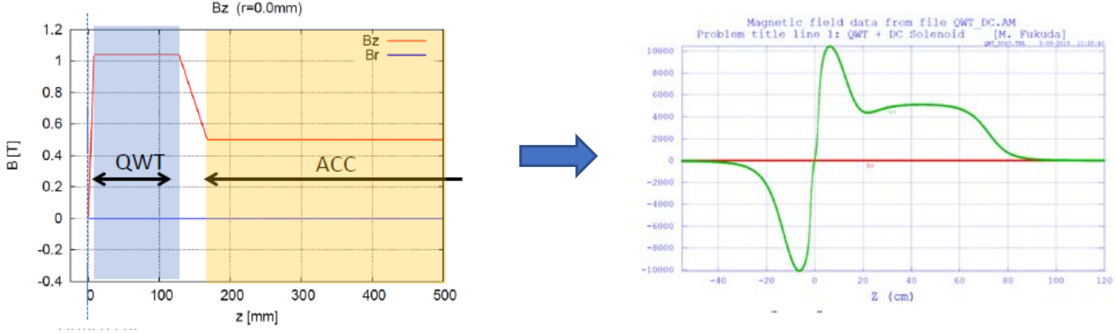

Positron profile after 125MeV NC linac


Transported to EC end

Analyzed by T. Okugi

Positron Yield for Undulator scheme

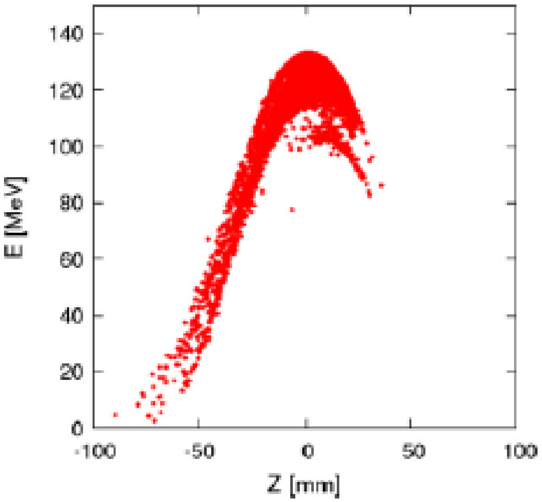
Input magnetic field



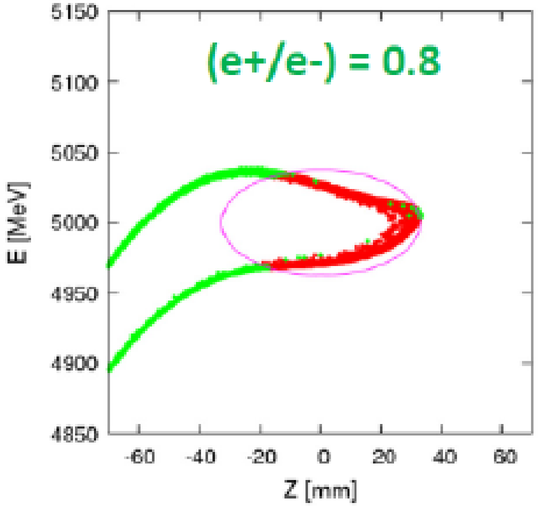
simulated by M. Fukuda

Target: Ti alloy (Ti-6AL-4V), 7mm
QWT: 1.04T
ACC SOL: 0.5T
ACC SWx2: Eacc 15.2MV/m
ACC TWx3: Eacc 7.2MV/m

Positron profile after 125MeV NC linac

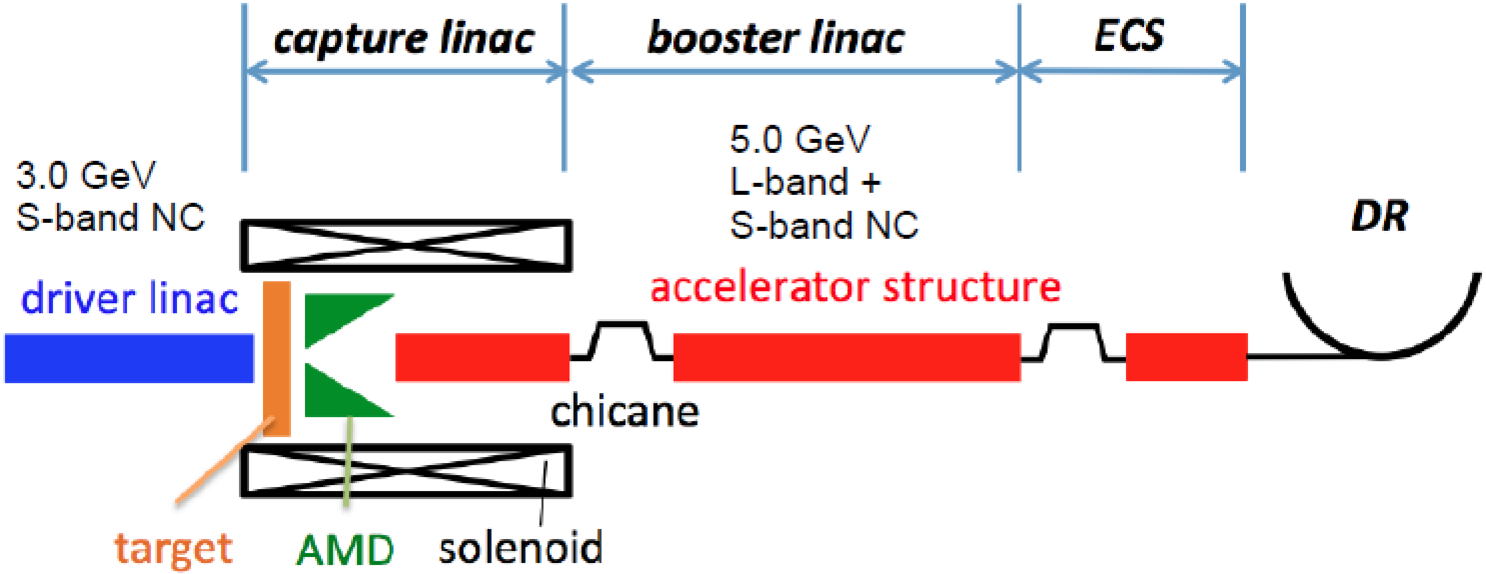


Transported to EC end



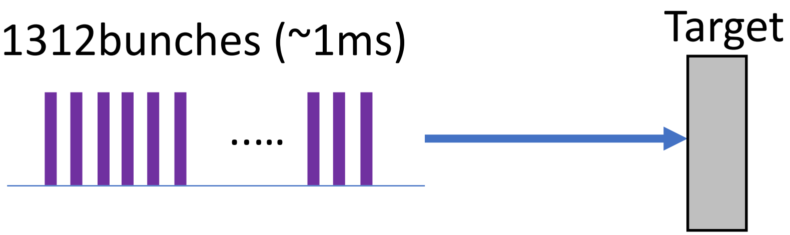
Analyzed by T. Okugi

E-driven scheme

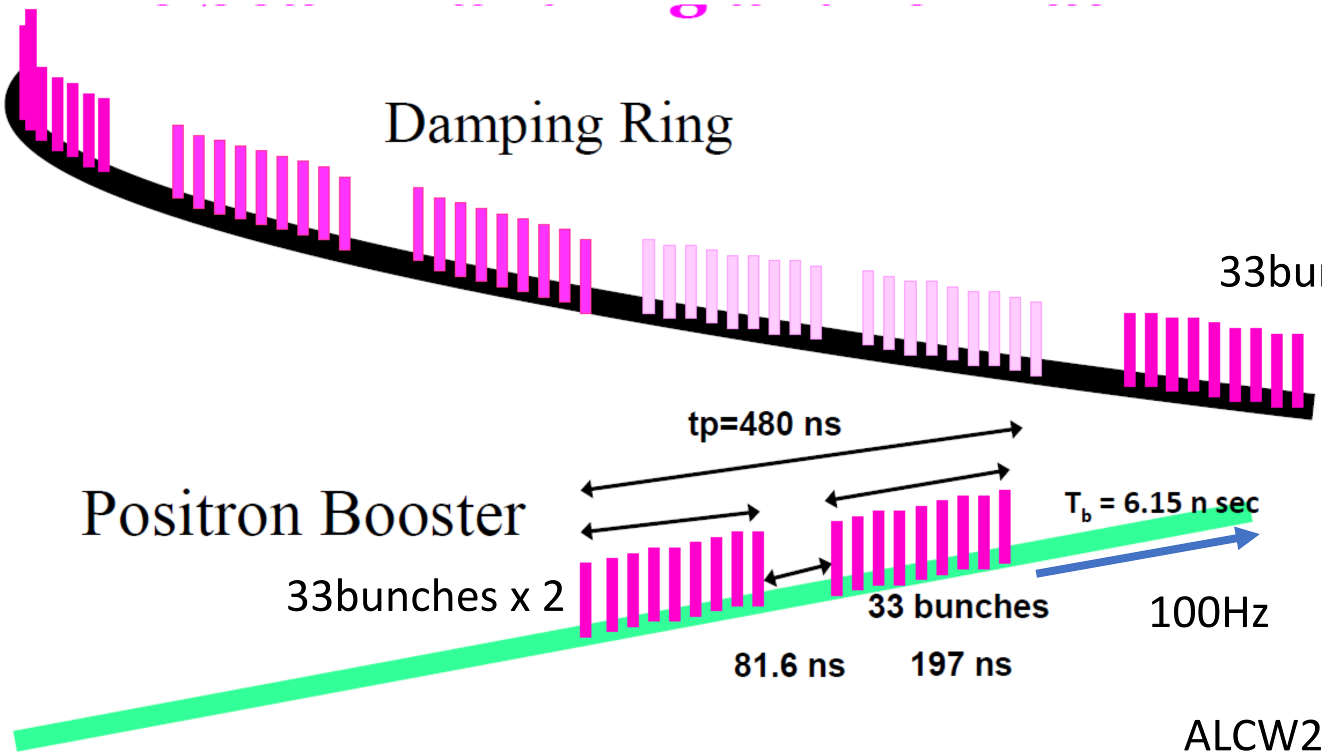


- 3GeV e- beam is injected to the target and positrons are generated by an electromagnetic shower.
- Rotating target, Material: W26Re
- Matching device : Flux concentrator
- Positrons are accelerated up to 250MeV in the capture linac.
- Chicane compresses the bunch length.
- Positrons are accelerated up to 5GeV by L-band and S-band NC accelerators.
- ECS reduced the energy spread for matching to DR aperture.

Pulse structure



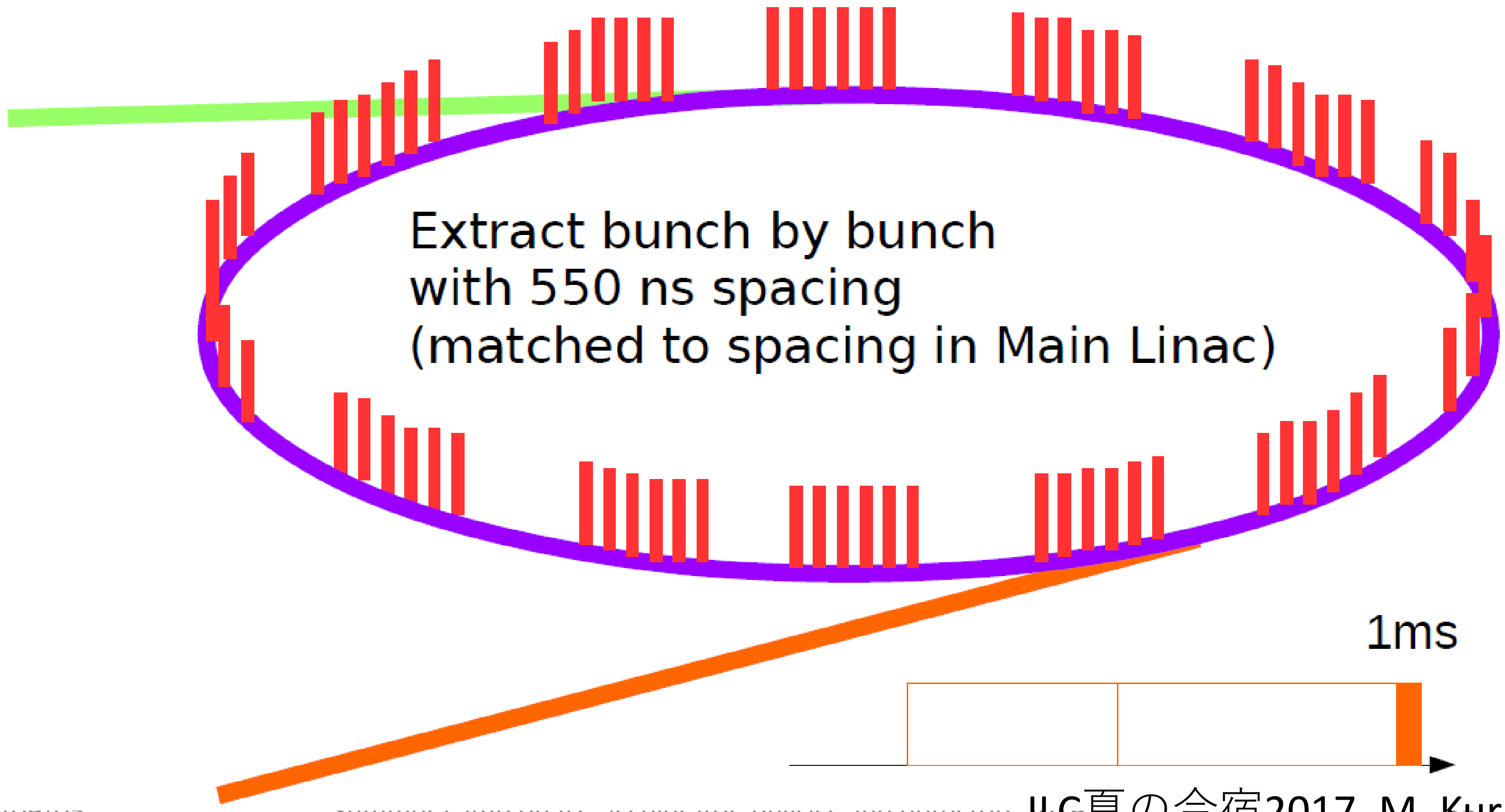
Heat load is too large.



ALCW2018, M. Kuriki

Beam extraction from DR

Multi-pulses for 1 pulse collision



Extract bunch by bunch
with 550 ns spacing
(matched to spacing in Main Linac)

ILC夏の合宿2017, M. Kuriki

Target

Requirements

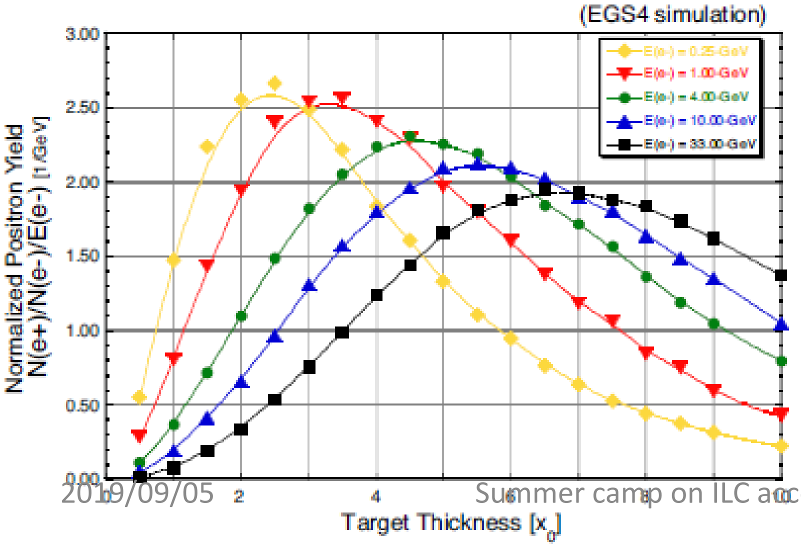
High Z (Cross section of Bremsstrahlung $\propto Z^2/A$)

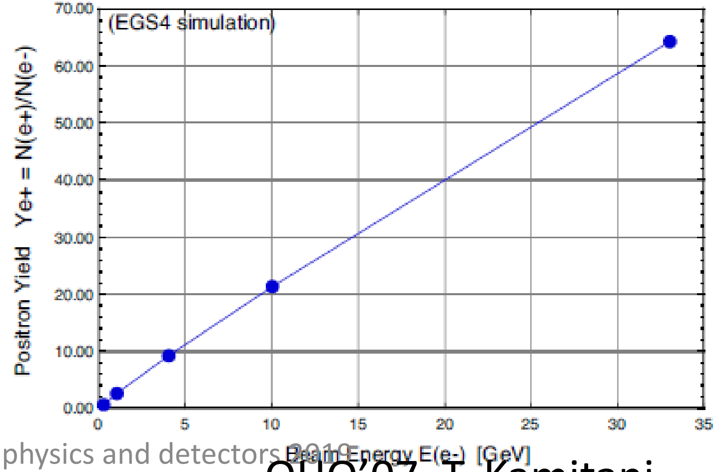
High melting point

→Tantalum(^{73}Ta), Tungsten(^{74}W), Tungsten- rhenium alloy (W-Re)

ILC:

Target material: W26Re 16mm (~4χ_0)





OHO’07, T. Kamitani

Rotating target

Rotating target：

Material: W26Re, thickness 16mm

Weight: ~70kg

Diameter: 0.5m

Rotation speed: 5m/s (~225 rpm)

Vacuum seal: ferrofluid seal

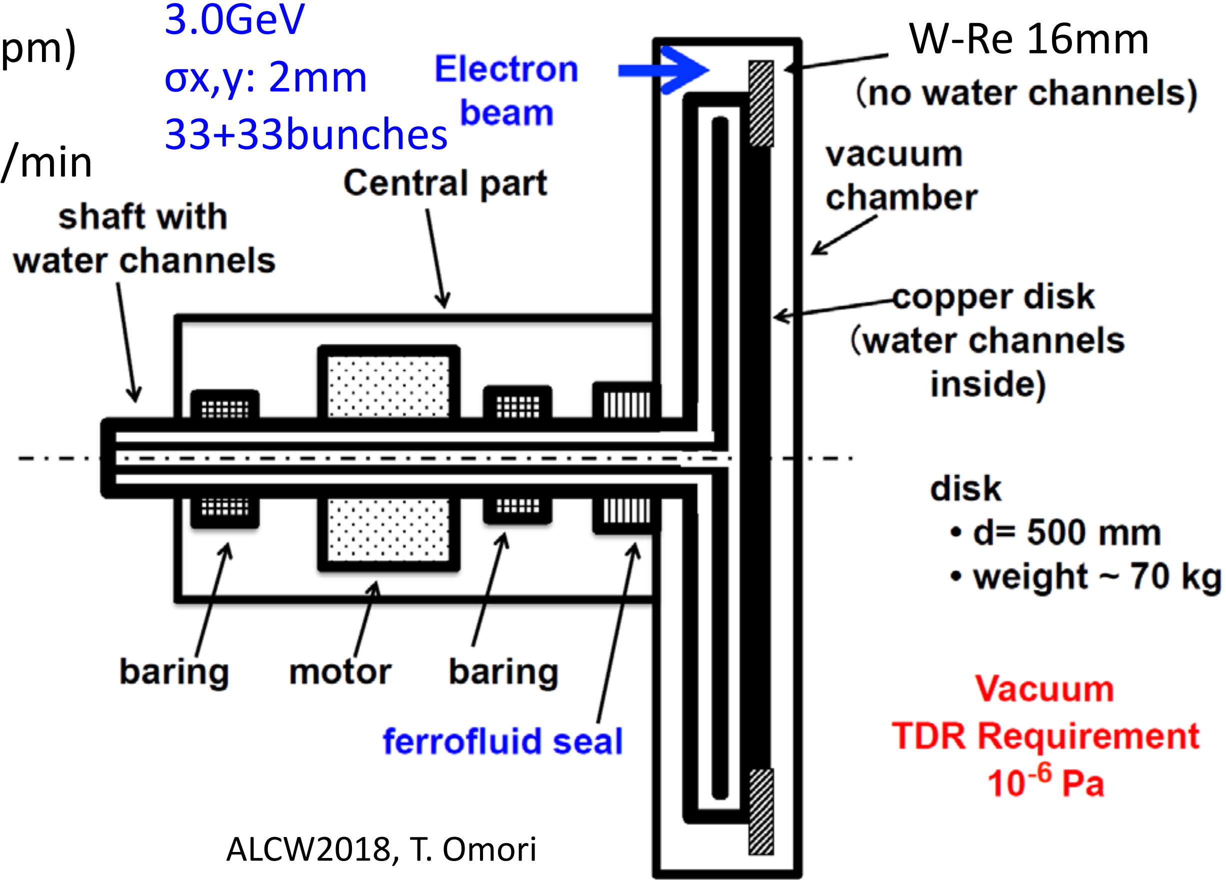
Cooling：Water cooling, 60L/min

Heat load: 16kW

3.0GeV

σx,y: 2mm

33+33bunches

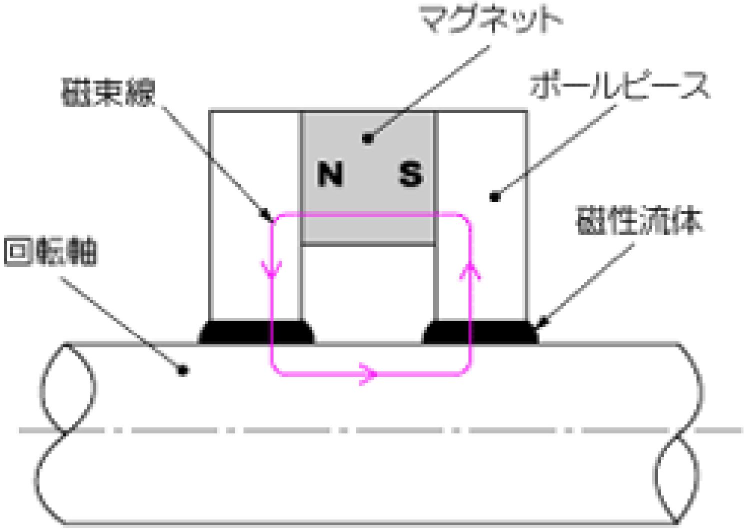


disk
- d= 500 mm
- weight ~ 70 kg

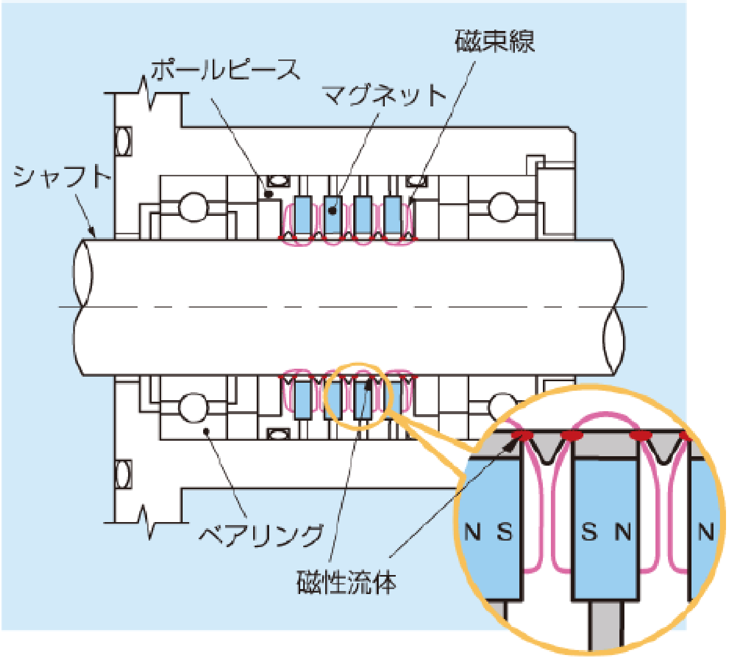
Vacuum
TDR Requirement
10^{-6} Pa

ALCW2018, T. Omori

Ferrofluid seal



磁性流体シールの基本構造



http://www.rigaku-mechatronics.com/technology/

Heat load for Rotating target

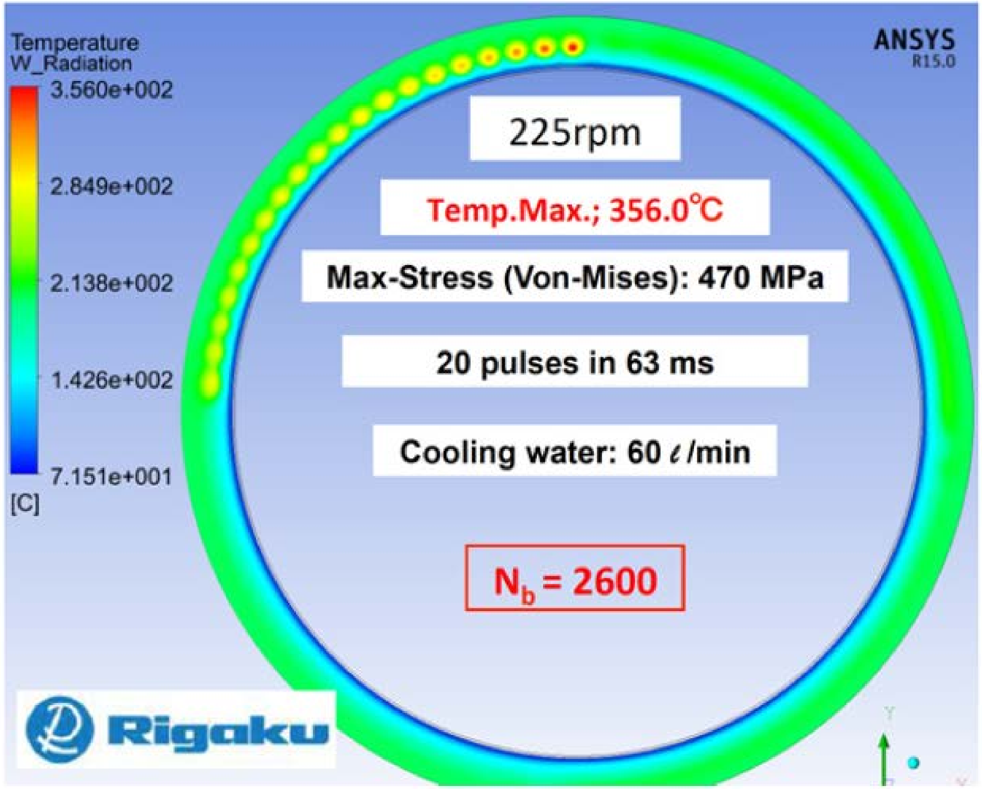


Figure 3.11: The result of the heat and stress simulation.

Report on the ILC Positron Source, Positron working group

Optical matching device (E-driven)

Flux concentrator is used in E-driven scheme.

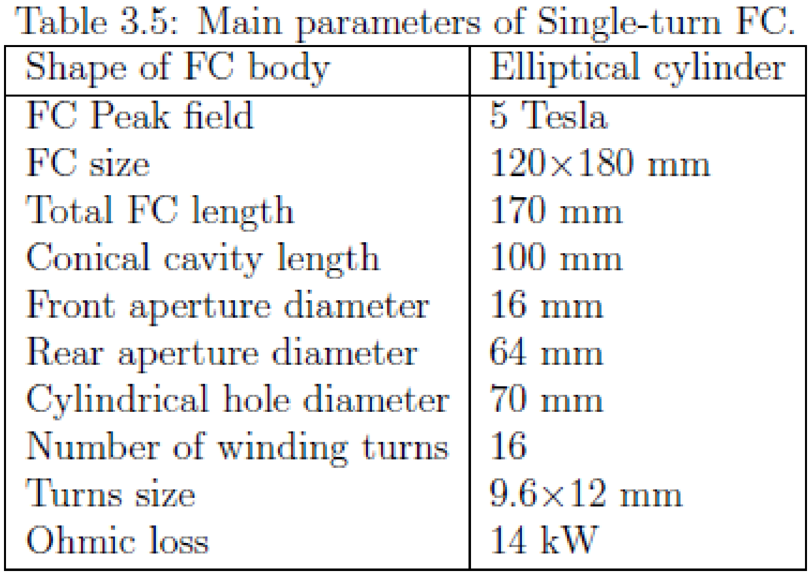
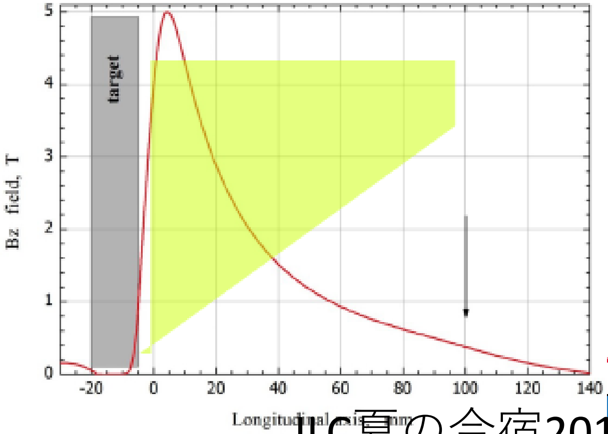


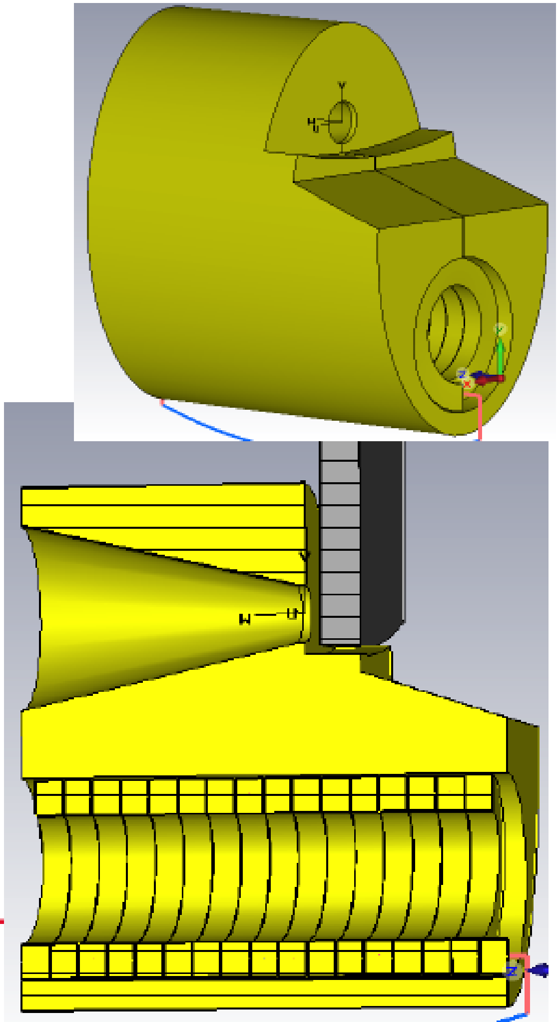
Table 3.5: Main parameters of Single-turn FC.

Shape of FC body	Elliptical cylinder
FC Peak field	5 Tesla
FC size	120×180 mm
Total FC length	170 mm
Conical cavity length	100 mm
Front aperture diameter	16 mm
Rear aperture diameter	64 mm
Cylindrical hole diameter	70 mm
Number of winding turns	16
Turns size	9.6×12 mm
Ohmic loss	14 kW

s.

Report on the ILC Positron Source, Positron working group





Capture section

Positrons are accelerated to 250 MeV by 36 L-band SW accelerator tubes surrounded by 0.5 T solenoid field.

The aperture of the acceleration tube is 60mm in diameter.

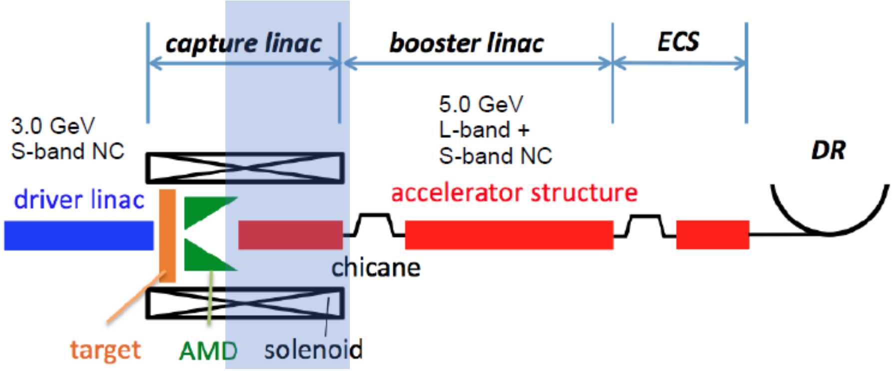
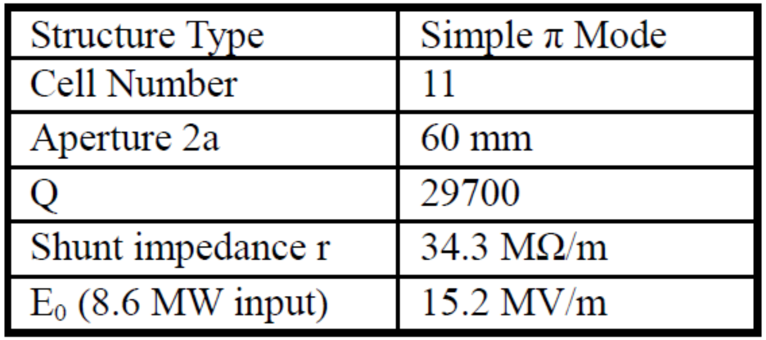


Table 1: Parameters of SW stricture.



Structure Type	Simple π Mode
Cell Number	11
Aperture 2a	60 mm
Q	29700
Shunt impedance r	34.3 MΩ/m
E_0 (8.6 MW input)	15.2 MV/m

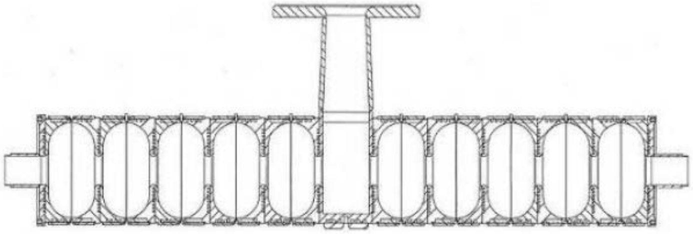


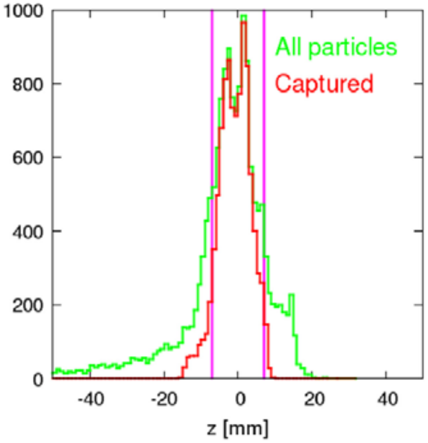
Figure3: 11–cell SW structure.

J. W. Wang SLAC-PUB-12412

Number of positrons at the end of capture section (250MeV)

The phase of accelerating field is scanned to find the maximum point of number of positrons.

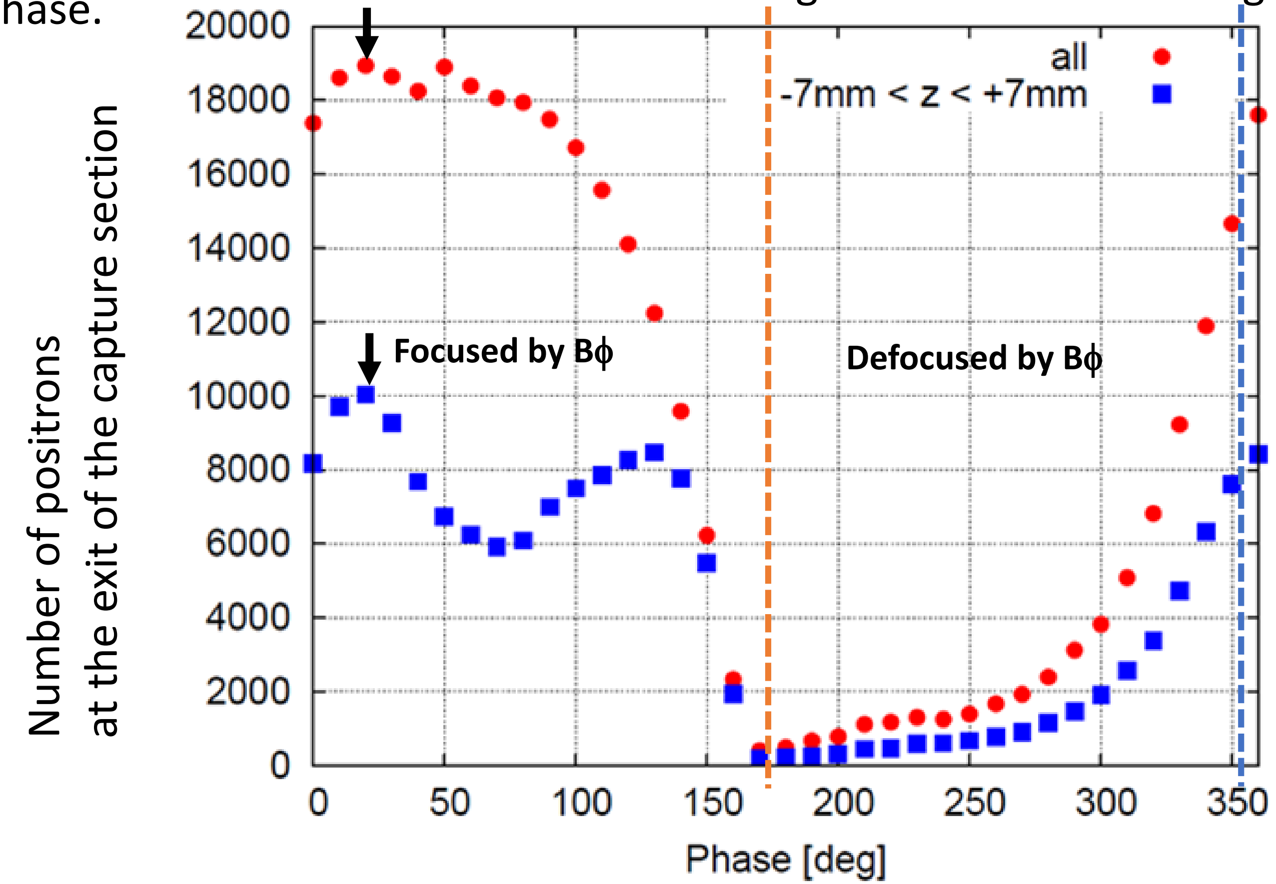
The best phase is +30deg from the decelerating phase.
→ 20deg in this graph.



Positrons within +/-7mm from the peak of longitudinal position distribution are captured in DR.

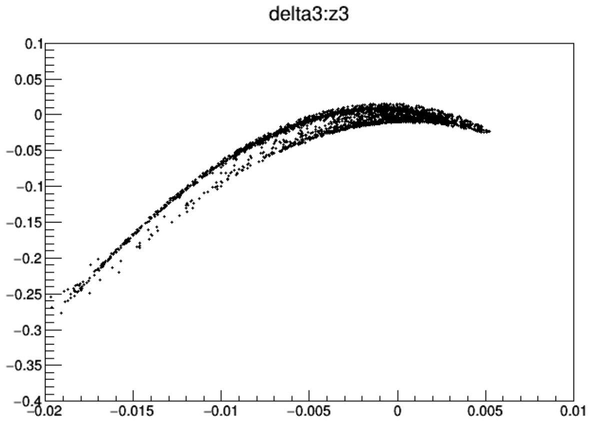
Accelerating phase
172deg

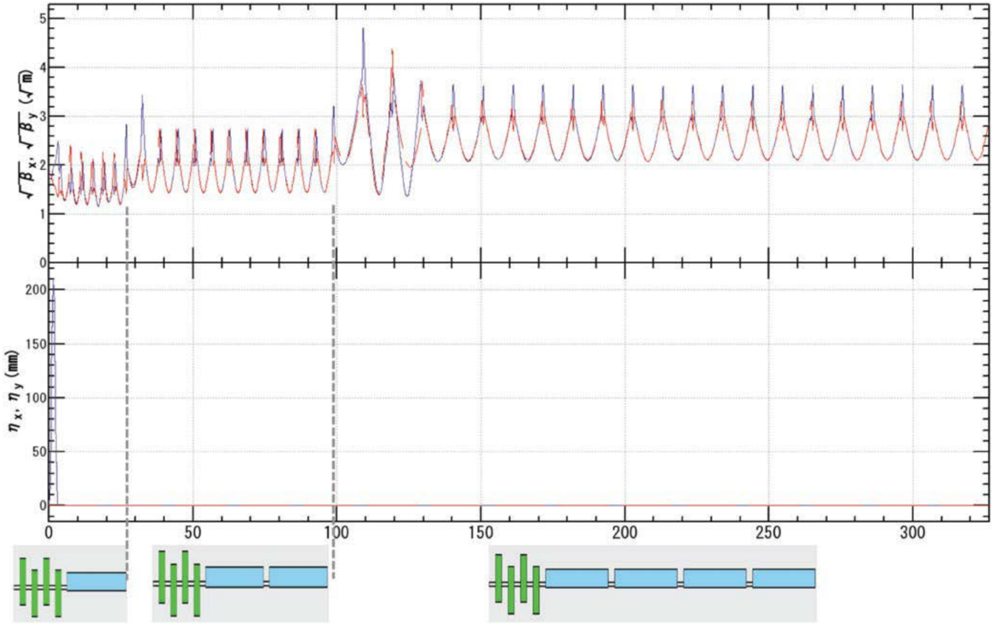
Decelerating Phase
352deg



Booster section

Positrons are accelerated to 5 GeV by L-band and S-band TW accelerator tubes.

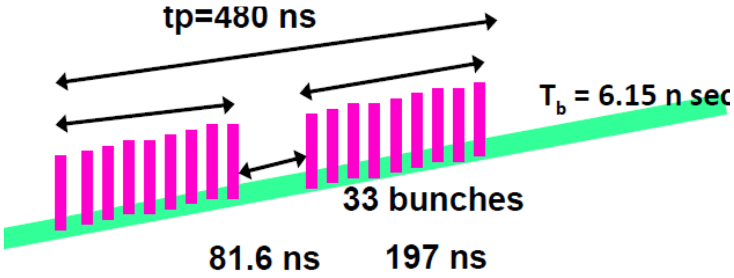




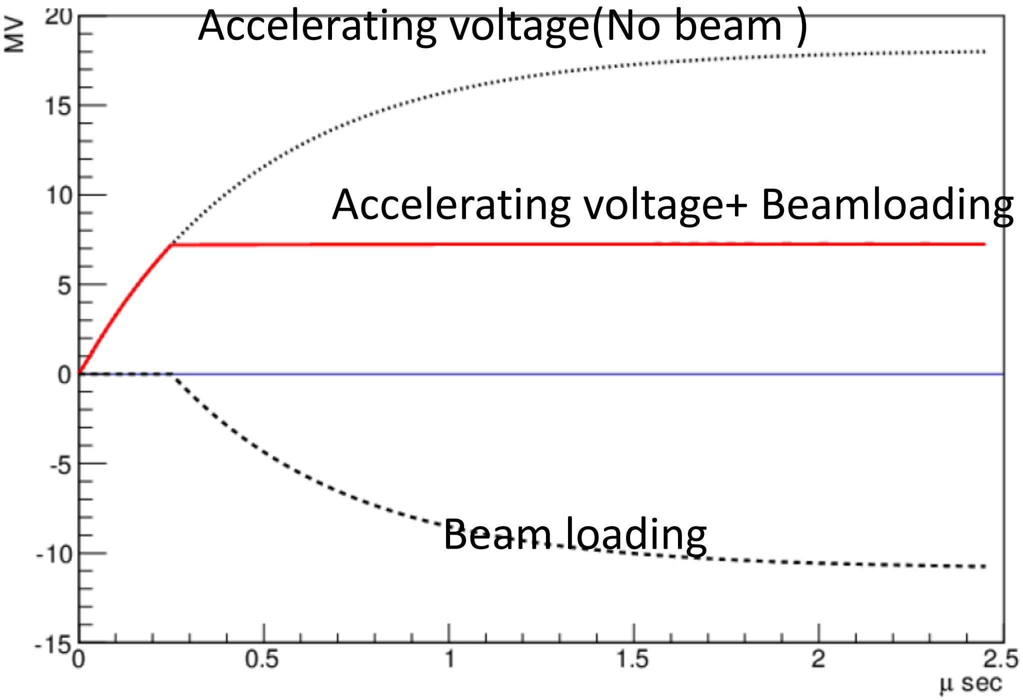
Lattice configuration	Number of lattice cells	Accelerating energy	energy at the exit
4Q + 1L	14	243 MeV	493 MeV
4Q + 2L	28	974 MeV	1467 MeV
4Q + 4L	19	1321 MeV	2788 MeV
4Q + 4S	23	2345 MeV	5133 MeV

Beam loading compensation

Positrons are accelerated by doublet multi-bunch pulse.



The beam loading compensation works well. Flatness is less than 0.1%.

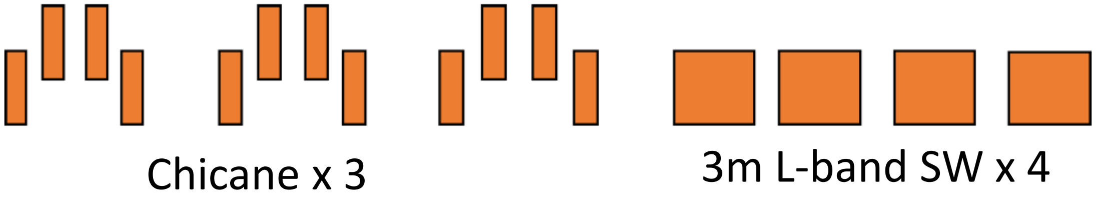


ILC夏の合宿2017, M. Kuriki

Energy Compressor Section(ECS)

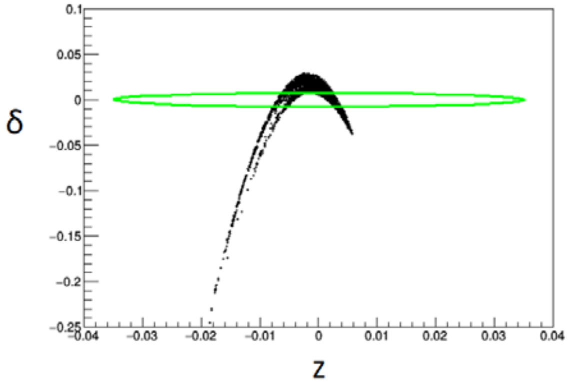
ECS reduces the energy spread.

Damping ring acceptance:
ΔE × Δz <=(±37.5 MeV) × (±3.5 cm).

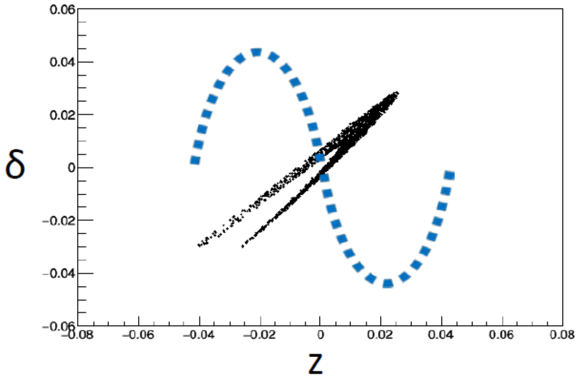


Low energy positrons will delay after passing chicanes.
The energy in a bunch is modulated by RF in accelerating tubes.

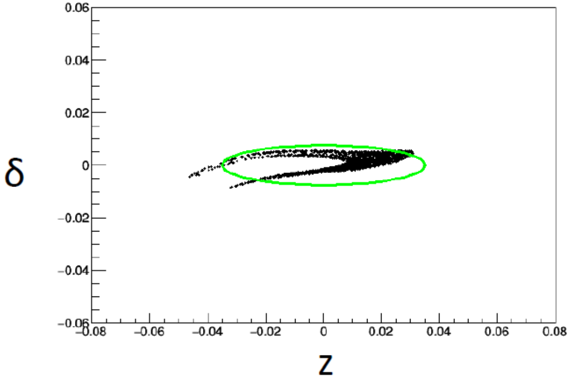
Booster出口の
縦方向位相空間分布



3つのシケイン通過後



ECS出口



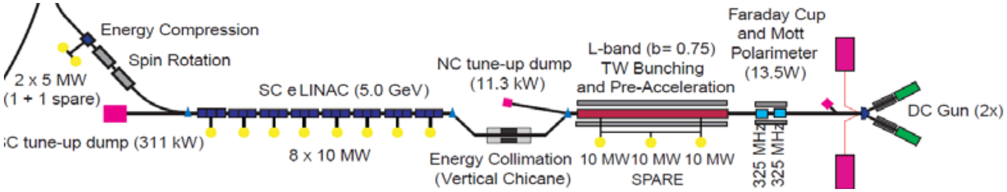
Z: longitudinal position、δ: エネルギー偏差

Positron Yield in DR:
Y(e+/e-) : 1.3

第15回 高輝度・高周波電子銃研究会、名越久泰

Summary

- Electron source
  - The design by simulation of the electron source is basically completed.
  - Strain-compensated superlattice GaAs/GaAsP, Pol. 92%, Q.E. 1.6%
  - 500kV DC electron gun



- Positron source
  - Undulator scheme, E-driven scheme
  - Both schemes continue to optimize the design through simulation.
  - Tunnel design including arrangement of beamline, radiation shield and so on is under consideration.