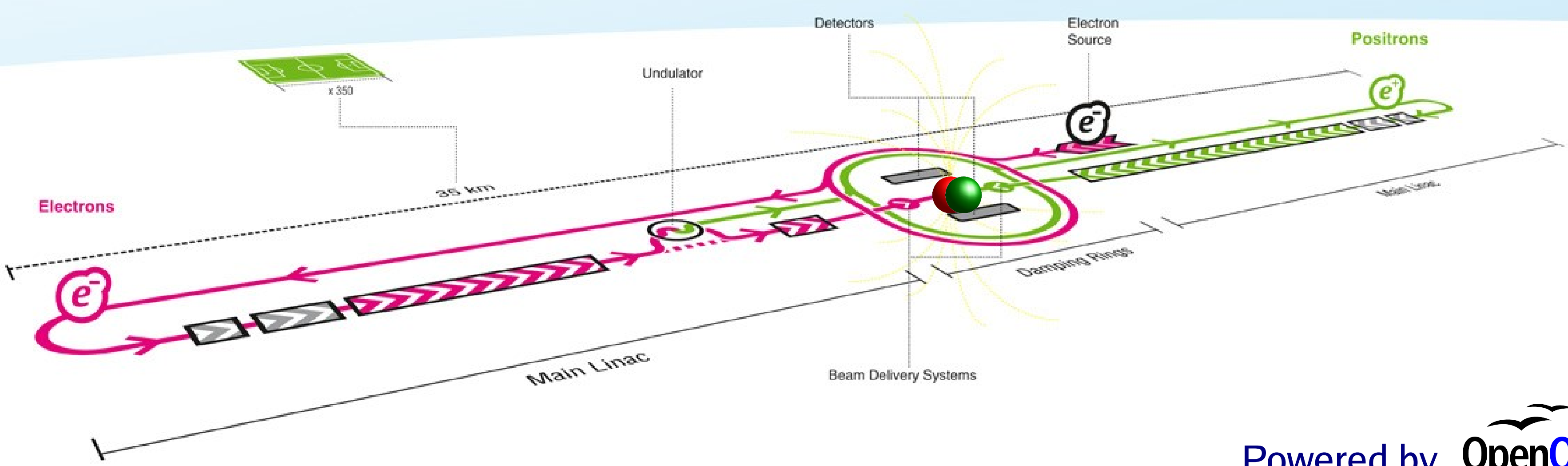
Positron Source for Linear Colliders

KURIKI Masao (Hiroshima/KEK)



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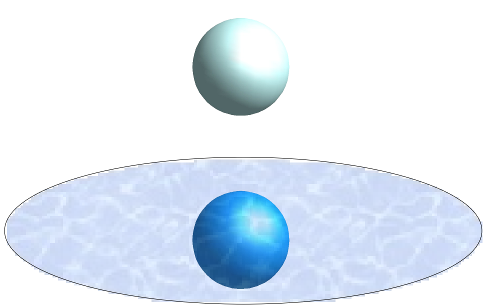
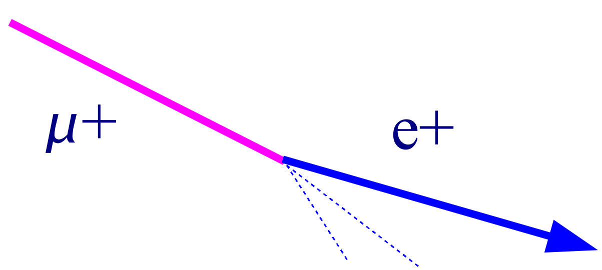
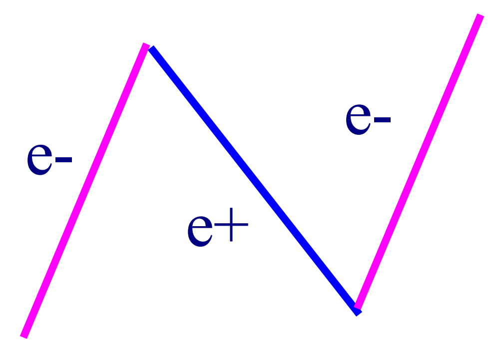
Contents

What is Positron?

- 1928: Dirac equation suggested electrons with negative energy. Hole hypothesis: "vacuum" is filled with this negative energy electrons to prohibit Klein's paradox. "hole" in the see of this electrons, acts as positrons.
- 1932:Anderson discovered positrons in cosmic rays with cloud chamber.
- In the modern field theory, positrons is considered to be electrons, which propagate inversely.

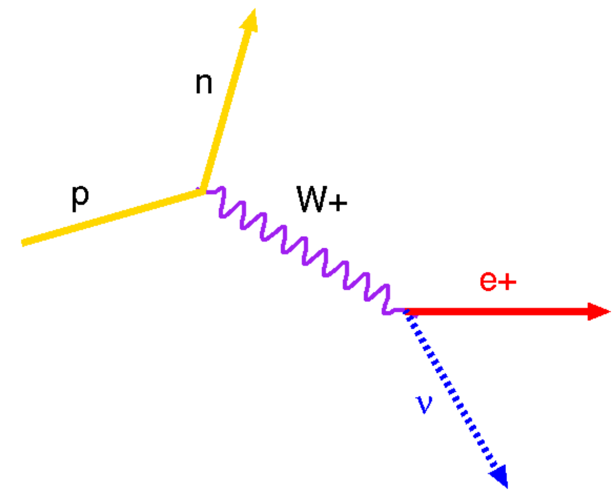


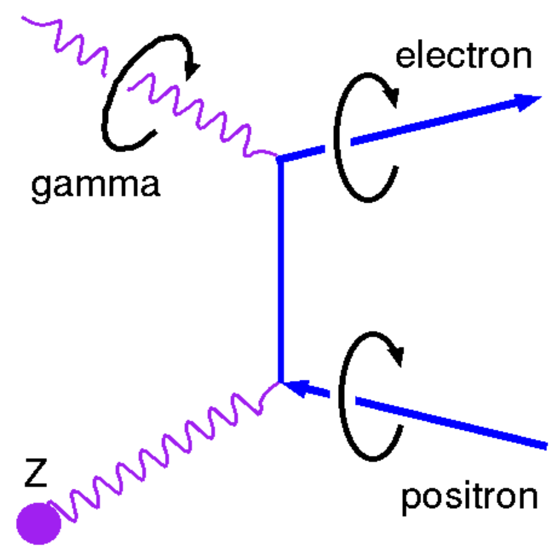




Positron Production (1)

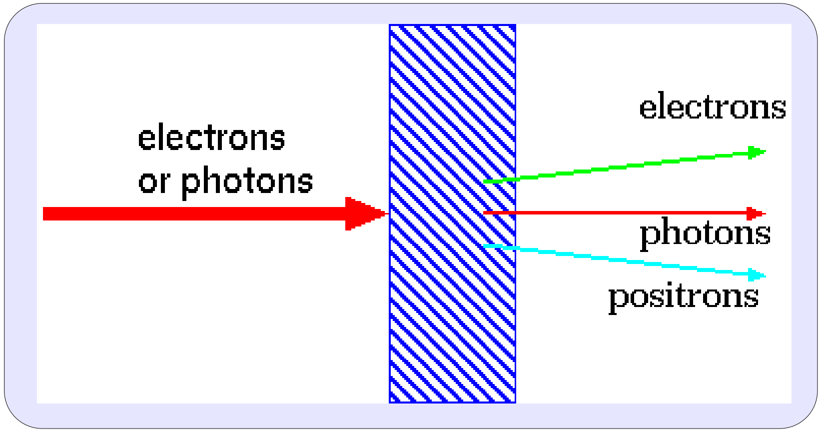
- There is only few positrons in nature.
- Two ways to produce positrons :
  - Create radio-active elements, which beta + decays;
    p ->n e+ neutrino.
  - Pair-creation ; gamma -> e+ e-
- All of the positron beam sources, employ the pair-creation process, which overcomes Compton scattering above 10 MeV region. Photon energy must be more than 10 MeV.





Positron Production (2)

- Pair-Creation is the only process, which generates positron with a time structure.
- More than 10MeV gamma ray is required for this process.
  - EM shower induced by injecting electron beam into a heavy material. (Electron Driven scheme)
  - High energy gamma is directly produced by
    - Undulator
    - Compton back scattering.



EM Shower Regime

Positron Generation
Positron Capture
Positron Source
ILC Positron Source
Summary

- Electron energy becomes 1/e by passing one radiation length, X_0. The lost energy is shared by the shower particles.
- EM shower is mixture of e-, e+ and gamma.
- # of particles is increased by developing the EM shower and decreased by absorption with the target. # of particle is peaked at the shower max. The shower max is a function of the initial energy; 3 – 5 X_0 for several GeV.
- Positron beam is obtained by extracting it from the mixed flux.

Non Shower Regime

- Principally, high energy photon can be a replacement of the high energy electron, but such high-energy photon is hard to obtain from undulator or Compton scattering (10 – 60 MeV).
- In such energy region, EM shower is not grown and photons directly generate positrons through pair creation process.
- Due to this simplicity, if the photons are polarized, the positrons are also polarized. (Polarized Positron)

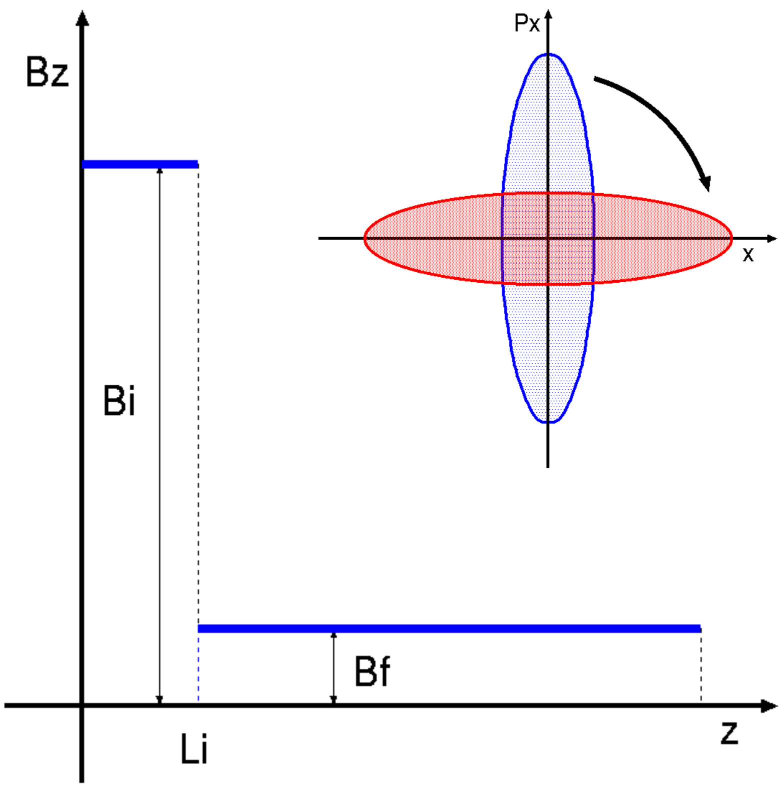
Positron Capture (1)

- Positron Generation
- **Positron Capture**
- Positron Source
- ILC Positron Source
- Summary

- Positrons are generated as a mixture of positrons, electrons, and gammas in a large area of phase space.
- To form the positron beam, we have to
  - **Select only positrons from the flux.**
  - **Capture the positron in a RF bucket.**
- The generated positrons are distributed in a small spot size and in a large momentum space.
- This divergent beam has to be converted into a parallel beam to fit the accelerator acceptance.
- There are two devices:
  - **QWT (Quarter Wave Transformer)**
  - **AMD (Adiabatic Matching Device)**

QWT(1)

- QWT consists from initial strong solenoid field , B_i, and weak solenoid field, B_f, along z direction.
- It has a good acceptance for a specific energy (longitudinal momentum, p_z), which is determined with $B_i L_i$.
- It transforms 90° in the phase space, that is why it is called as Quarter Wave Transformer.



QWT(2)

- Positrons at (r,z)=(0,0) circulates with radius $\rho = \frac{p_t}{eB_i}$ in r-ϕ plane.
- If a positron travels L_i in z and $\pi\rho$ (180°) in r-ϕ, the momentum satisfy,

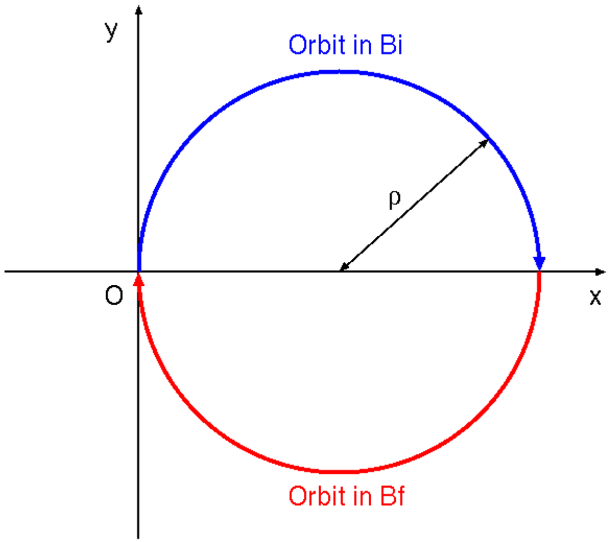
$$p_z = \frac{eB_i L_i}{\pi} \qquad \frac{L_i}{\pi\rho} = \frac{p_z}{p_t}$$

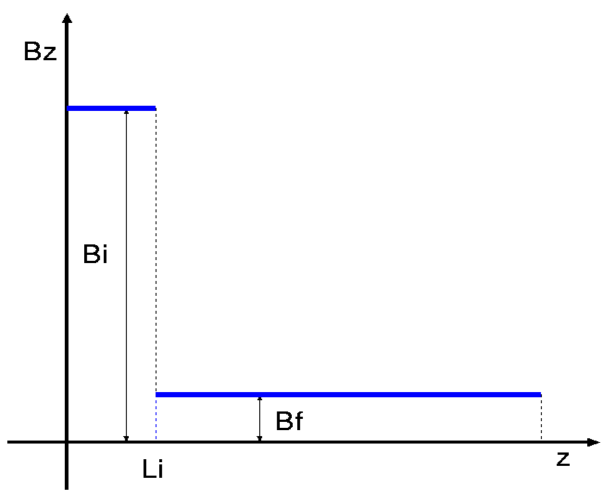
- The positron is kicked at the boundary of B_i and B_f and the transverse momentum becomes,

$$p_t \rightarrow p_t \frac{B_f}{B_i}$$

- The orbit radius in B_f area is

$\rho_f = \frac{p_t}{eB_f}\frac{B_f}{B_i} = \frac{p_t}{eB_i}$, which is same as ρ.



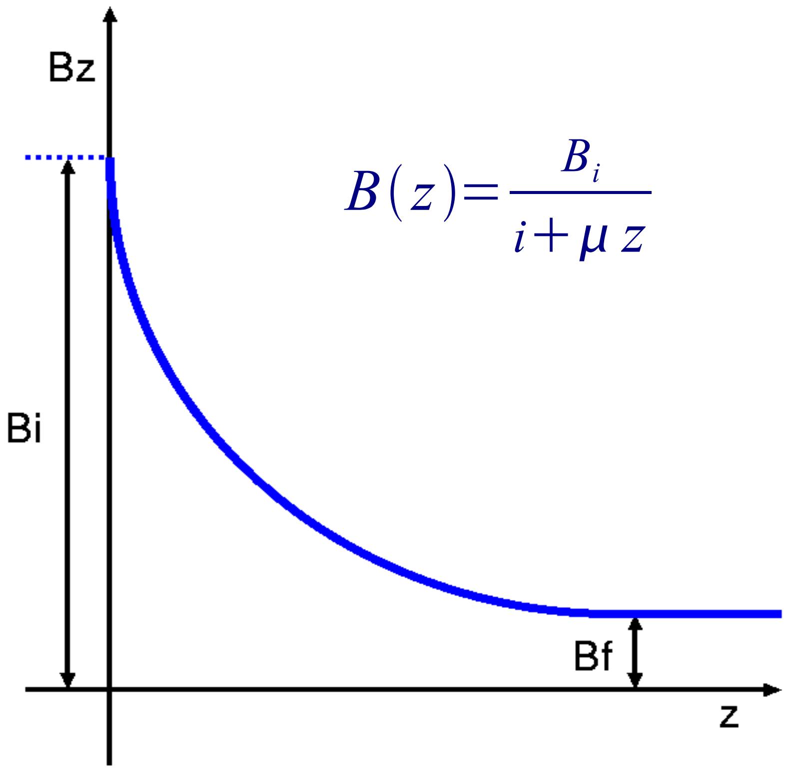


QWT(3)

- The only positrons, which satisfy $p_z = eB_i L_i / \pi$, continue the circulation with a common radius, ρ in QWT.
- Those positrons are captured by the accelerating field, which is placed in Bf area.
- Orbit of off momentum positron is not a circle. They will be lost by hitting the wall.
- Acceptance
  - Energy : $\frac{\delta E}{E} \sim \frac{B_f}{B_i}$
  - Transverse momentum: $p_t < \frac{eB_i a}{2}$, where a is iris radius.

AMD(1)

- AMD consists from the initial strong solenoid field along z direction, B_i, which is decreased down to B_f continuously.
- AMD has relatively large energy acceptance.
- Positrons, which start at r=0 with pt(0), perform helical motion with radius increasing along z.



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

AMD(2)

- The positron motion is varied adiabatically with an invariant of

$$\int p\,dq = \frac{\pi p_t^2}{eB}$$

- Then pt(z) is expressed as

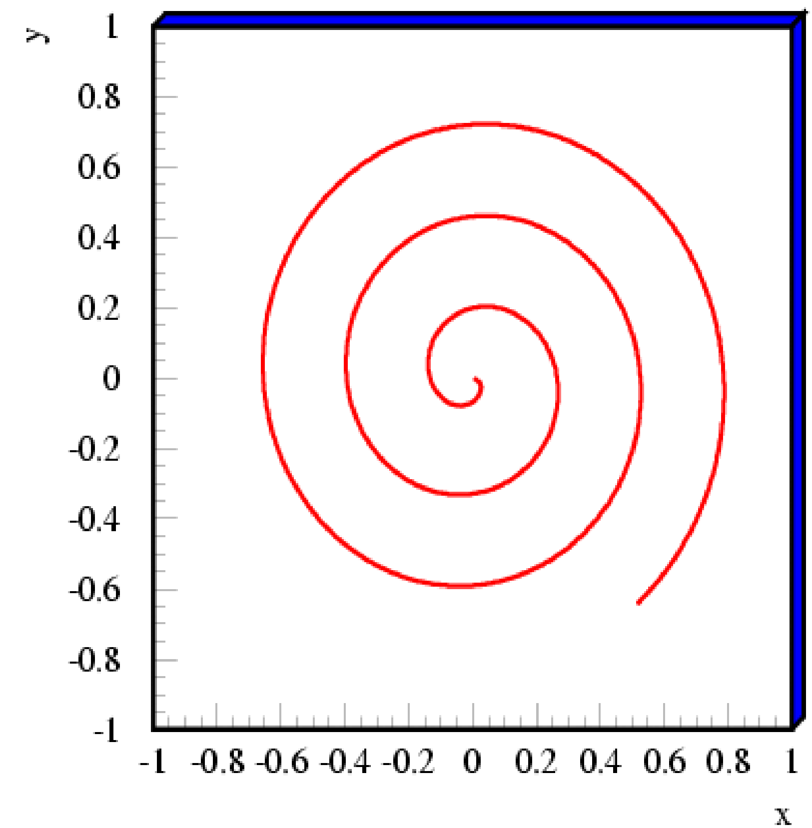
$$p_t(z) = \sqrt{\frac{B(z)}{B_i}}\, p_t(0)$$

- The radius of the circular motion is

$$\rho(z) = \frac{p_t(z)}{eB(z)} = \frac{1}{e\sqrt{B(z)B_i}} p_t(0)$$

- The radius is increased up to

$$\rho_f = \frac{1}{e\sqrt{B_f B_i}} p_t(0)$$



AMD(3)

- $2\rho_f$ has to be within aperture, a. Then, the transverse momentum has to be

$$p_t < \frac{a}{2} e \sqrt{B_f B_i}$$

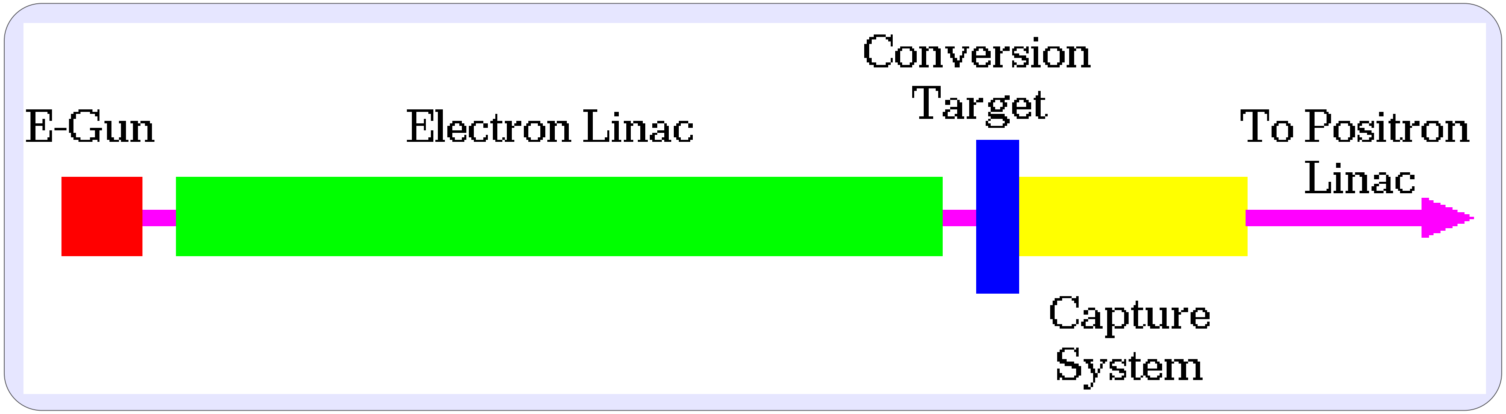
- If the longitudinal momentum is too large, the variation of the solenoid field, B(z), becomes too fast to break the adiabatic condition.

$$p_z < 0.5 \frac{eB_i}{\mu}$$

- These conditions give p_{tmax} and p_{zmax}.

Electron Driven Scheme

- Several GeVs driver electron beam.
- High Density Material for EM shower evolution.
- Positron capture by QWT or AMD + NC accelerator tube with solenoid focusing.
- 6 GeV drive electron with $4X_0$ target yields one e+/e-.



EM Shower Max

Positron Generation
Positron Capture
Positron Source
ILC Positron Source
Summary

- An empirical expression for X_0;
  - A, Z : mass number and atomic number

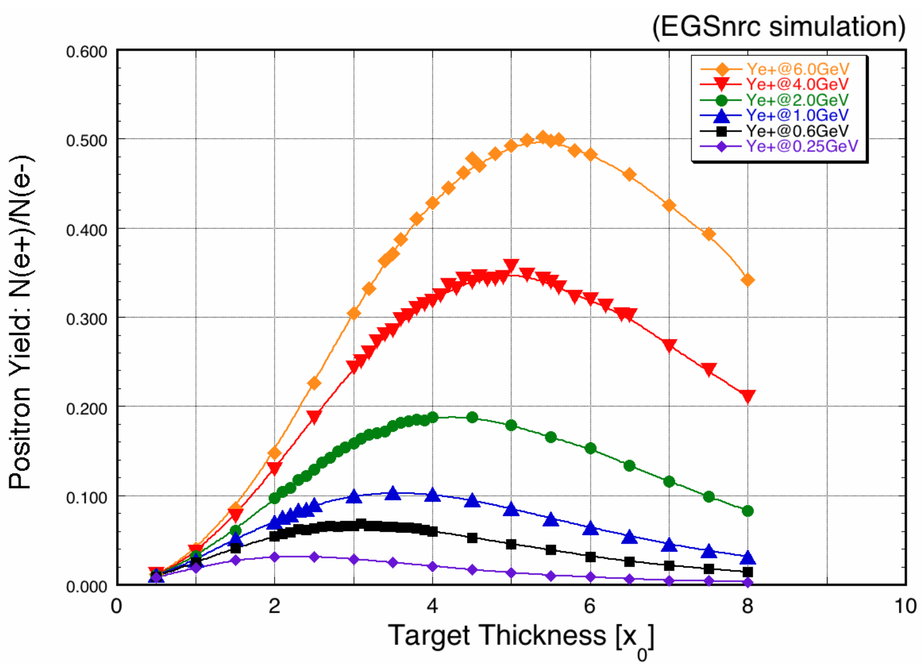
$$X_0 = \frac{716.4[g.cm^{-2}]A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

- Approximated expression for the shower max length in X_0;

$$T_{max} = 1.01\left[\ln\left(\frac{E_0}{\epsilon_0}\right) - 1\right]$$

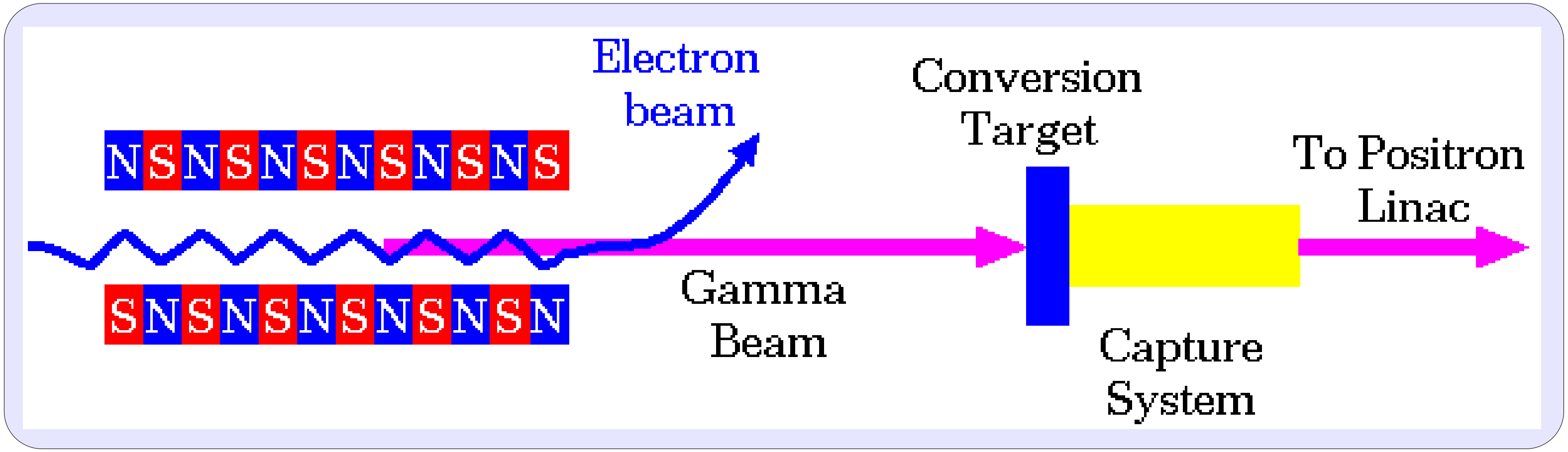
  - E_0: Injected electron energy
  - ε_0: critical energy

Courtesy of T.Kamitani



Undulator Scheme

- By passing more than 100 GeV energy electrons through a short period undulator, more than ~10MeV energy gamma rays are generated.
- This gamma ray is converted to positrons in a heavy material.
- Same capture system.



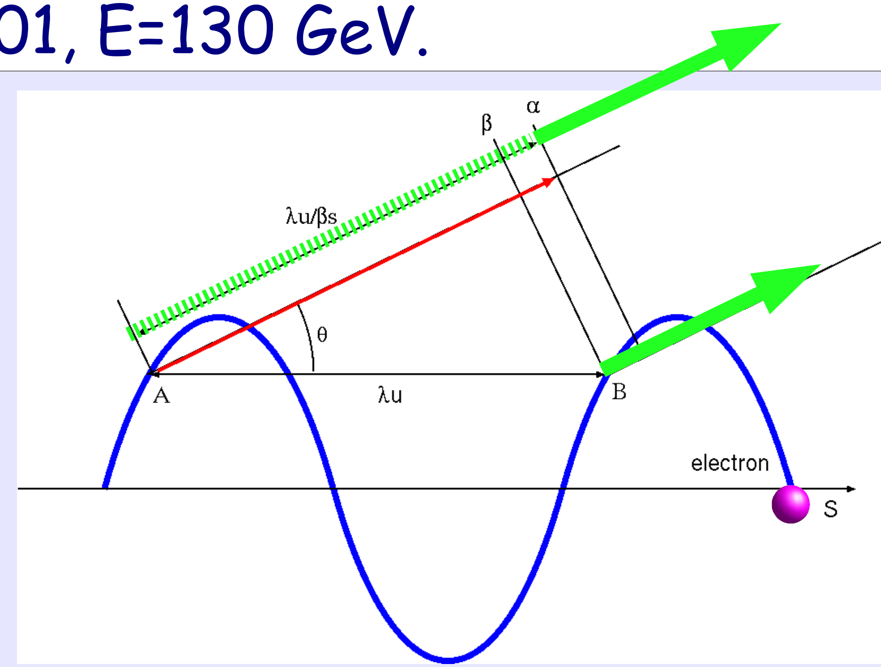
Undulator Radiation

Positron Generation
Positron Capture
Positron Source
ILC Positron Source
Summary

- Electron speed in undulator along the longitudinal axis is less than speed of light due to zig-zag motion.
- Photons are emitted if the wave-plane path-length difference between undulator periods is quantized with the photon wave length.
- E_{ph} = 10 MeV photons (1st harmonic cut off) are obtained with K=1.0, λ_u=0.01, E=130 GeV.

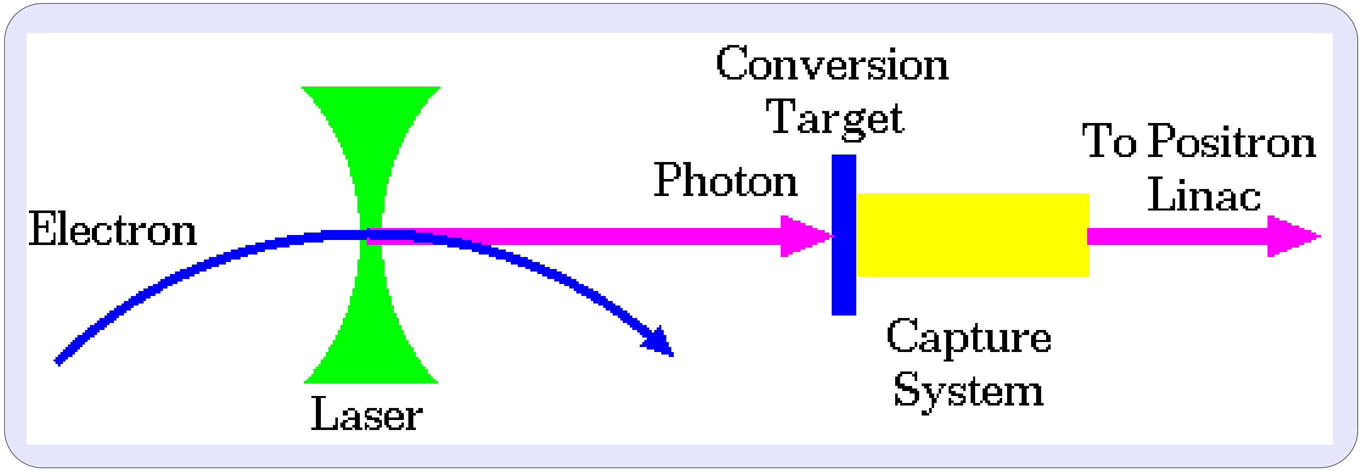
$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1+\frac{K^2}{2}\theta^2\gamma^2\right)$$

$$E_{ph}[eV]=9.50\frac{nE^2[GeV]}{\lambda_u[m](1+\frac{K}{2}+\theta^2\gamma^2)}$$



Compton Scheme

- Compton back scattering between several GeVs electron and laser photons generates ~ 30 MeV gamma rays.
- These gamma rays are converted to positrons.
- If the laser is circularly polarized, positron can be polarized.

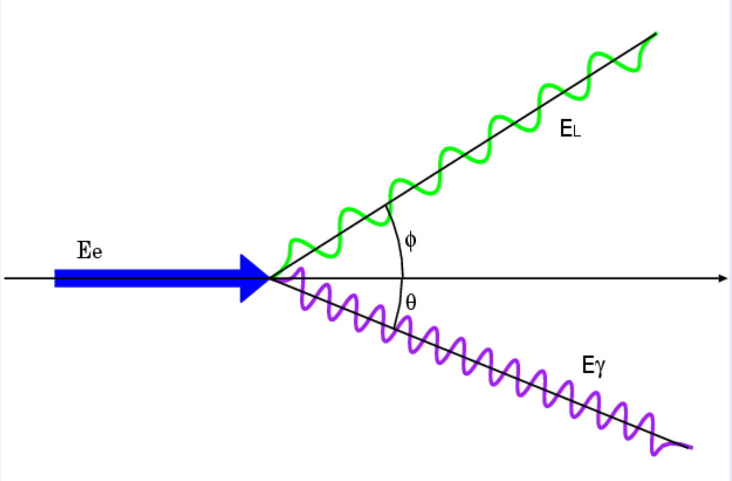


Compton Back-scattering

- Inverse Compton scattering between laser photon and electron beam.
- Laser acts as a quite short period undulator; high energy gamma (several 10s MeV) is obtained with few GeV electron beam.

$$E_\gamma \sim \frac{4\gamma^2 mc^2 E_L}{mc^2 + 4\gamma E_L}$$

- E_L : Laser energy 1eV @ 1um.
- Electron beam 1GeV, $\gamma = 2000$.
- E_γ ~ 16MeV



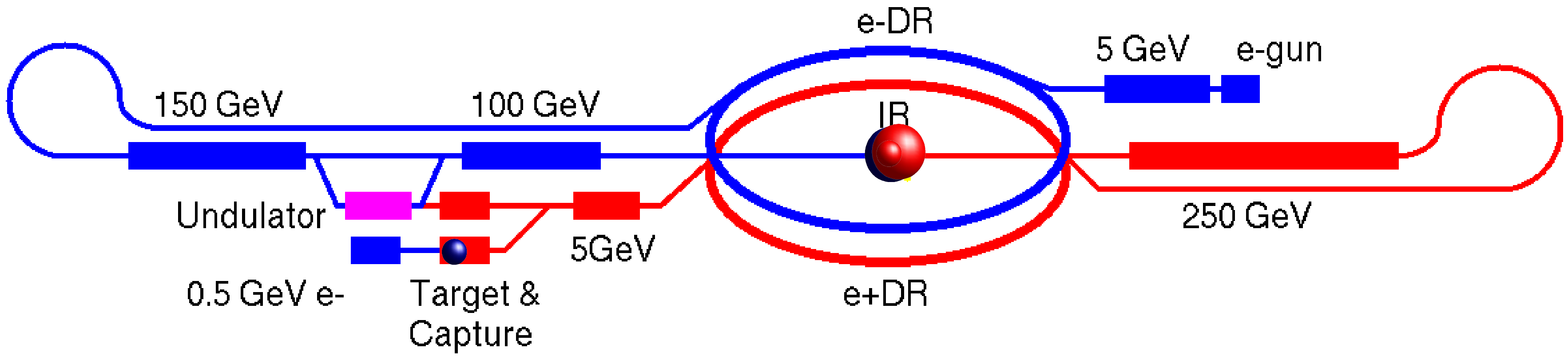
ILC Positron Source

Parameter	Value	Unit
Bunch charge	3.2(1.6)	nC
Bunch length (rms)	4.3	ps
Norm. emittance (εx+εy)	0.09	m.rad
Bunch separation	369 (189)	ns
Bunch number in macro pulse	2625(5120)	number
Macro pulse length	0.9	ms

- Undulator scheme+ low intensity electron driven scheme (10%) is a baseline configuration.
- Compton scheme is an advanced alternative.
- Electron driven scheme is a back up option (when any unexpected serious difficulties were appeared for the baseline).

ILC Positron Source

- A System-wide Sub-system -

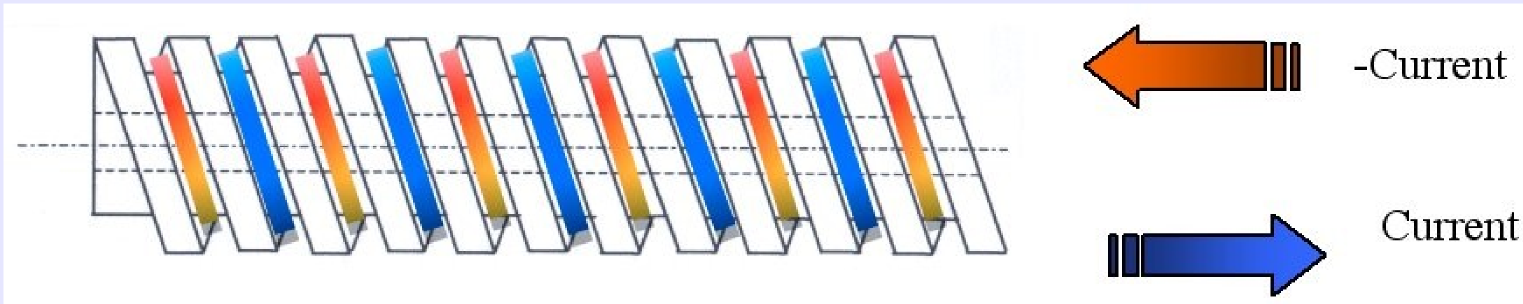


- Gamma rays for positron generation is produced by passing 150 GeV electron through undulator.
- Gamma rays are converted to positron.
- A positron source driven by 0.5 GeV electron is a back up for high availability.
- A common 5 GeV positron booster.

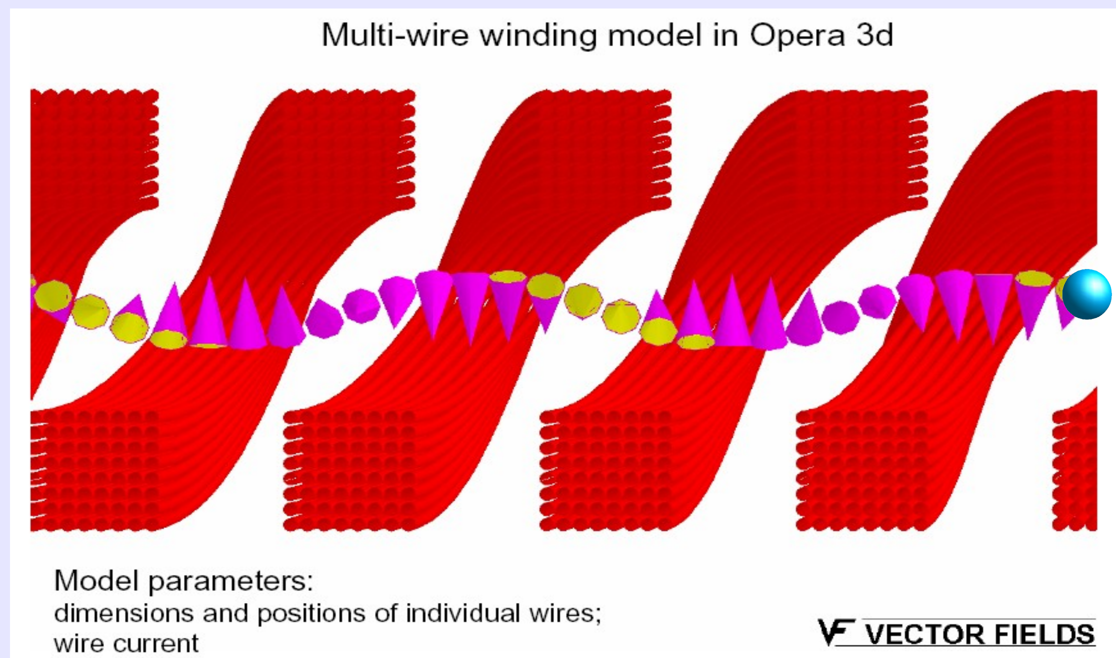
System Specifications

Parameter	Value	Unit
Gamma/bunch	1.20E+13	Number
Positrons/bunch	2.0E+10(1.0E+10)	Number
Positron yield	1.5	e+/e-
Electron drive energy	150 GeV	GeV
Drive beam energy loss	4.8 (9.6)	GeV
Undulator length	147 (300)	m
Polarization (upgrade with 300m und.)	60	%

Helical Undulator



- Two helical coils powered by opposite currents.
- Longitudinal field are cancelled and spiral transverse fields is appeared.



By Yury Ivanyushenkov

Undulator Specifications

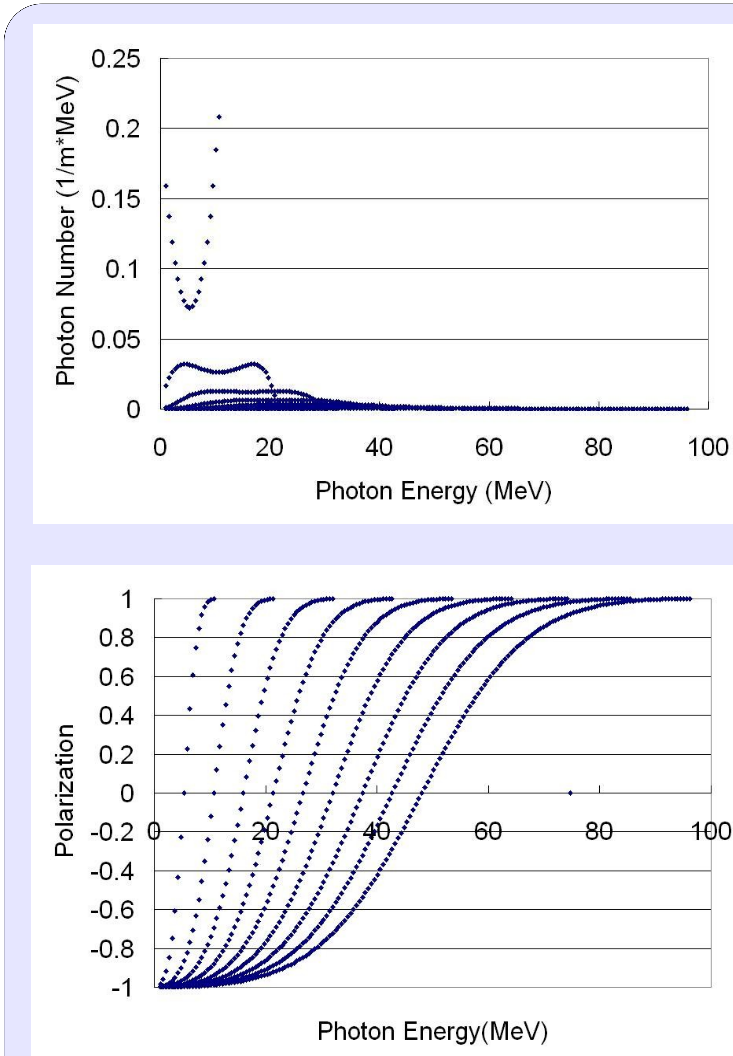
Undulator Type	SC Helical	-
Undulator period	11.5	mm
Undulator Strength (K)	0.92	-
Magnet Current	205 (86% of critical)	A
Magnetic field (on axis)	0.86	T
Undulator Length (unpolarize)	147	m
Beam Aperture	5.85	mm
Photon Energy (1st hrm)	10.07	MeV
Max. photon power	131	kW

Polarized Positron

- Energy, angle, and helicity from undulator radiation are correlated.
- By taking gammas in super-forward direction, gamma rays and positrons are polarized.
- Number of particle is decreased by the collimation; need longer undulator.

$$\frac{dN_n}{dE}\left[\frac{1}{MeV}\right]=\frac{10^6 e^{2L}}{4\pi\epsilon c^2 h^2}\frac{K^2}{\gamma^2}\left[J_n'(x)^2+\left(\frac{\alpha_n}{K}-\frac{n}{x}\right)^2 J_n(x)^2\right]$$

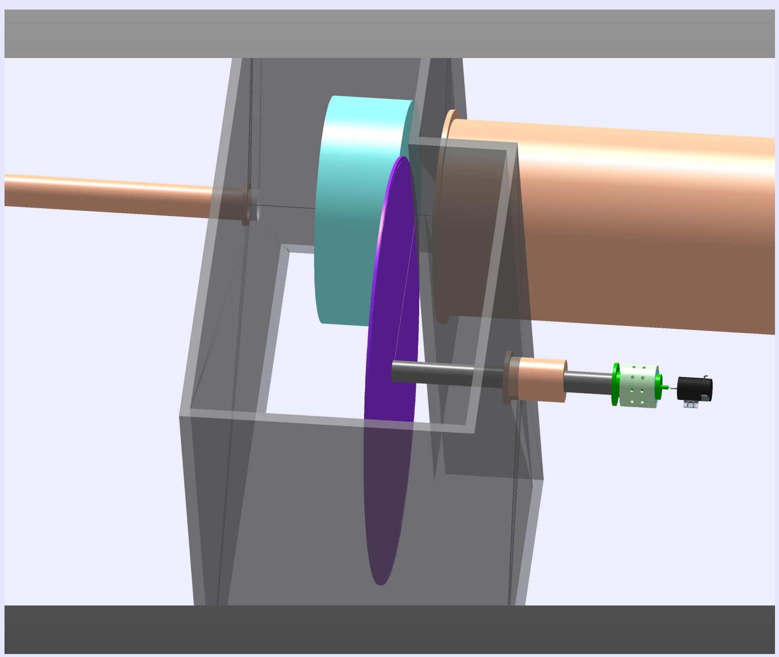
$$\theta=\frac{1}{\gamma}\sqrt{n\frac{\omega_n(1+K^2)}{\omega}-1-K^2}$$

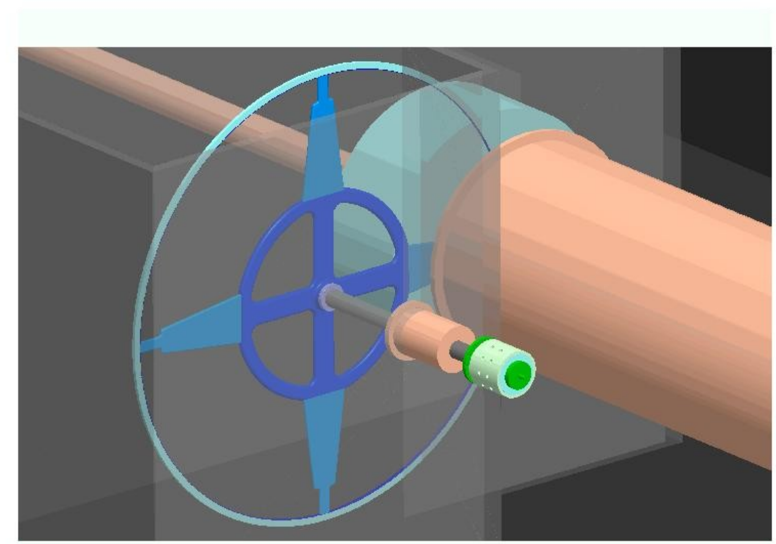


By W. Gai

Target

- Target : Ti-6% Al-4% V with 0.4 X_0, rotating with tangential speed 100 m/s .
- Beam spot : 1.5 mm
- Heat load by gamma : 18 kW
- Heat load by Eddy current : 2MW (solid plate), 20kW (rim).

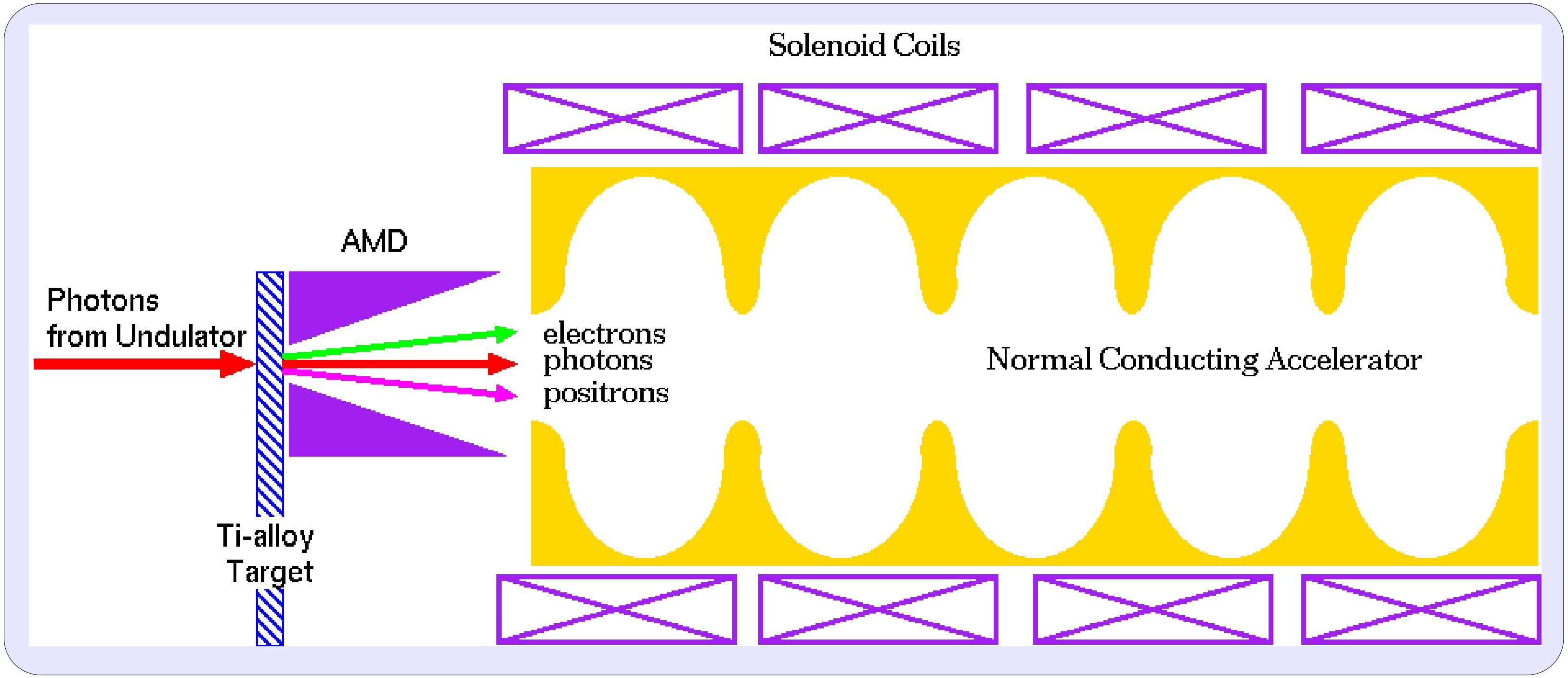




LLNL draft design

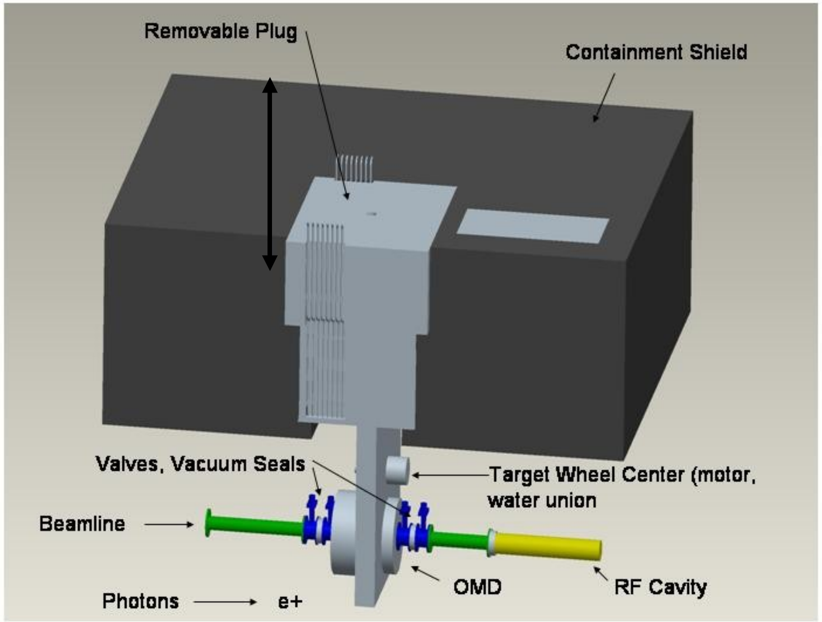
Positron Capture

- AMD (B_i~5T, B_f~0.5T in 20cm): pulsed coil with bucking coil to shield any magnetic field in the target to avoid Eddy current problem.
- L-Band NC accelerator tube with 12 ~ 15 MV/m.



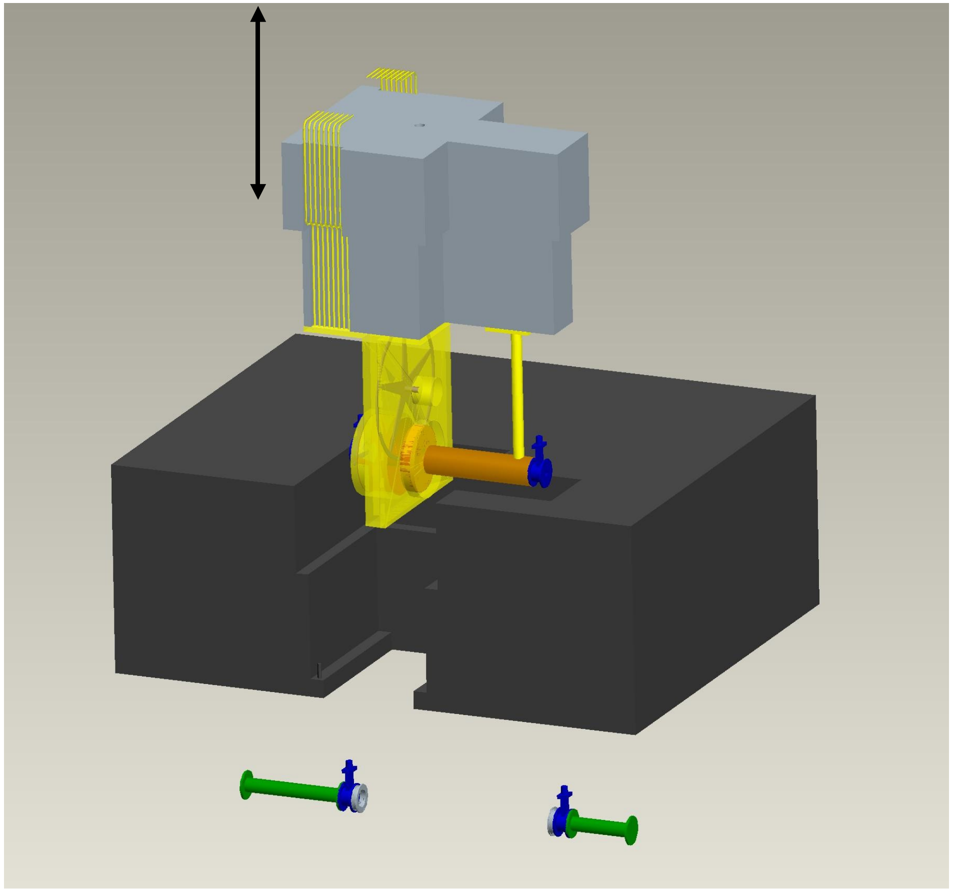
Remote Handling

Target Assembly In Place



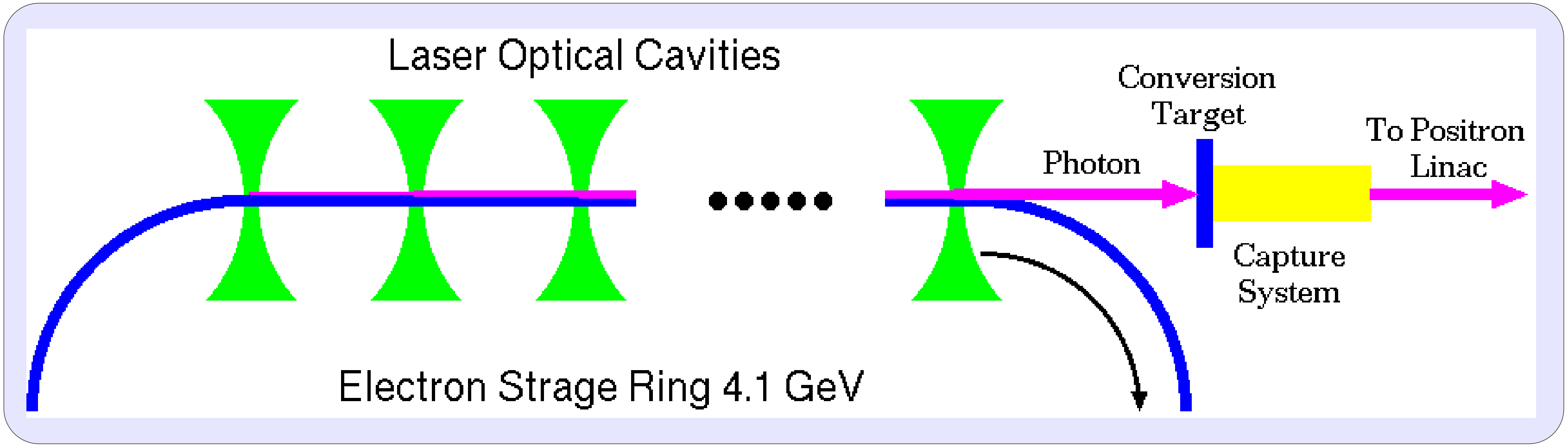
1.25 m

Target Assembly Lifting Out



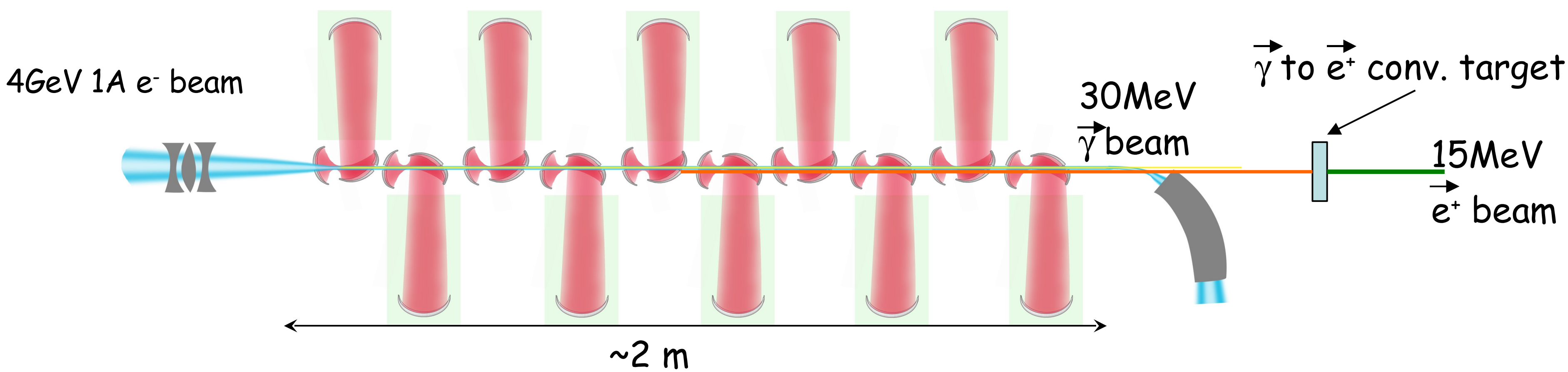
Laser Compton Scheme

- Compton Ring : 1/10 of DR circumference storing 280 6.2(3.1)nC 1.3 GeV bunches with 6.16 (3.08) ns spacing.
- 10 optical cavities, which store 600mJ mode lock YAG laser (600μJ/pulse) by pulse-stacking technology.
- 1.7E+10 γ in 23-29 MeV energy range are generated every 6.2 ns; 2.4E+8 positron per bunch are obtained.
- 28000 bunch train with 10ms interval are repeated 10 times; 100 bunches are filled to each bucket in DR.



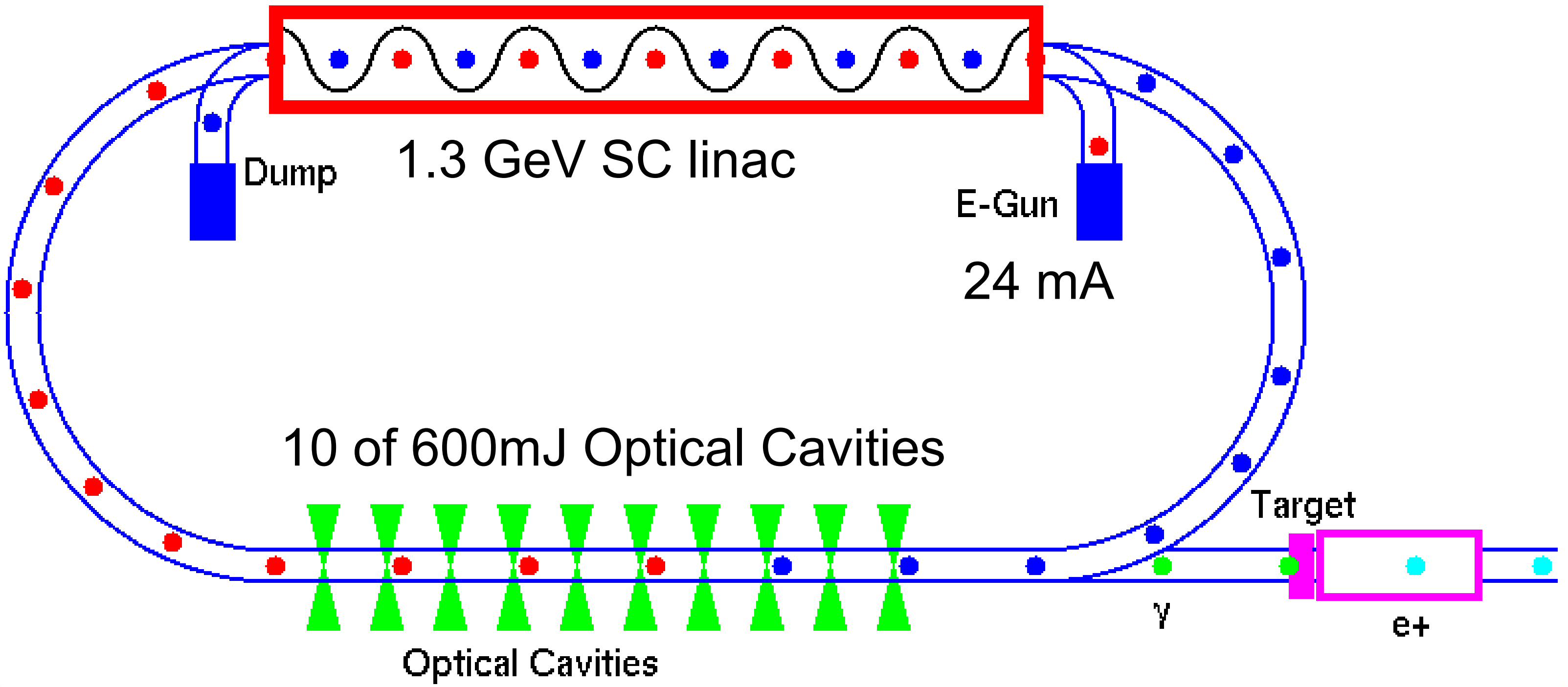
Linac Laser Compton

- Polarized gamma-ray beam is generated in the Compton back scattering inside optical cavity of CO_2 laser beam and 4 GeV e-beam produced by linac.
- Laser system relies on the commercially available lasers but need R&D for high repetition operation.
- Ring cavity with laser amplifier realizes the CO_2 laser pulse train.



ERL Laser Compton

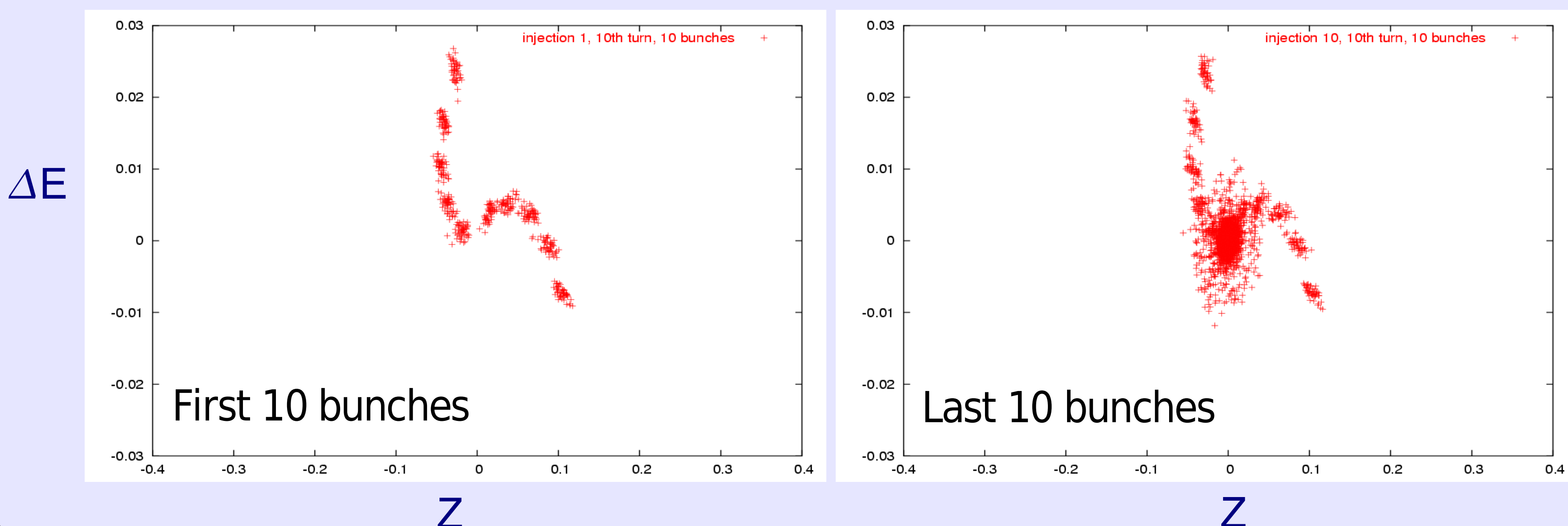
- Short bunch (<1ps) makes gamma yield higher.
- 1.5nC electrons with 62ns (24mA) -> 8.2e+10 γ.
- 7.5e+7 e+/bunch is obtained.
- Top-up injection up to 400 bunches in a same bucket make 3.0e+10 e+/bunch.
- Another 100ms is for damping.



Positron Stacking

- Except the linac based Laser Compton scheme, number of positron generated by one collision is not sufficient.
- Many positron bunches are stacked in a same bucket in DR.
- Stacking scheme with less beam loss is under study.

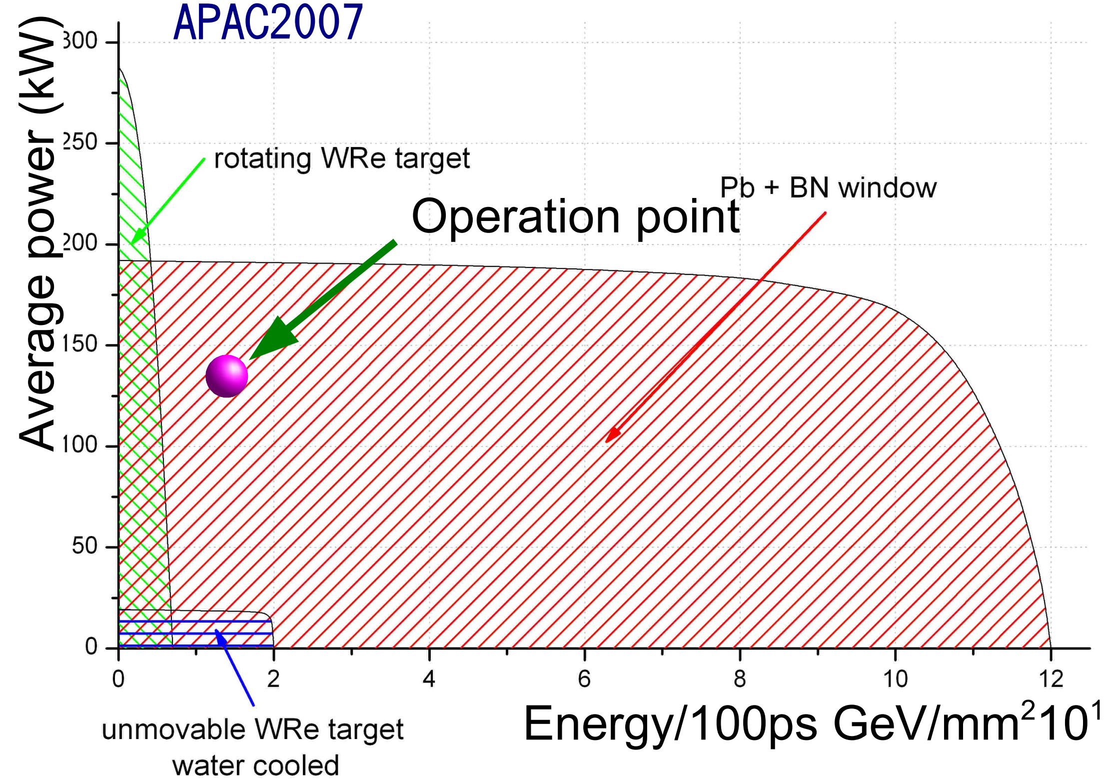
By F. Zimmermann

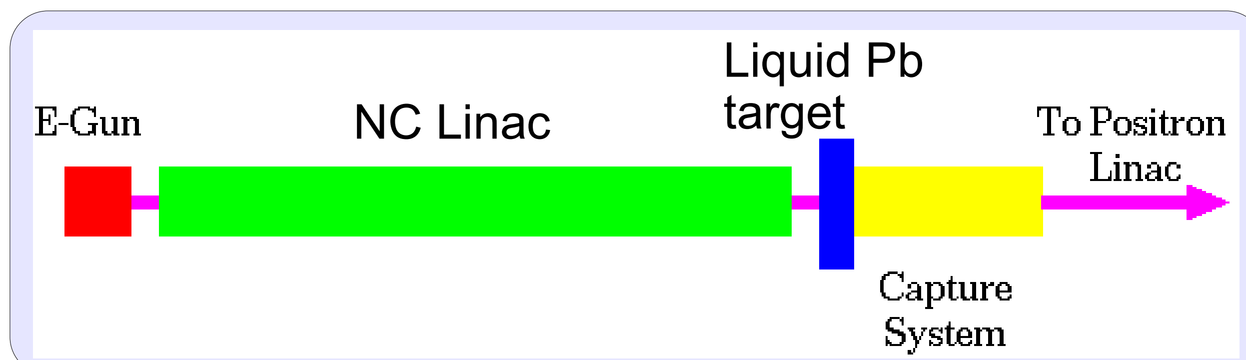


Electron Driven Scheme (1)

- Liquid Pb target + BN window is very strong against high peak power.
- Short bunch spacing mode (2625 6.2GeV 10^{10} bunches 6.2ns spacing) in $1mm^2$ spot makes 1.0 $GeV/mm^2 10^{12}$.
- The load to the target is tolerable.

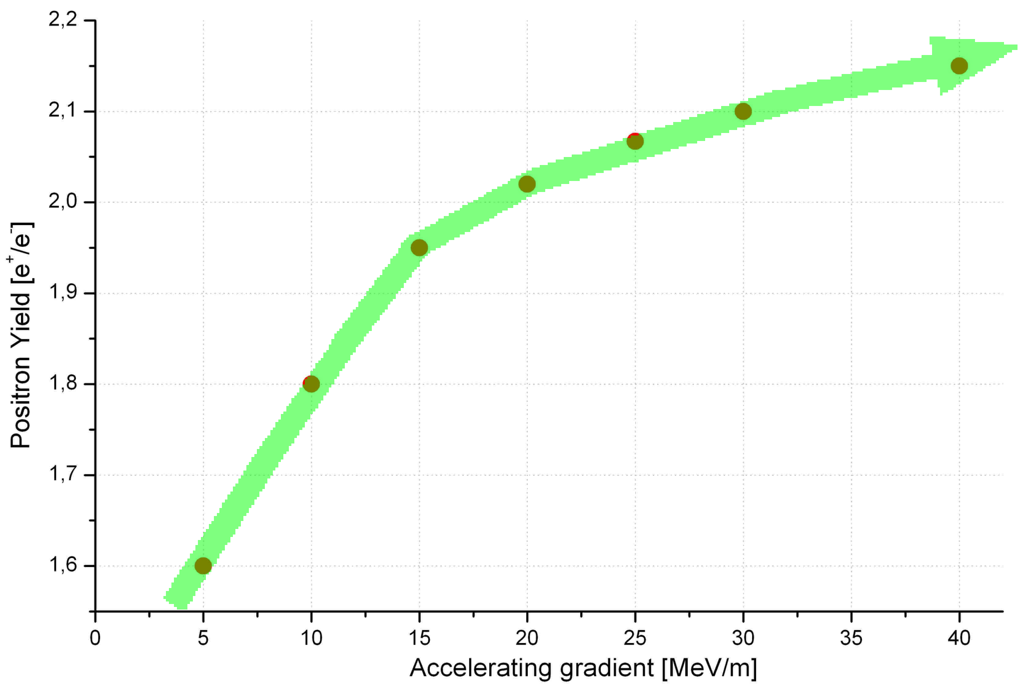
P. Logachov et al. in APAC2007





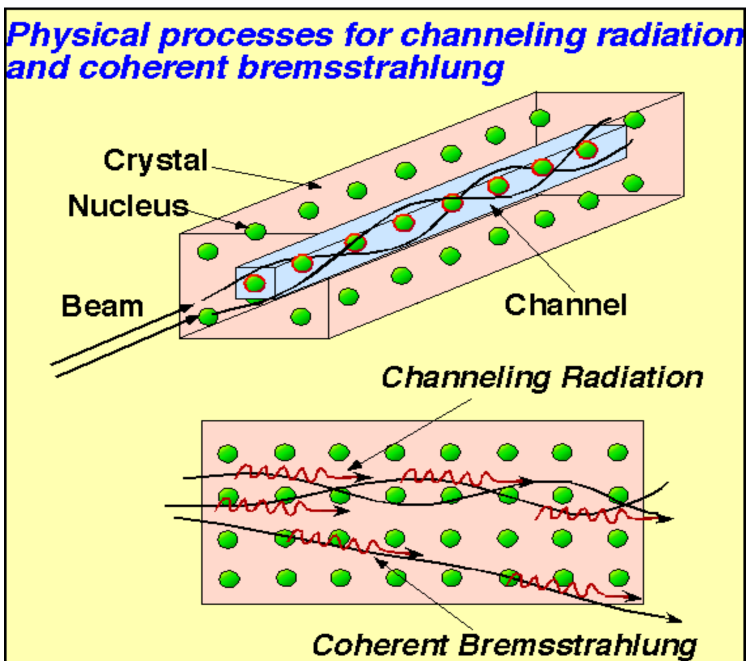
Electron Driven Scheme (2)

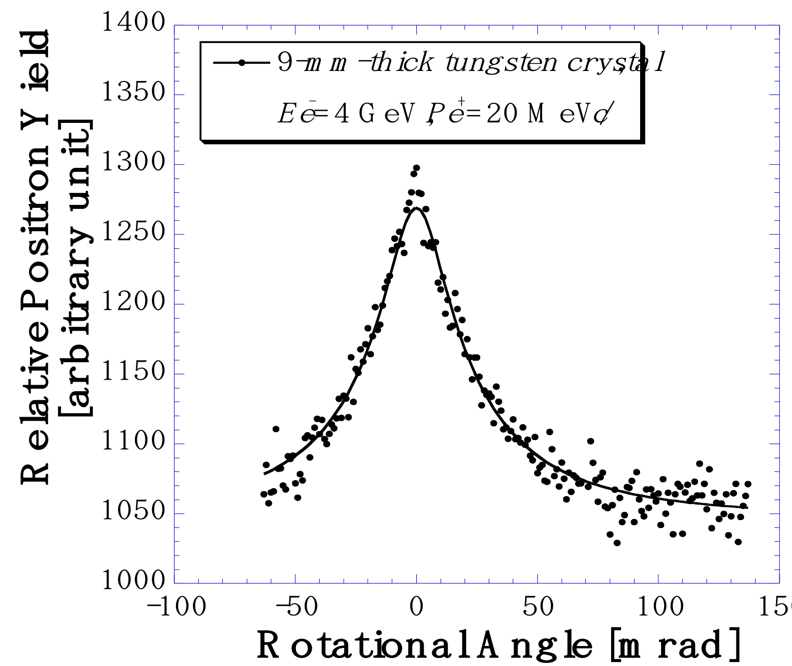
- Short pulse operation (16μs) allows higher gradient, eg. 25 MeV/m with positron yield 2.1 e+/e-.
- Positron per bunch is 2.1×10^{10}.
- 10T Flux concentrator increases the capture and relaxes the condition.
- NC accelerator for e- driver and e+ booster.



Crystalline Target (1)

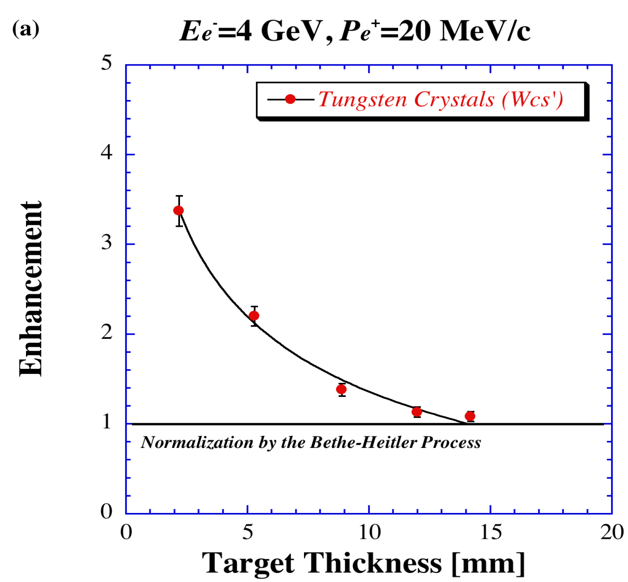
- Gamma radiation by e- beam in a crystalline W target along the crystal axis is enhanced by channeling and coherent bremsstrahlung.
- A clear enhancement on the positron generation with the crystalline W target is experimentally confirmed at KEKB injector.

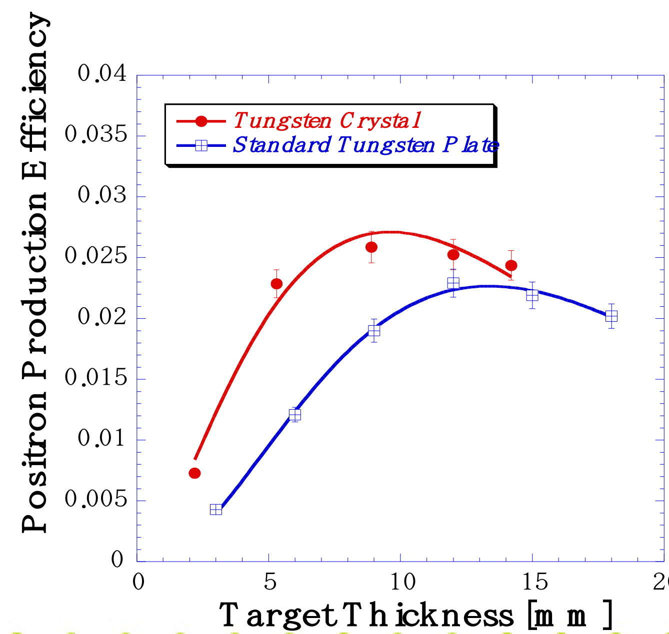




Crystalline Target (2)

- Positron yield by the crystalline target is enhanced by ~30% with thinner (~9mm) target thickness.
- The heat load becomes almost half compare to the amorphous target.
- The heat load normalized to the generated positron flux is 40% of that by amorphous target. It relaxes the technical limitation very much.





Summary

- Fundamentals of positron generation and its capture system are explained .
- ILC Positron Source is based on Undulator Scheme with auxiliary source based on electron driven scheme.
- Laser Compton scheme is advanced alternative.
- Electron driven is still a vital option.
- Need a lot of interesting works to implement the positron source.

Reference

Positron Generation
Positron Capture
Positron Source
ILC Positron Source
Summary

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Home Work

2-1) How much beam energy, E, is neccesary to obtain 10 MeV photons from undulator? Undulator strength parameter, K, is given as

$$K = 93.4\, B_0[T]\lambda_p[m]$$

- λ_p: undulator period length; λ_p=0.01m
- n: harmonic number=1
- B_0: Peak magnetic field, 1T

2-2) How much beam energy, E, is neccesary to obtain 10 MeV photons from Laser Compton? Assume 1μm wave length for laser.

- Planck constant : 6.63E-34 Js
- Speed of light : 3.00E+8 m/s