Positron Source for Linear Colliders

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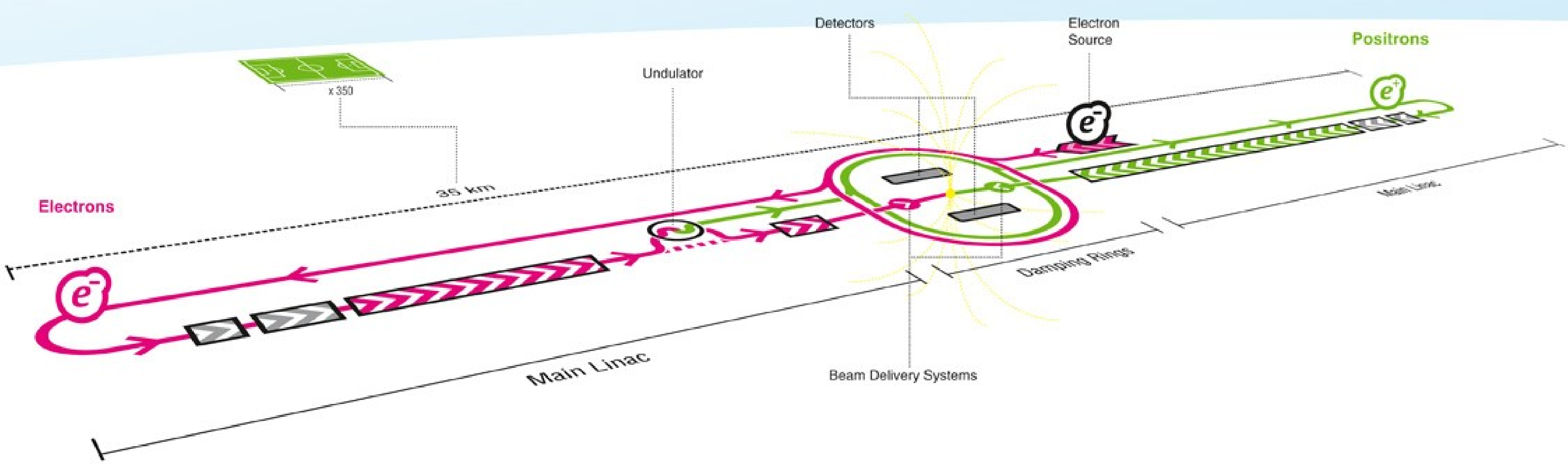

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- Positron Generation
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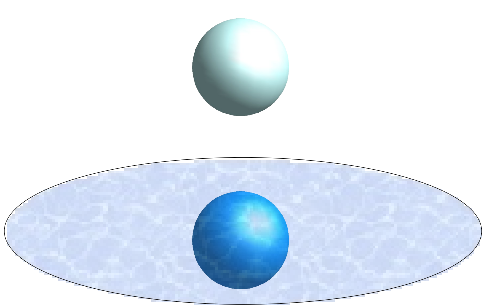
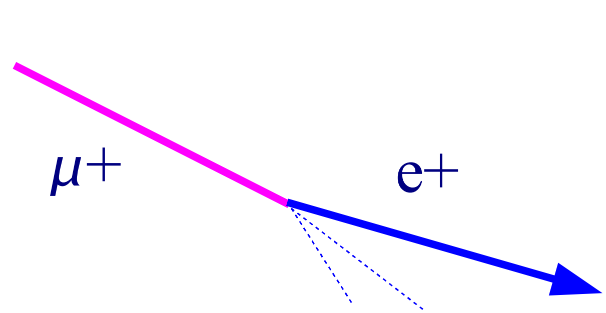
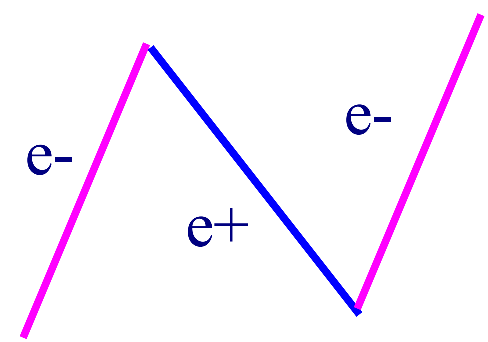
- Summary

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)

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

▶ There is only few positrons in nature.

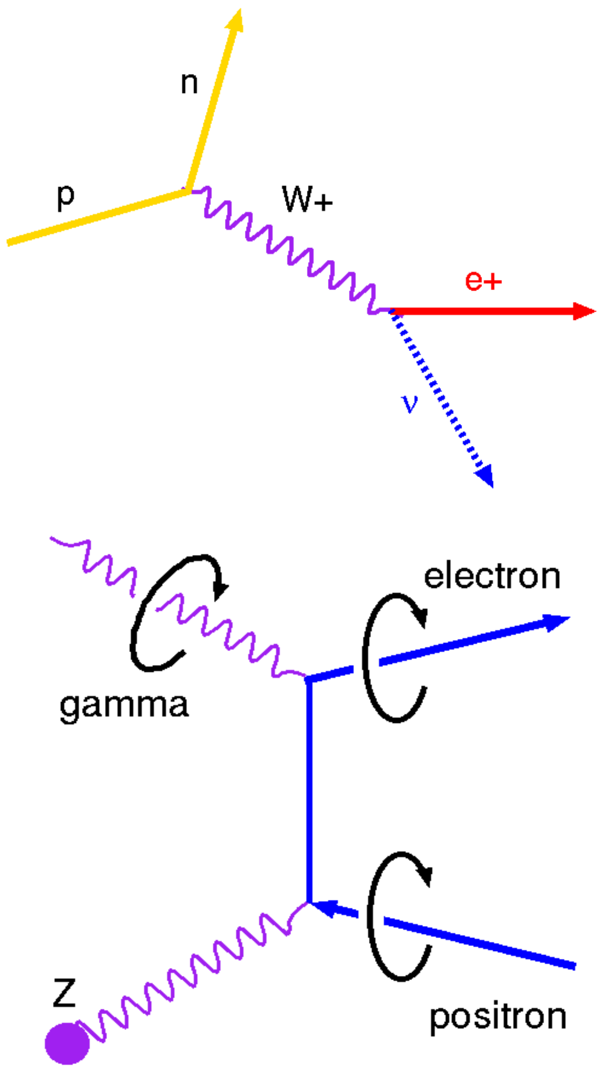
▶ Two ways to produce positrons :

– Create radio-active elements, which beta + decays;

p ->n e+ neutrino.

– Pair-creation ; gamma -> e+ e-

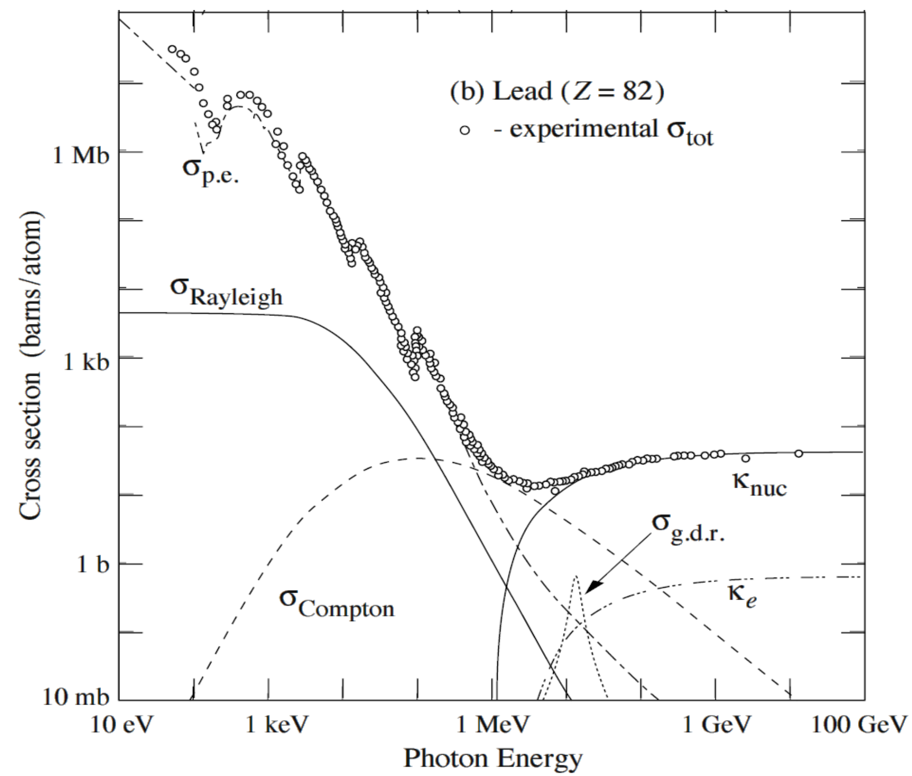
▶ All of the positron beam sources, employ the pair-creation process.



Positron Production (2)

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

- Photon interaction in material:
  - Photo-electron effect(<1MeV)
  - Compton scattering (1-10MeV)
  - Pair-creation (>10MeV)
- Gamma ray, energy >10MeV is required for effective pair creation.

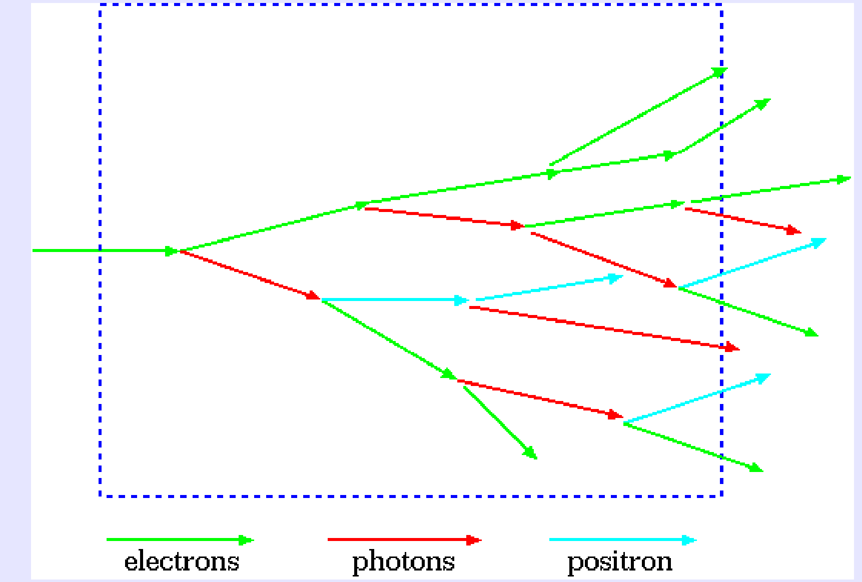


$\sigma_{p.e.}$: photo-electron
$\sigma_{Compton}$:Compton scattering
κ_{nuc}, κ_e: pair creation
(from Particle Data Group, http://pdg.lbl.gov)

EM Shower

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

- High energy electrons (>100 MeV) interact through various process in a material;
  - Bremsstrahlung (gamma radiation)
  - Electron excitation
  - Pair creation,
  - Compton scattering,
- As consequences, EM shower (mixture of electrons, positrons and gammas) is developed.



EM Shower (2)

- EM shower is characterized by radiation length X_0.
- Electron energy becomes 1/e by passing one radiation length, X_0. The lost energy is shared by the shower particles.
- An empirical expression for X_0;
  - A, Z : mass number and atomic number

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

- Heavier material has small X_0 and it is effective converter for positron generation.

EM Shower (3)

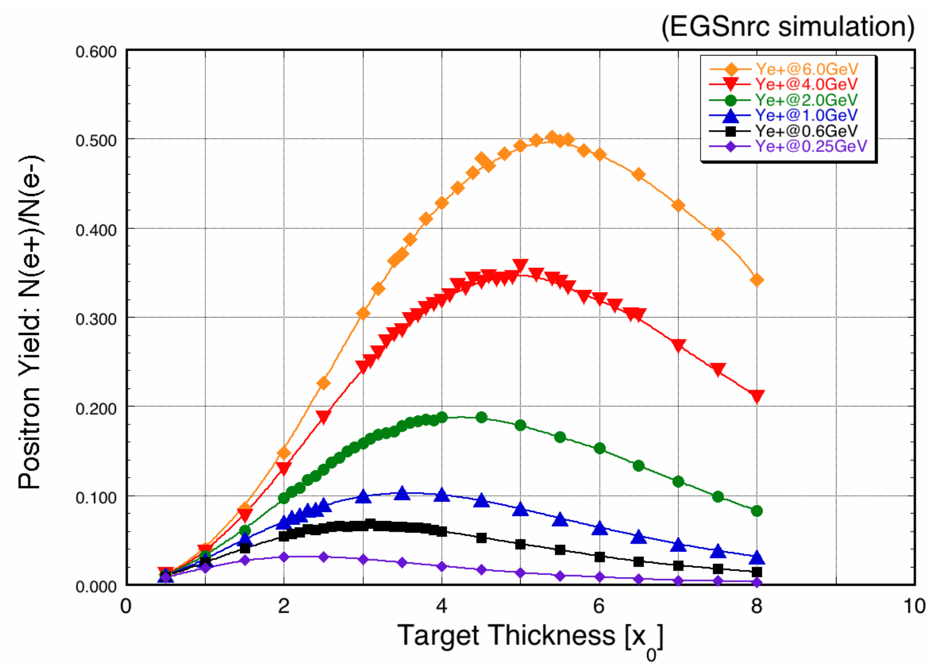
Positron Generation
Positron Capture
Positron Source
ILC Positron Source
Summary

- # of particles is increased by developing the EM shower and decreased by absorption. # of particle is peaked at the shower max, which depends on the beam energy.
- Approximated expression for the shower max length in X_0;

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

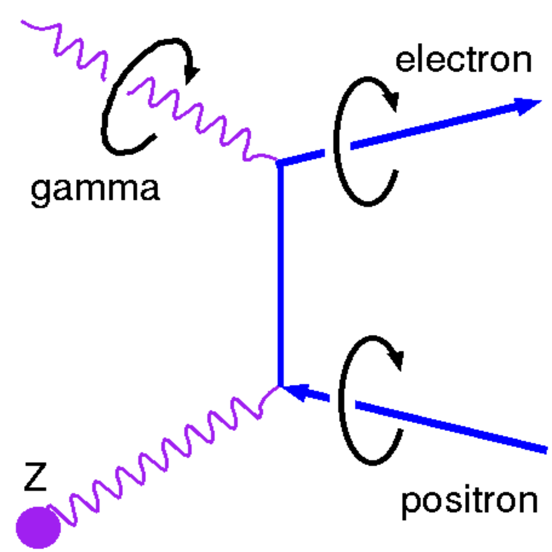
  - E_0: Injected electron energy
  - ϵ_0: critical energy

Courtesy of T.Kamitani



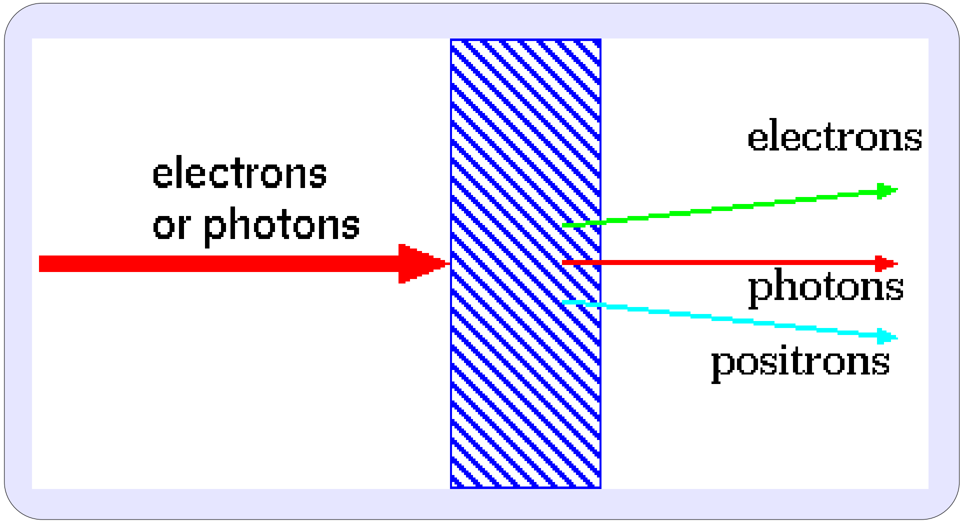
Non Shower Regime

- Principally, high energy photon can be a replacement of the high energy electron, but such high-energy photon is practically hard to obtain.
- With 10s MeV photons, 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)



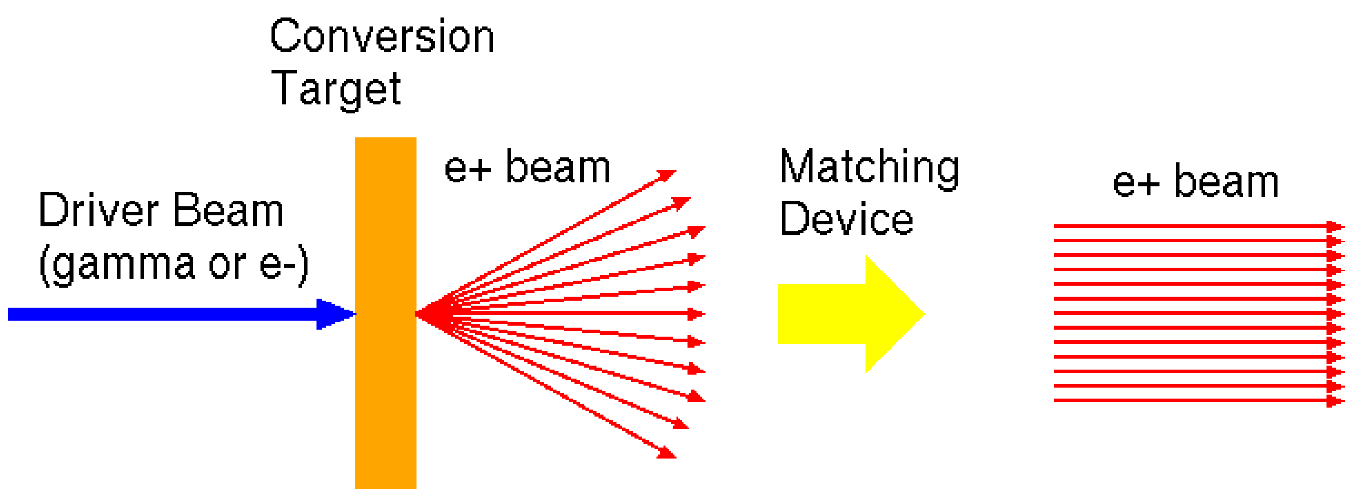
Summary for Positron Generation

- Positron is generated through pair-creation process.
- Driver beam (electron >100s MeV or photon > 10 MeV) is injected onto the converter and positron is obtained as a mixed flux of e+, e-, and photon.
- Regime is different : EM shower for electron and non-shower for photon.



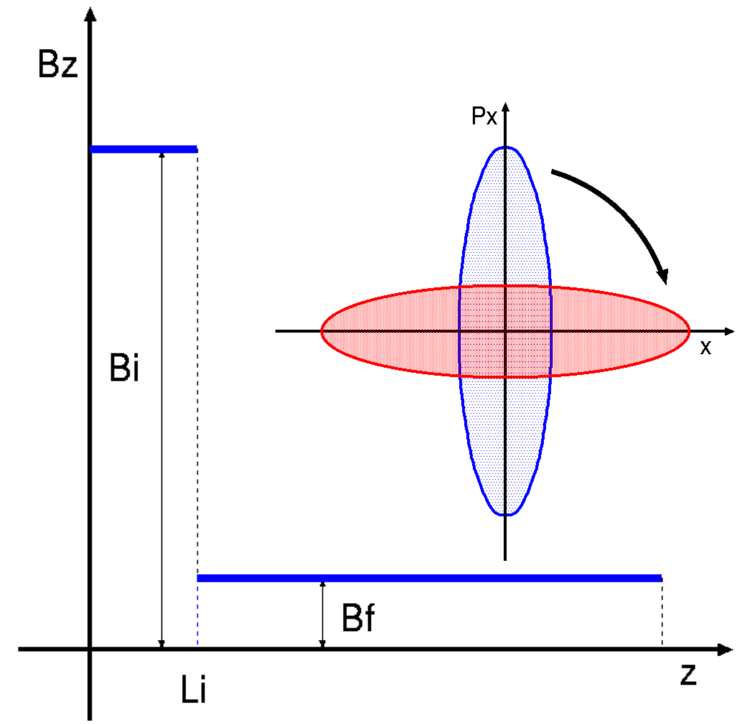
Positron Capture (1)

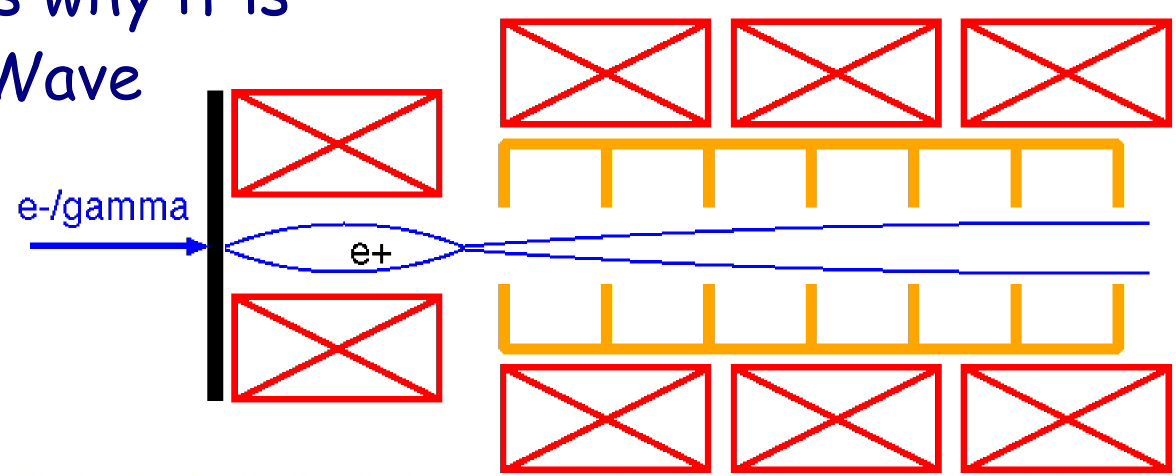
- Positrons are generated as a mixture of positrons, electrons, and gammas.
  - Select only positrons from the flux.
  - Capture the positron in a RF bucket.
- The generated positrons are distributed in a small spot size and in a large momentum space. To parallel beam,
  - QWT (Quarter Wave Transformer)
  - AMD (Adiabatic Matching Device)



QWT(1)

- QWT consists from initial strong solenoid field , B_i, and weak solenoid field, B_f, along z direction.
- Accelerator is placed in Bf region compensating relative transverse motion.
- It transforms 90° in the phase space, that is why it is called as Quarter Wave Transformer.

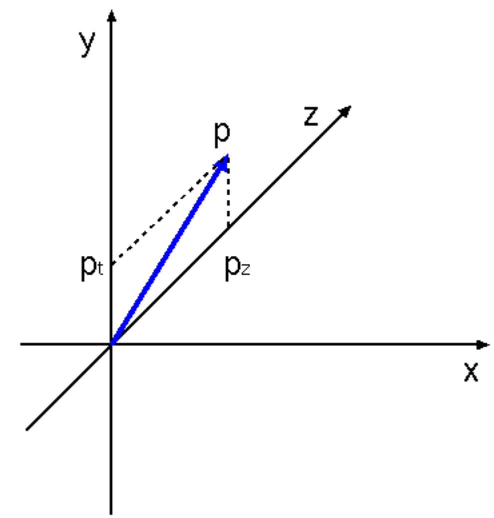




QWT(2)

- Assume positrons start at $(x,y,z)=(0,0,0)$ with momentum $p=(0,p_{t0}, p_z)$.
- In xy plane, positrons are deflected by Bi and circulated with radius ρ.

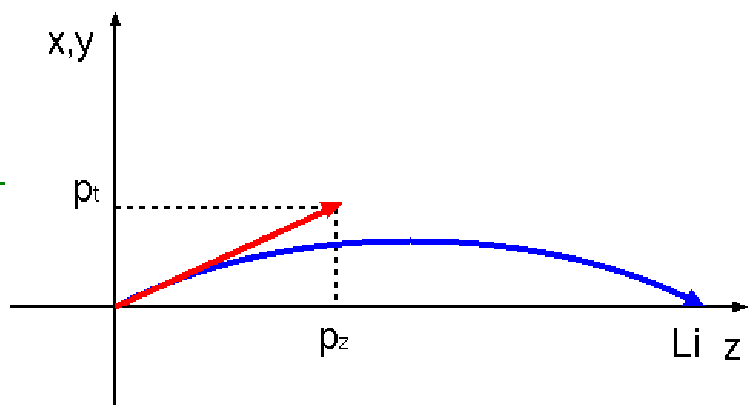
$$\rho = \frac{p_{t0}}{eB_i}$$

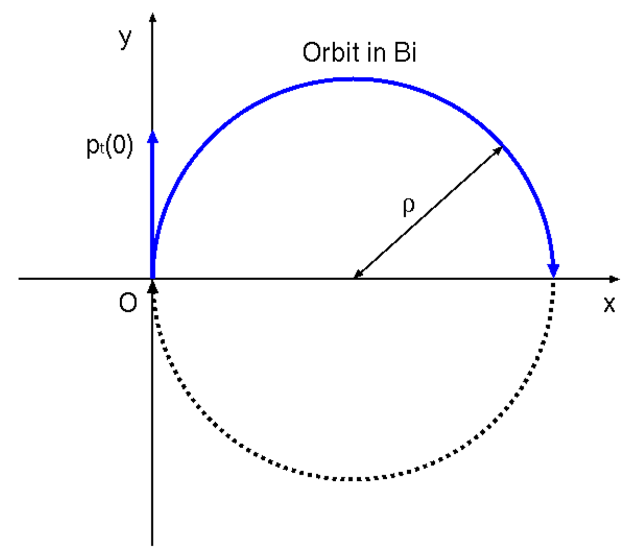


- Positron travels L_i in z and $\pi\rho$ (180°) in xy are captured.

$$\Delta t = \frac{L_i m \gamma}{p_z} = \frac{\pi \rho m \gamma}{p_{t0}}$$

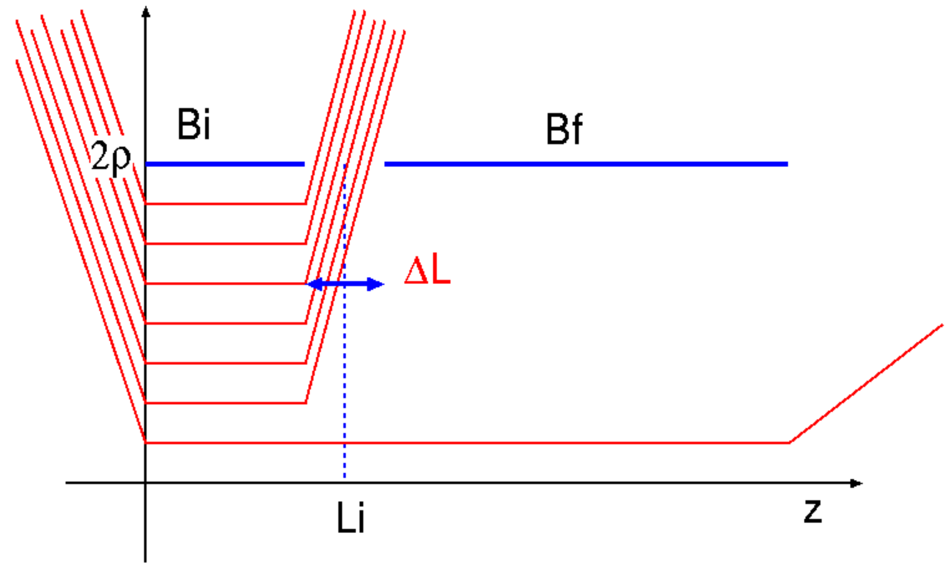
$$\frac{L_i}{\pi \rho} = \frac{p_z}{p_{t0}}$$





QWT(3)

- At the boundary of B_i and B_f, transverse component of magnetic flux density $B_t(z)$ is appeared.



- In radius 2ρ, Magnetic flux in B_i region is

$$\Phi_i = \pi (2\rho)^2 B_i$$

- Magnetic flux in B_f region is

$$\Phi_f = \pi (2\rho)^2 B_f$$

- Taking the integral of $B_t(z)$ along z,

$$\int 4\pi \rho B_t(z) dz = \Phi_i - \Phi_f$$
$$= 4\pi \rho^2 (B_i - B_f)$$
$$\int B_t(z) dz = \rho (B_i - B_f)$$

QWT(4)

- Momentum change by the kick at the boundary is

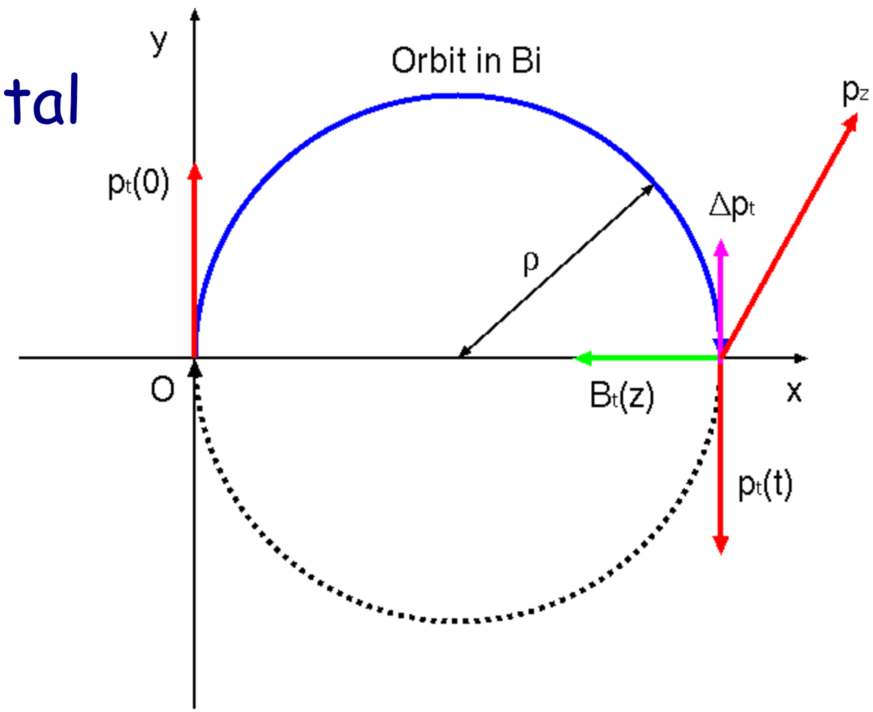
$$\frac{dp_t(t)}{dt} = e\,v_z\,B_t(z)$$

- Integrating this equation, total momentum change is

$$\Delta p_t = e\,v_z \int B_t(z)\,dt = e\,v_z \int B_t(z)\frac{dz}{v_z} = e\,\rho\,(B_i - B_f)$$

- The kick is opposite to $p_t(t)$, then $p_t(t)$ after the kick is

$$p_t(t) = p_{t0} - \Delta p_t = p_{t0} - \frac{p_{t0}}{B_i}(B_i - B_f) = p_{t0}\frac{B_f}{B_i}$$



QWT(5)

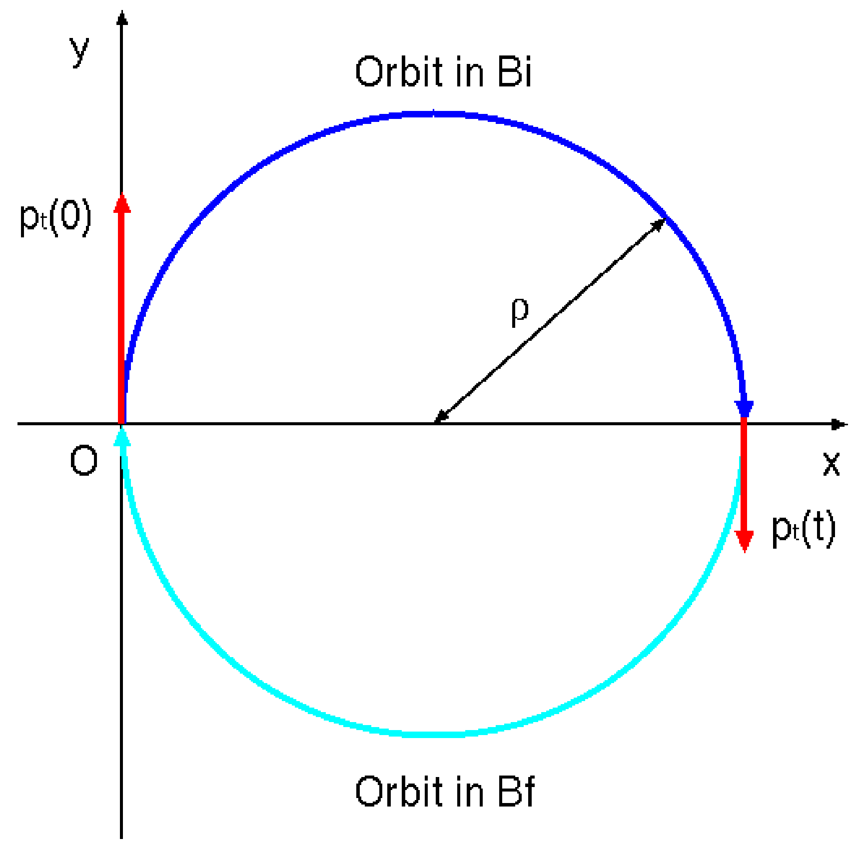
- Pt(t) after the kick is

$$p_t(t) = p_{t0}\frac{B_f}{B_i}$$

- Radius of circulating motion of this particle in B_f is

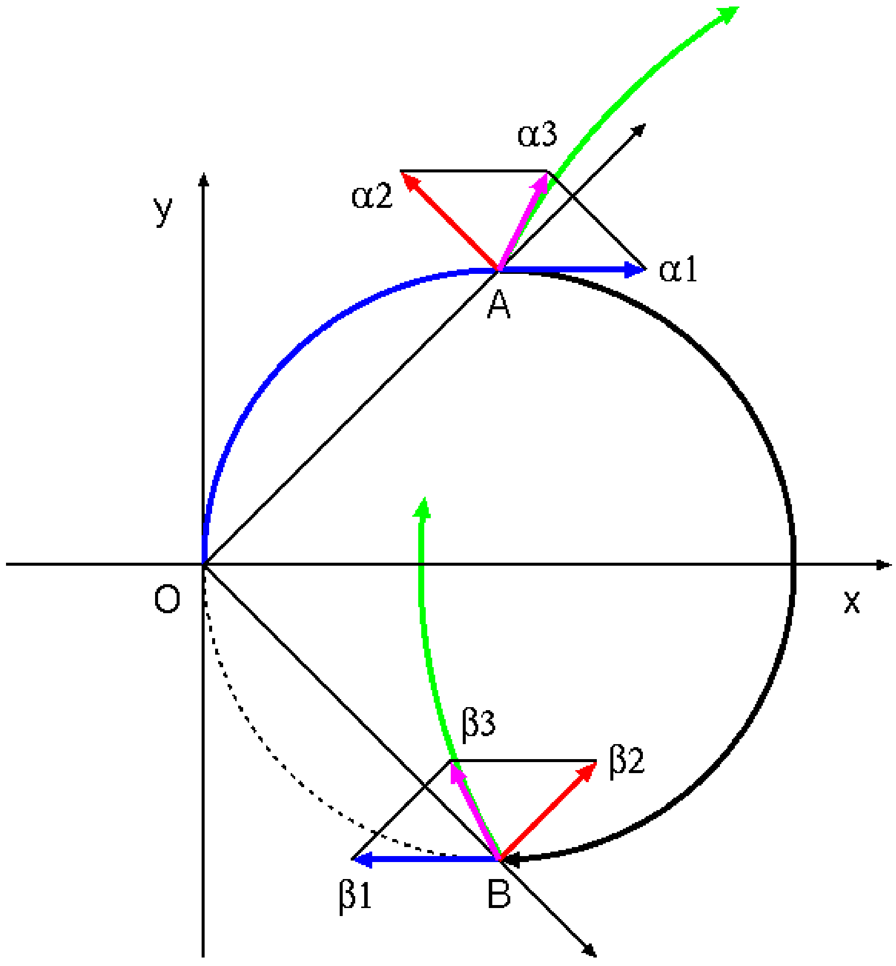
$$\rho_f = \frac{1}{eB_f}\frac{P_{t0}B_f}{B_i} = \frac{p_{t0}}{eB_i}$$

which is identical to that in B_i region. The particle continues the circulation with the same radius, but less Pt.



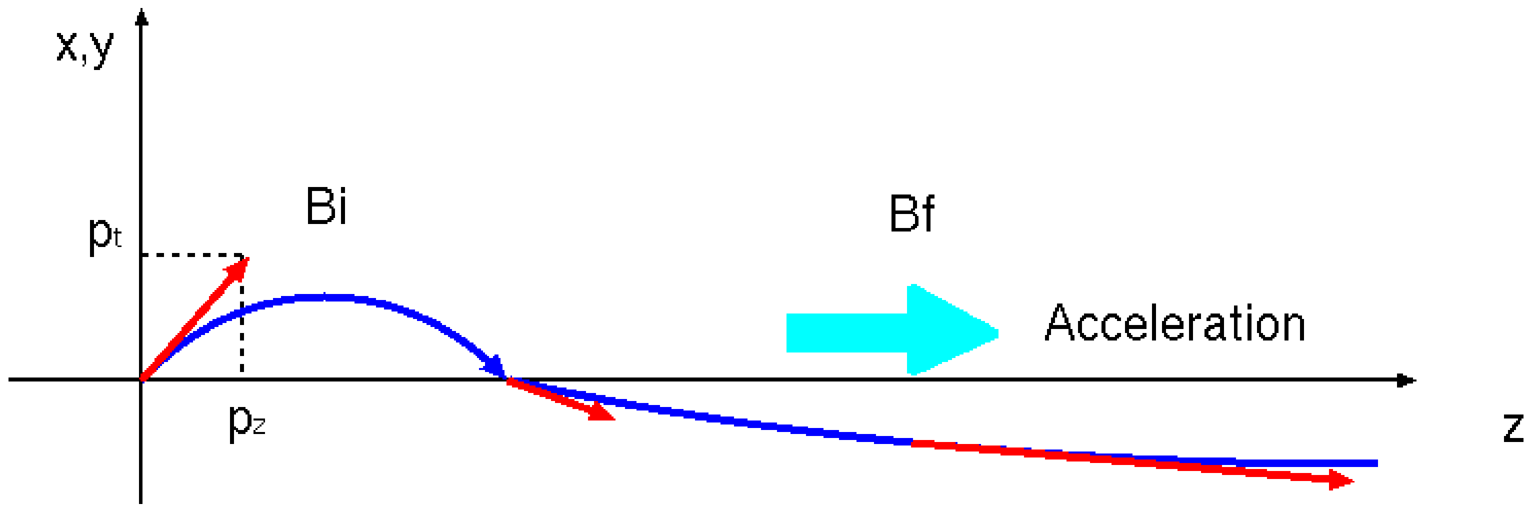
QWT(6)

- Kick to off momentum positrons, which is not circulate ρπ, is not parallel to Pt.
- The center of the circulating motion is always shifted to outer side from the center.
- As consequences, most of the off-momentum positrons are lost by hitting the wall.



QWT(6)

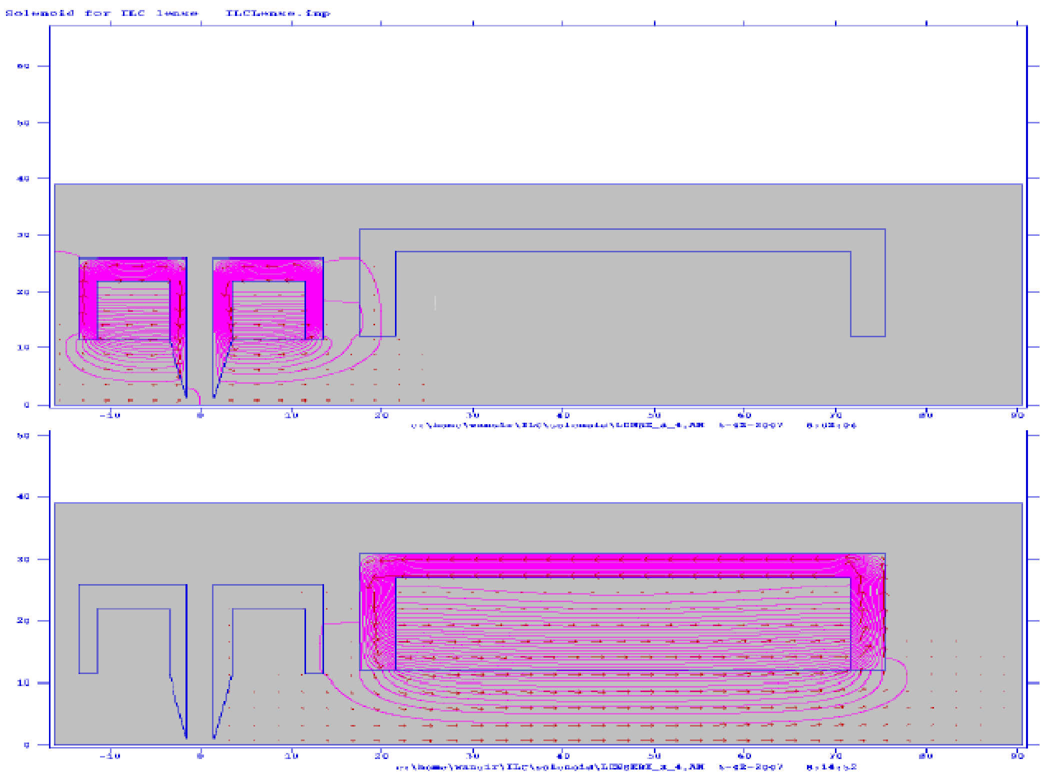
- Positrons, which continue the circulating motion in B_f region, is simultaneously accelerated and transverse momentum is suppressed relatively further.

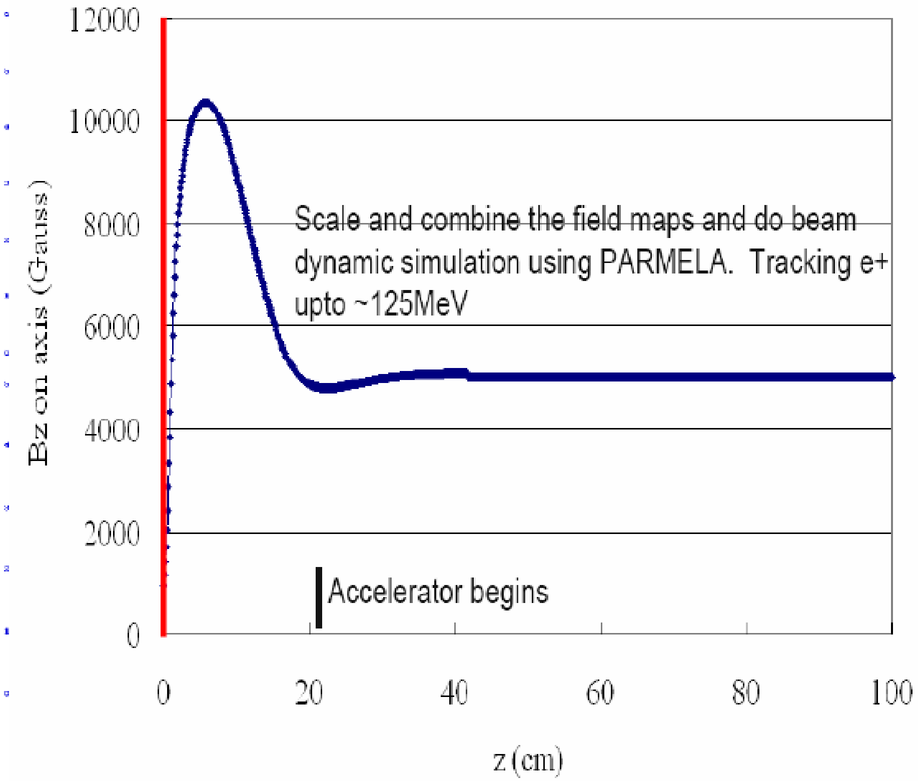


QWT(7)

- The only positrons, which satisfy $p_z = eB_i L_i / \pi$, continue the circulation with a common radius, ρ in QWT and captured.
- Acceptance
  - Energy : $\frac{\delta E}{E} \sim \frac{B_f}{B_i}$
  - The circulating motion should be within the radius of accelerating structure, a, then $2\rho = \frac{2p_t}{eB_i} < a$
  - Acceptance on pt is $p_t < \frac{eB_i a}{2}$

QWT(8)



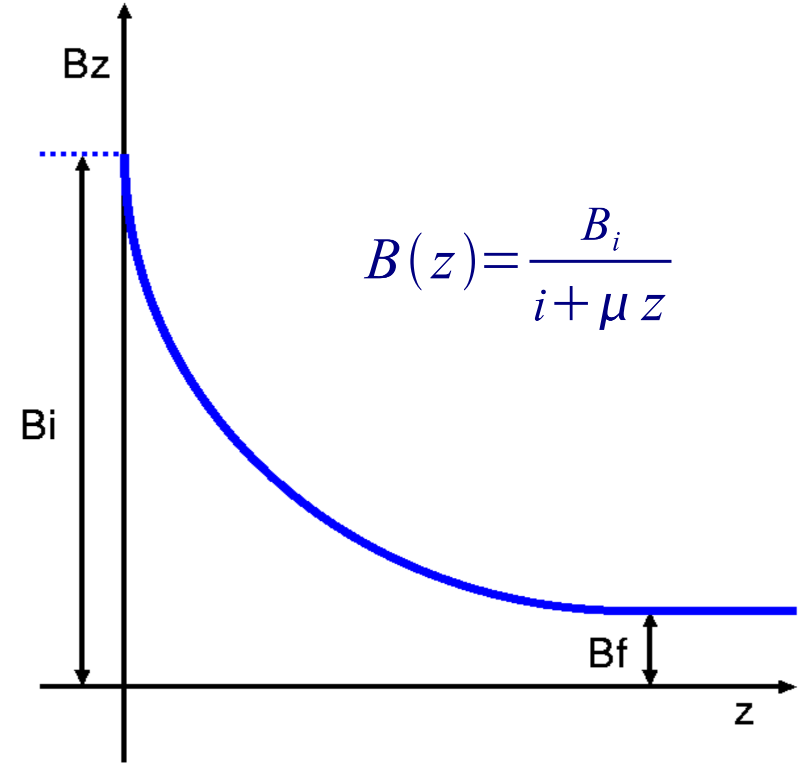


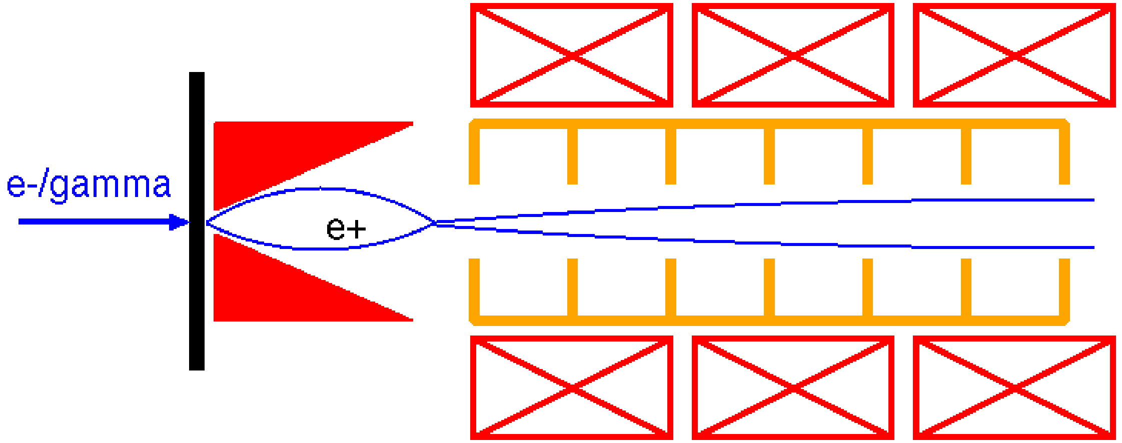
W. Liu

- Initial strong solenoid magnet with bucking to cancel B field on target.
- Ramping from 0T to 1T(B_i) in 5cm.
- B_f is 0.5 T.
- NC L-band accelerator is placed in Bf region.

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.





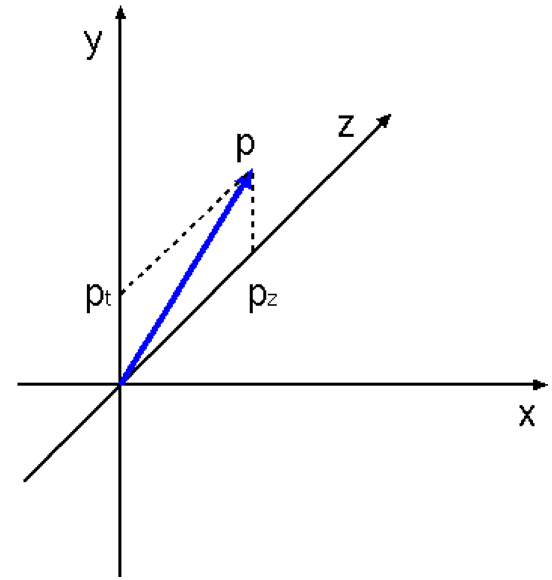
AMD (2)

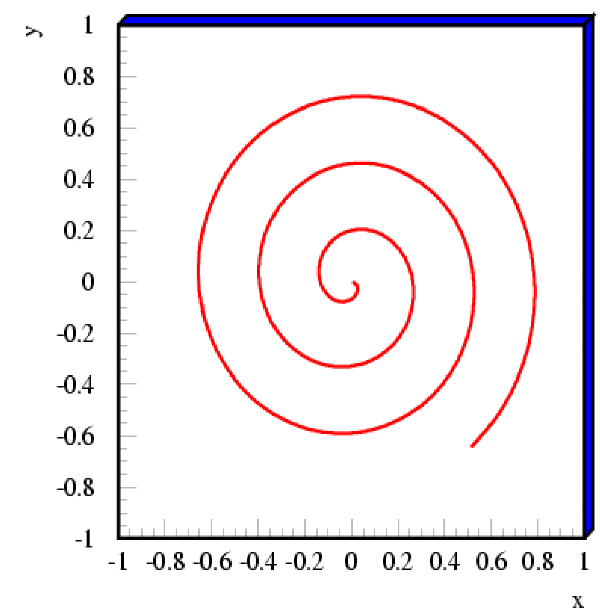
- Assume positrons start at (x,y,z)=(0,0,0) with momentum $p=(0,p_{t0}, pz)$.
- In xy plane, positrons are deflected by B(z) and circulated with radius ρ(z), but it is now a function of z.

$$\rho(z)=\frac{p_t(z)}{eB(z)}$$

- If a parameter of a motion is changed slowly compare to the circulating frequency, an adiabatic invariant exists and is kept constant during the motion.

$$\frac{1}{2\pi}\int p dq=2\rho\, p_t(z)=2\frac{p_t(z)^2}{eB(z)}$$





AMD(3)

- Due to the adiabatic motion,

$$\frac{p_t(z)^2}{eB(z)} = \frac{p_{t0}^2}{eB_i}$$

- Then $p_t(z)$ is expressed as

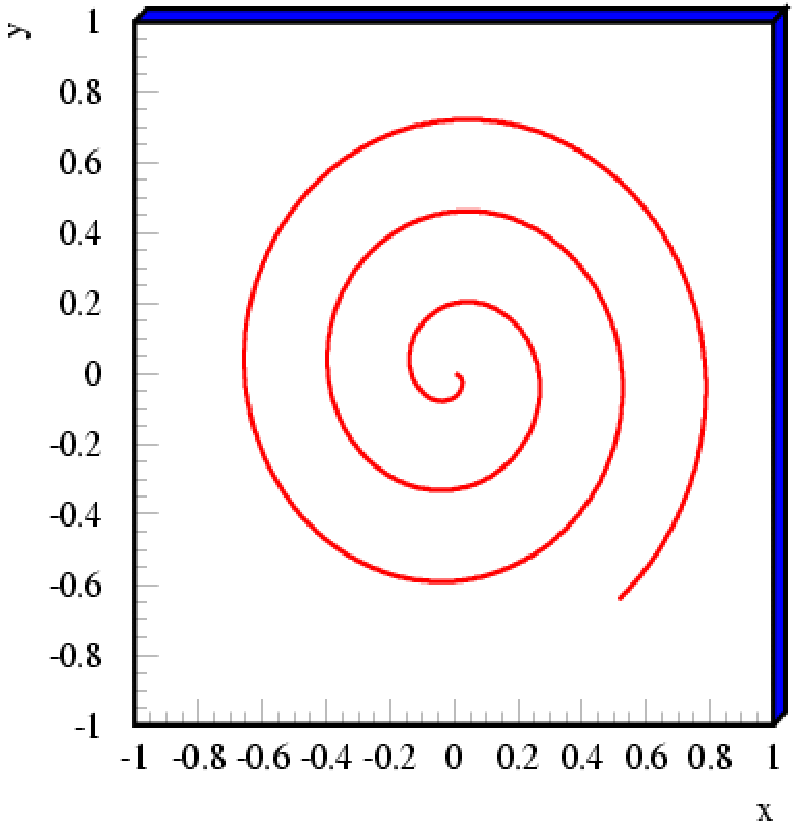
$$p_t(z) = \sqrt{\frac{B(z)}{B_i}}\, p_{t0}$$

- The radius of the circular motion is

$$\rho(z) = \frac{p_t(z)}{eB(z)} = \frac{1}{e\sqrt{B(z)B_i}}\, p_{t0}$$

The radius is increased up to

$$\rho_f = \frac{1}{e\sqrt{B_f B_i}}\, p_{t0}$$



AMD(4)

- If the radius of the motion is just scaled as B(z) (no adiabatic case)

$$\rho_{na}(z)=\frac{p_{t0}}{eB(z)}$$

which should be compared to

$$\rho_a(z)=\frac{1}{e\sqrt{B(z)B_i}}p_{t0}$$

- At last, the radius is smaller than that in non-adiabatic case.

$$\rho_{na}(z)=\frac{p_{t0}}{eB_f}$$

$$\rho_a=\frac{p_{t0}}{e\sqrt{B_f B_i}}$$

$$\frac{\rho_a}{\rho_{na}}=\sqrt{\frac{B_f}{B_i}}$$

AMD(5)

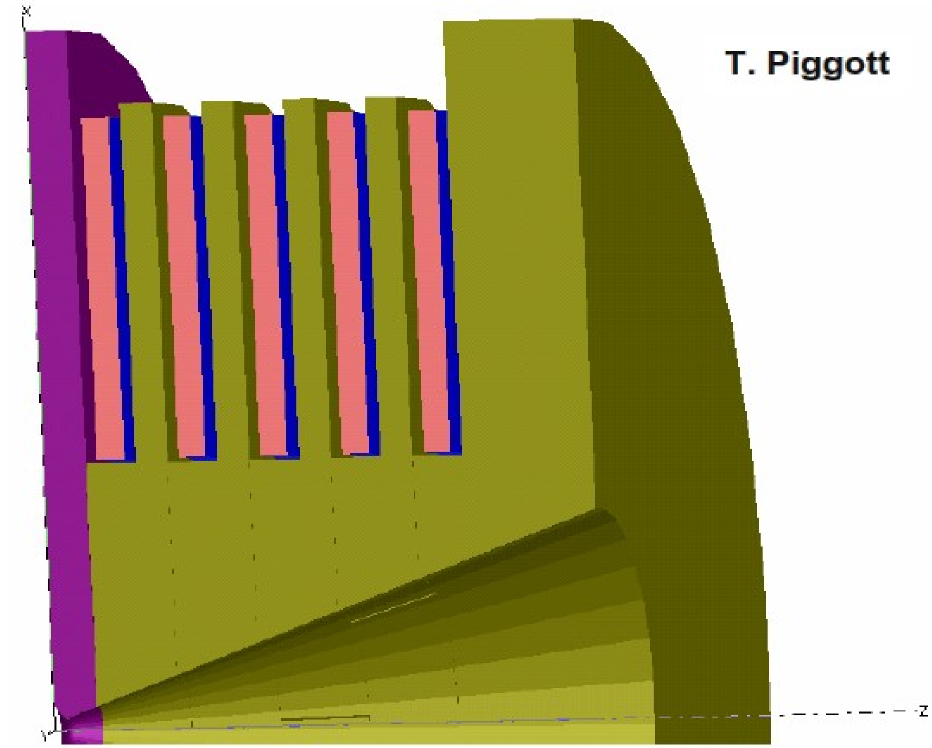
- $2\rho_f$ has to be within aperture, a. Then, the transverse momentum has to be

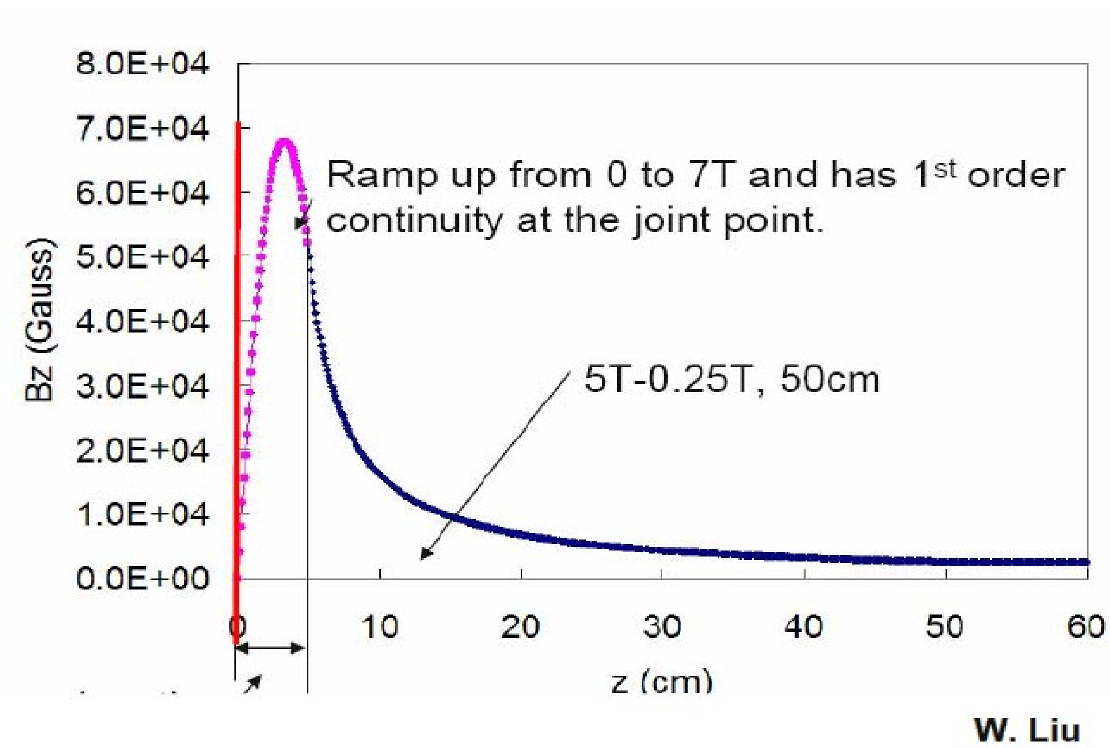
$$p_t < \frac{a}{2} e \sqrt{B_f B_i}$$

- 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}.

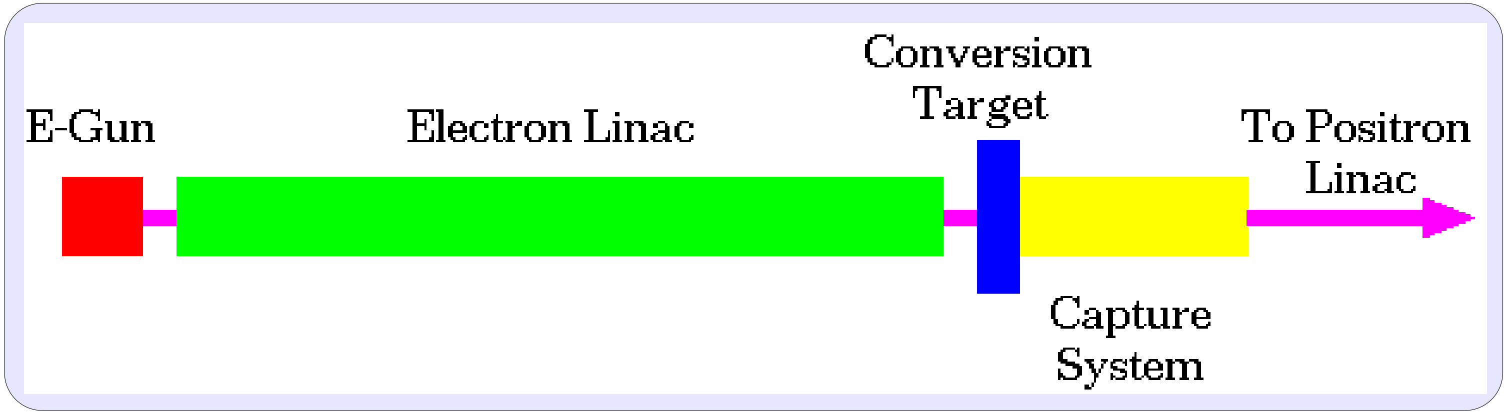




- Ramping from 0T to 7 T in 2cm (no field on target).
- B_i=5T and B_f is 0.25T.

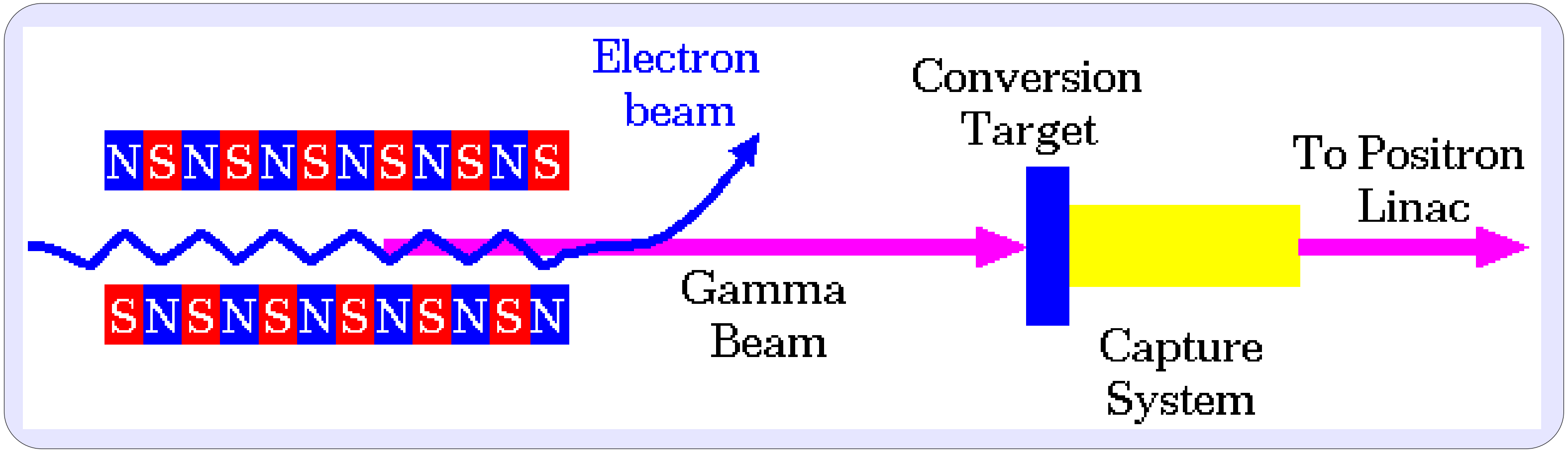
Electron Driven Scheme

- Several GeVs driver electron beam.
- High Density Material for EM shower evolution.
- Positron capture by QWT or AMD + NC accelerator tube with solenoid focusing.



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.

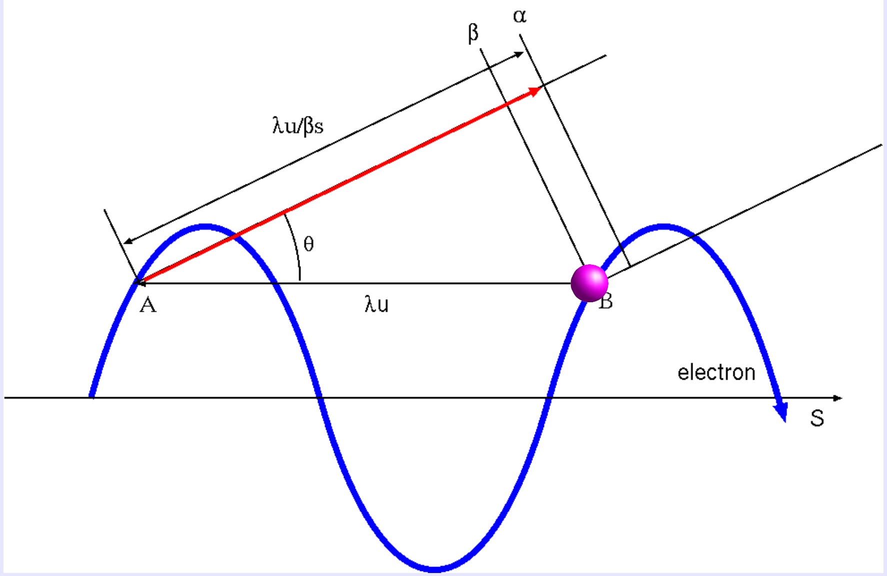


Undulator Radiation

- 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.

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

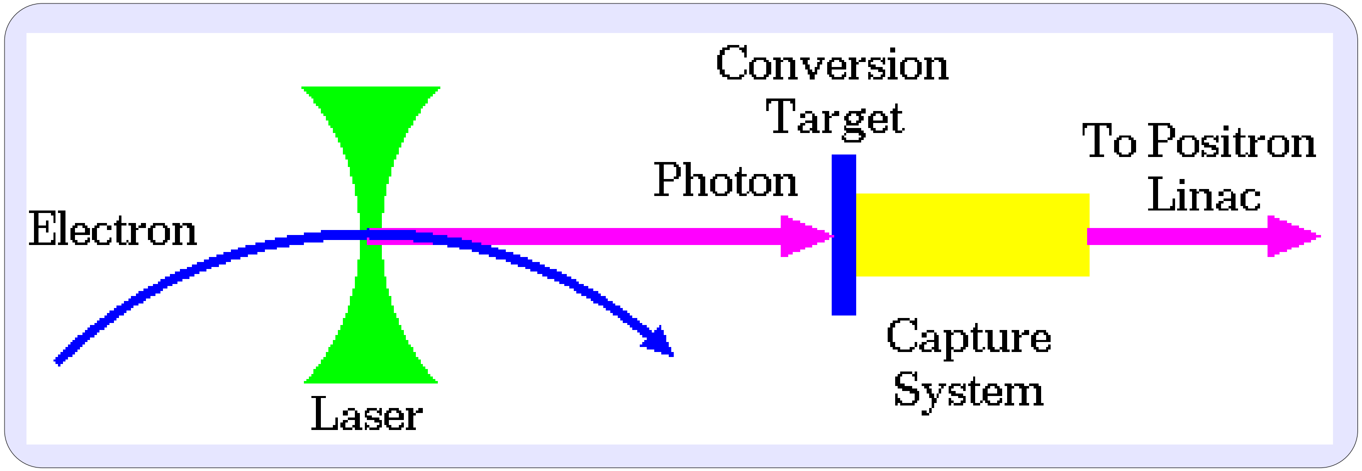
$$E_{ph}[eV] = 9.50\frac{nE^2[GeV]}{\lambda_u[m](1+\frac{K}{2}+\theta^2\gamma^2)}$$



Compton Scheme

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

- 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.

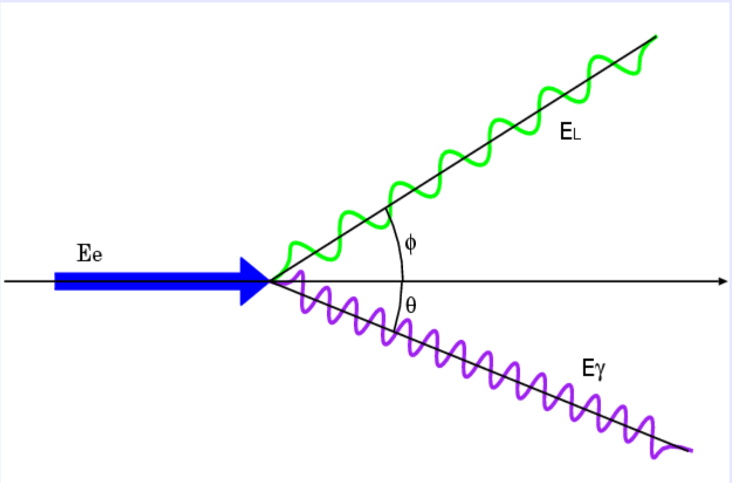


Compton Back-scattering

- 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

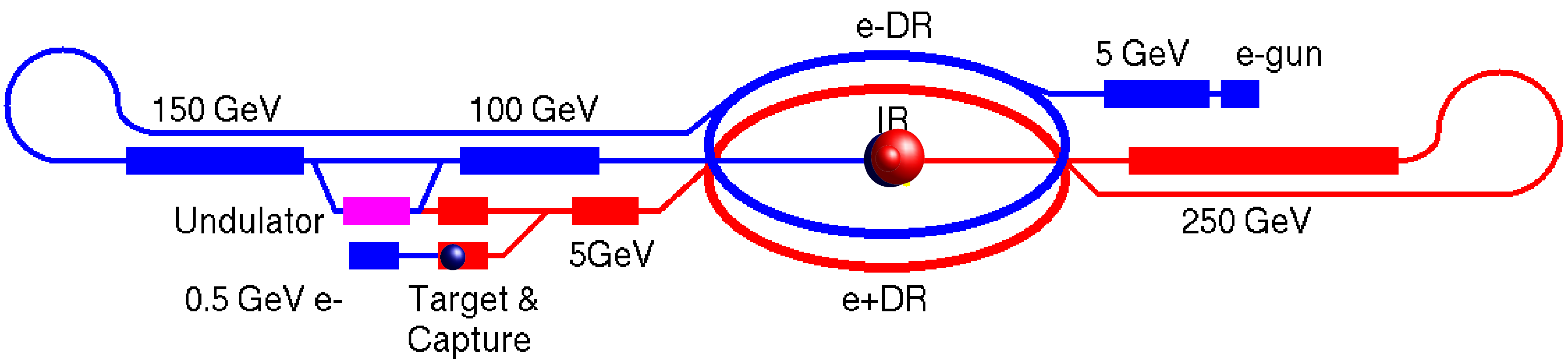


ILC Positron Source

Parameter	Value	Unit
Bunch charge	3.2(1.6)	nC
Bunch length (rms)	4.3	ps
Norm. emittance ($\varepsilon x+\varepsilon y$)	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 fall back.

ILC Positron Source
- A System-wide Sub-system -

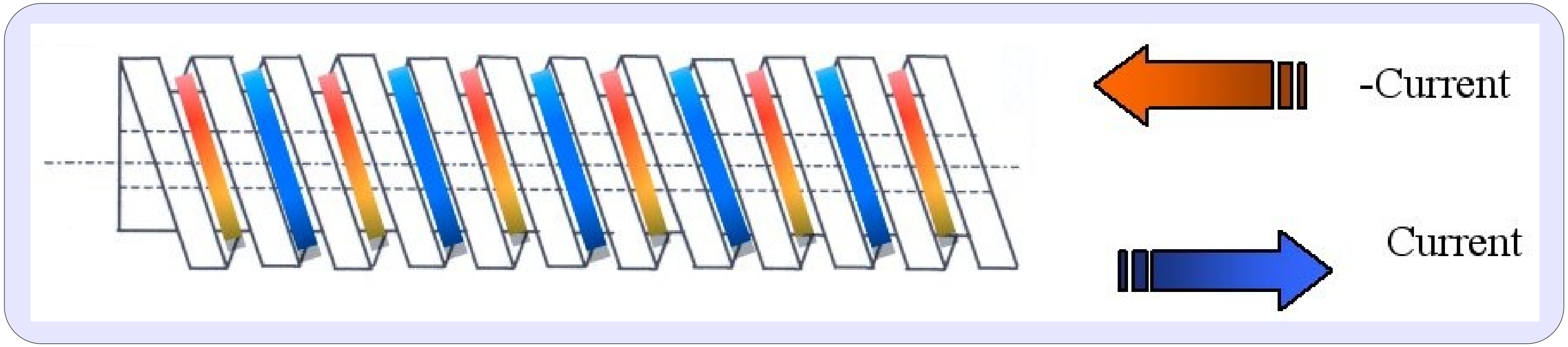


- Gamma rays for positron generation is produced by passing 150 GeV electron through undulator.
- Gamma rays are converted to positron.
- A positron source driven by 0.5 GeV electron is a back up for high availability.
- A common 5 GeV positron booster.

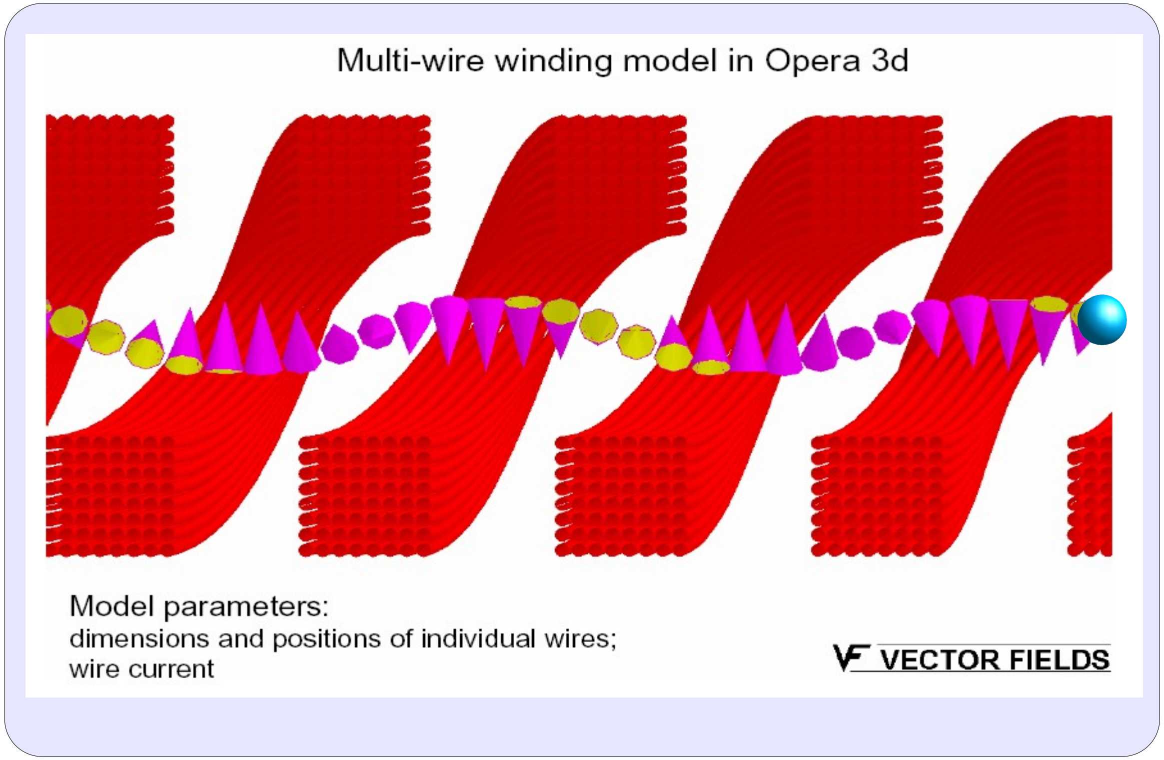
System Specifications

Parameter	Value	Unit
Gamma/bunch	1.20E+13	Number
Positrons/bunch	2.00E+10	Number
Positron yield	1.5	e+/e-
Electron drive energy	150 GeV	GeV
Drive beam energy loss	4.8	GeV
Undulator length	147	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

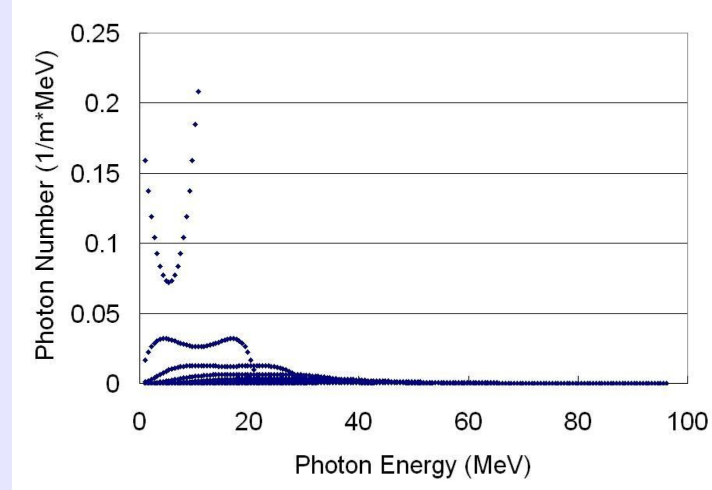
Undulator Type	SC Helical	-
Undulator period	11.5	mm
Undulator Strength (K)	0.92	-
Magnet Current	205 (86% of critical)	A
Magnetic field (on axis)	0.86	T
Undulator Length (unpolarize)	147	m
Beam Aperture	5.85	mm
Photon Energy (1st hrm)	10.07	MeV
Max. photon power	131	kW

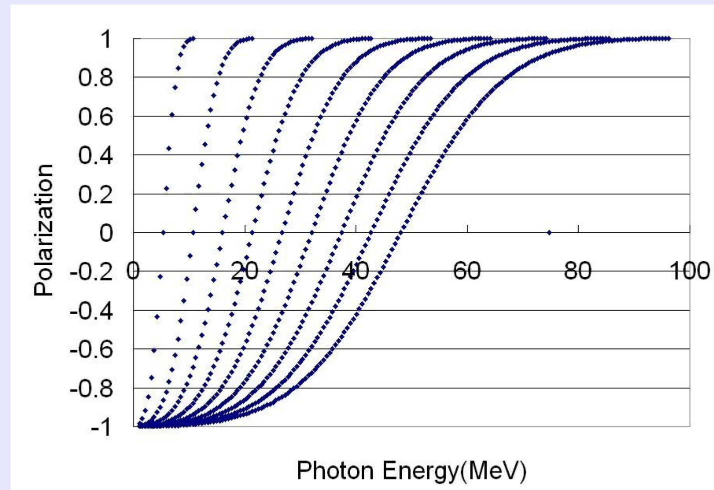
Polarized Positron

- 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.

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

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



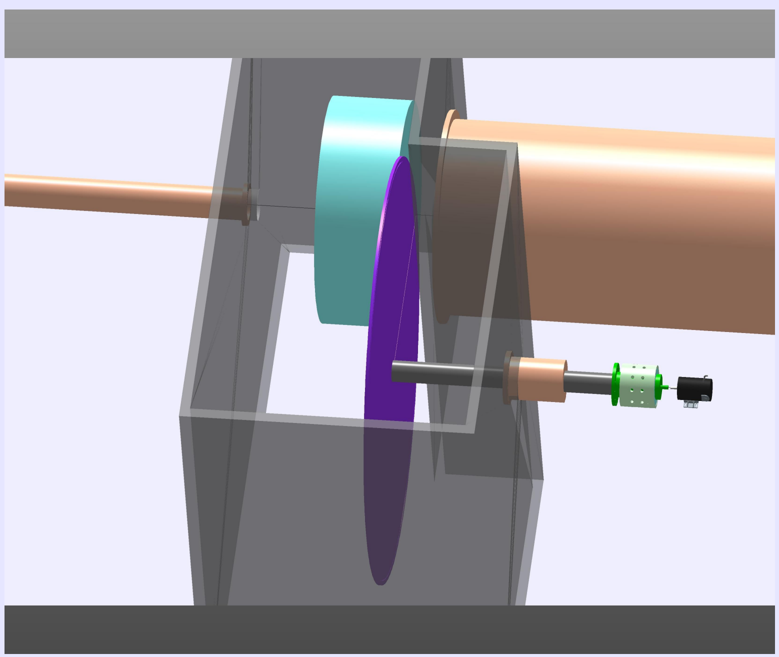


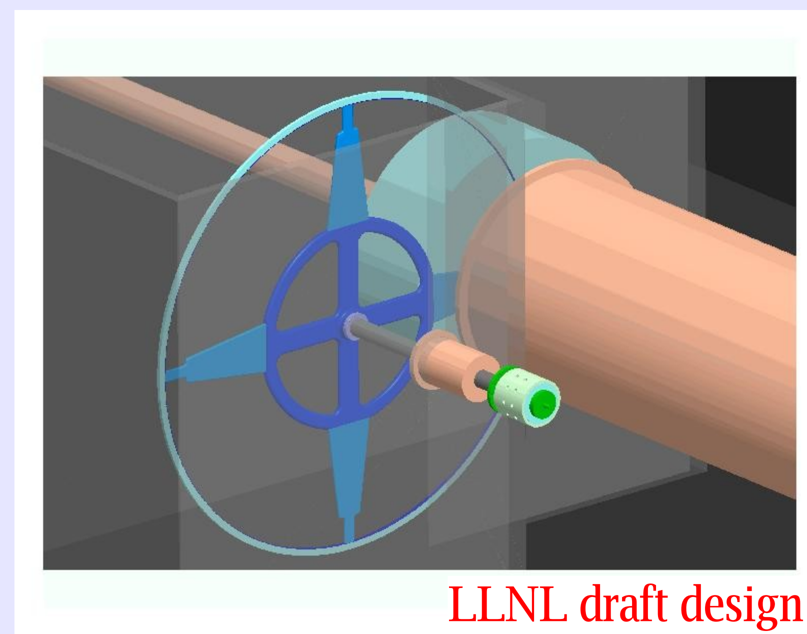
By W. Gai

Target

Positron Generation
Positron Capture
Positron Source
ILC Positron Source
Summary

- 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 :20kW (rim) when the target is immersed in B field. Must be no B field.



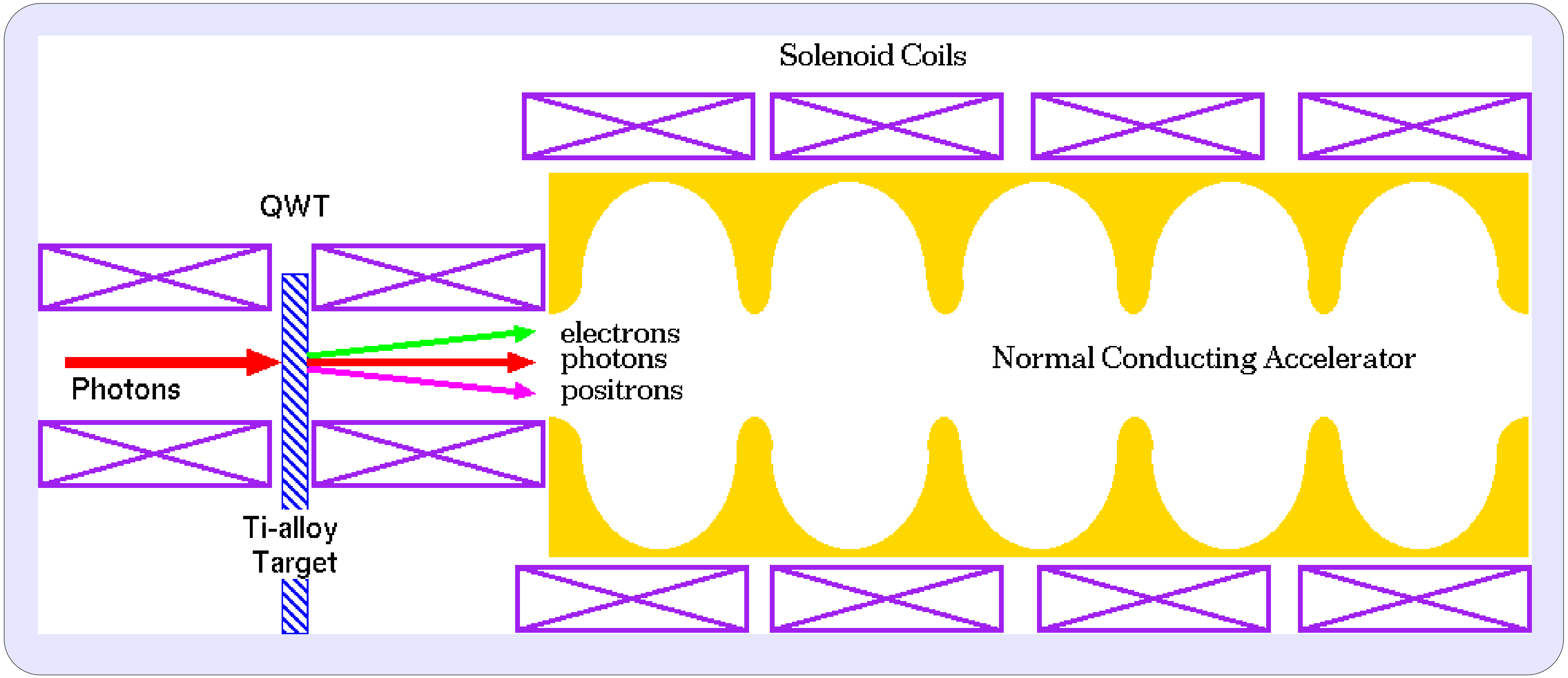


Positron Capture

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

► QWT (B_i~1T, B_f~0.5T in 20cm): pulsed coil with bucking coil to shield magnetic field on target.

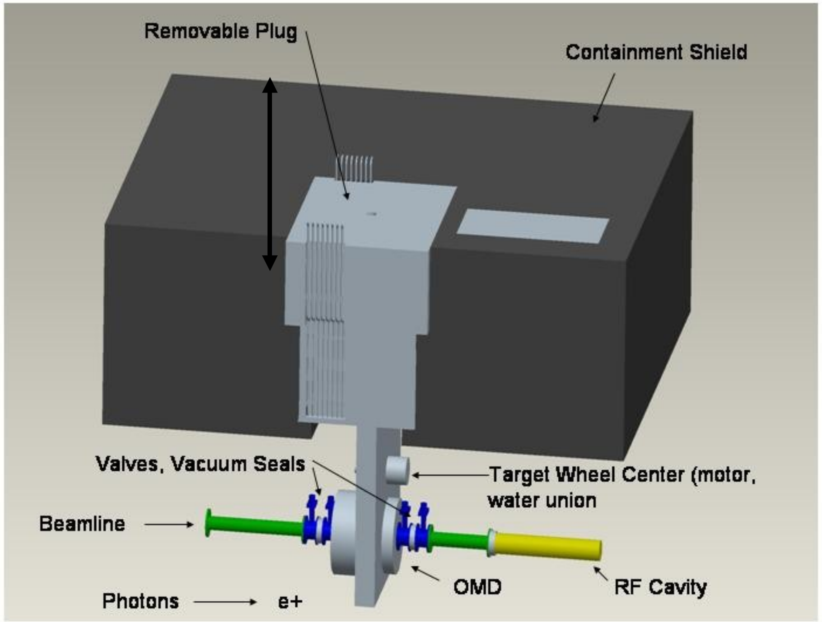
► L-Band NC accelerator tube with 12 ~ 15 MV/m.



Remote Handling

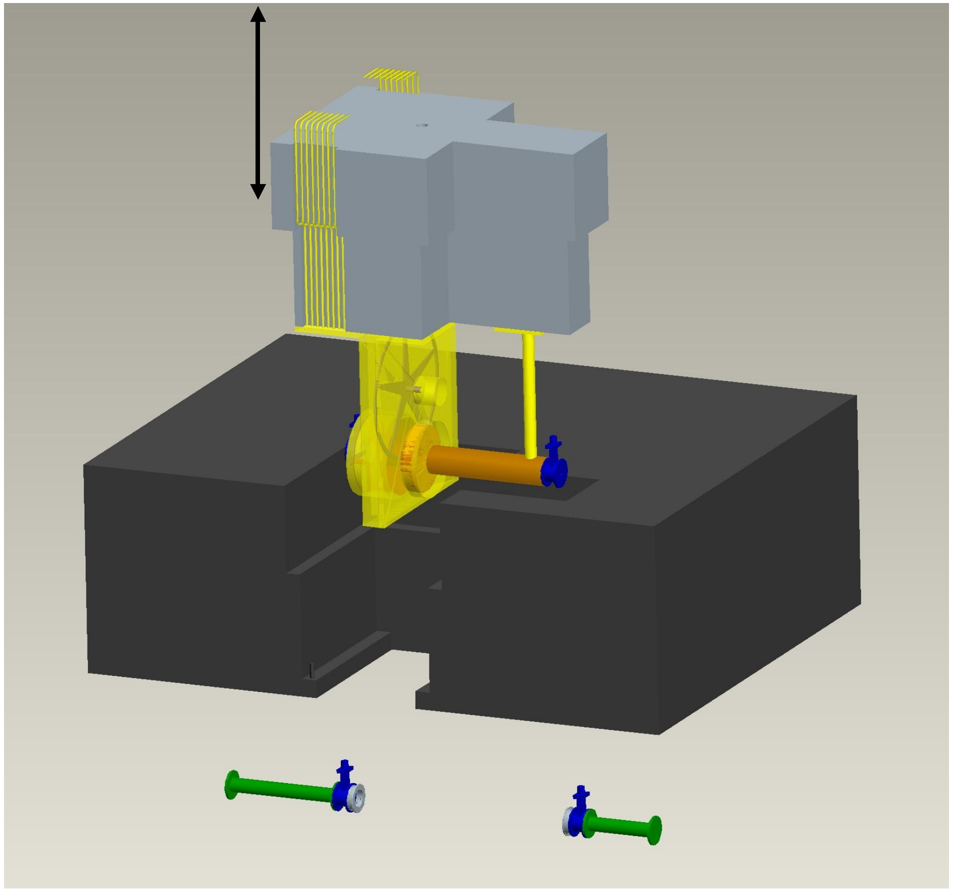
Positron Generation
Positron Capture
Positron Source
ILC Positron Source
Summary

Target Assembly In Place



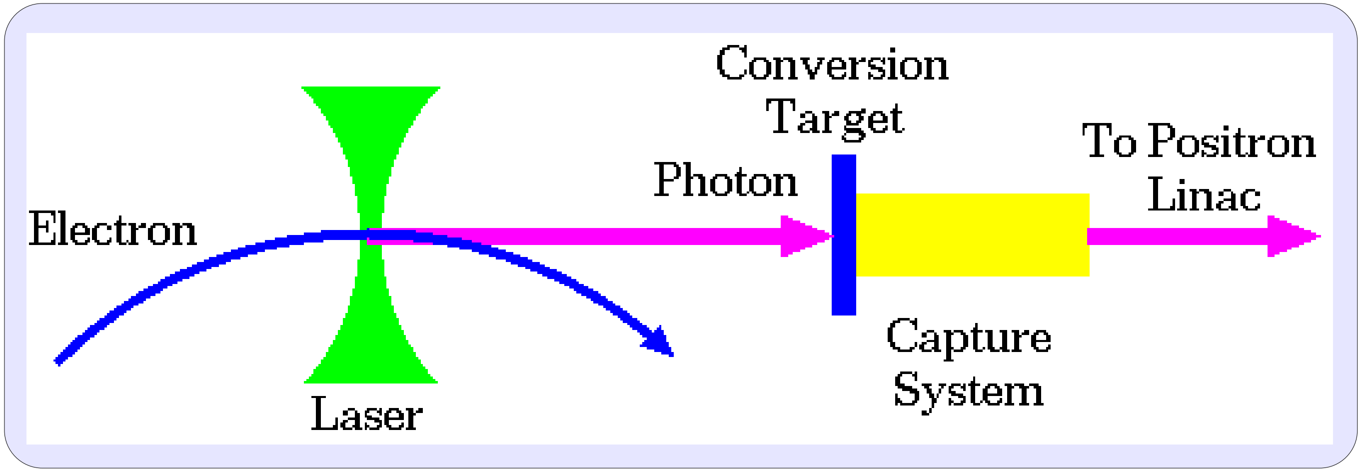
1.25 m

Target Assembly Lifting Out



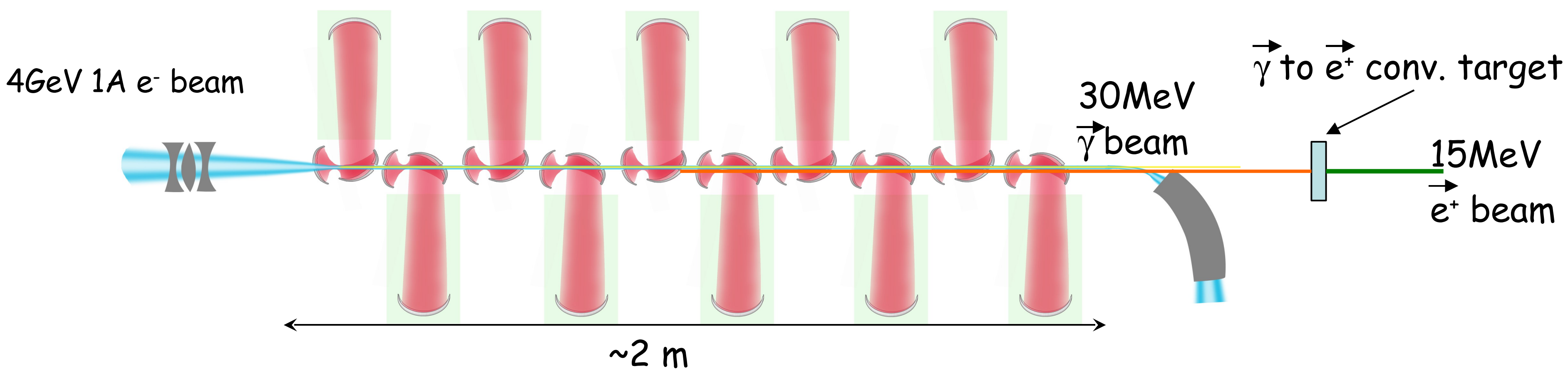
Laser Compton Scheme

- Several proposals with different electron drivers and photon (laser) sources.
  - Storage ring, ERL(Energy Recovery Linac), Linac
  - Nd:YAG, CO2 + Optical cavity,
- The required electron energy is a few GeV and a dedicated electron driver is reasonable,
- But it is a technical challenge to obtain an enough amount of e+ for ILC



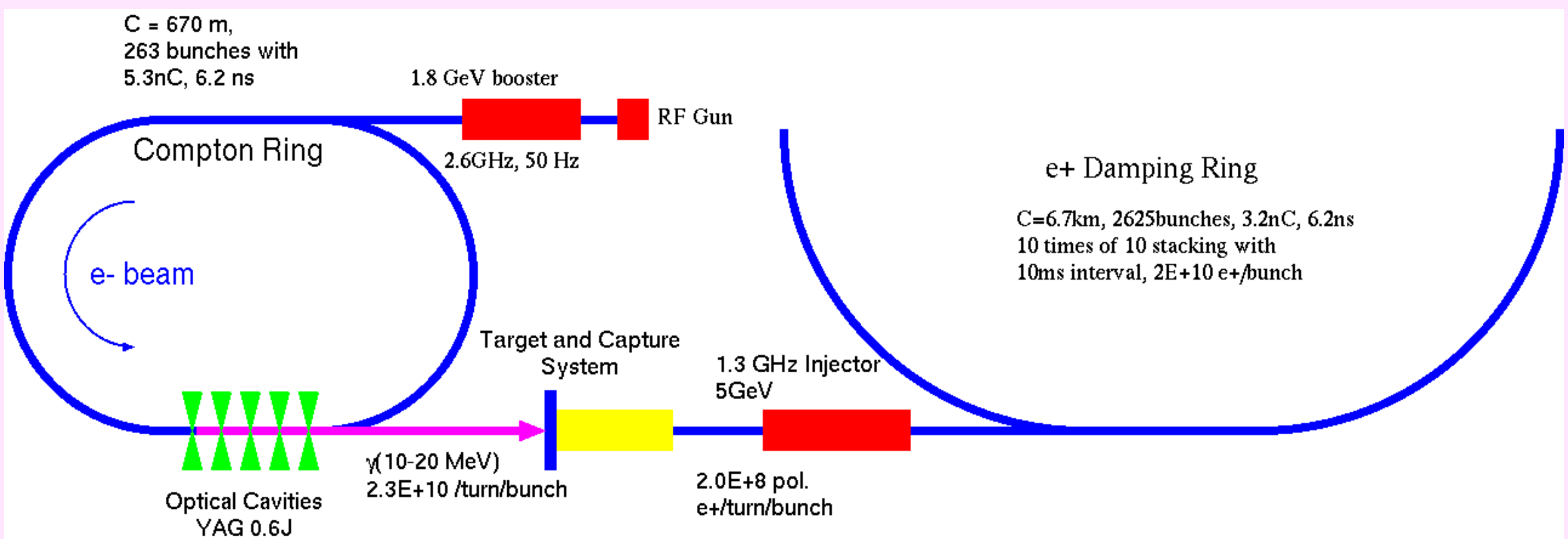
Linac Laser Compton

- 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.



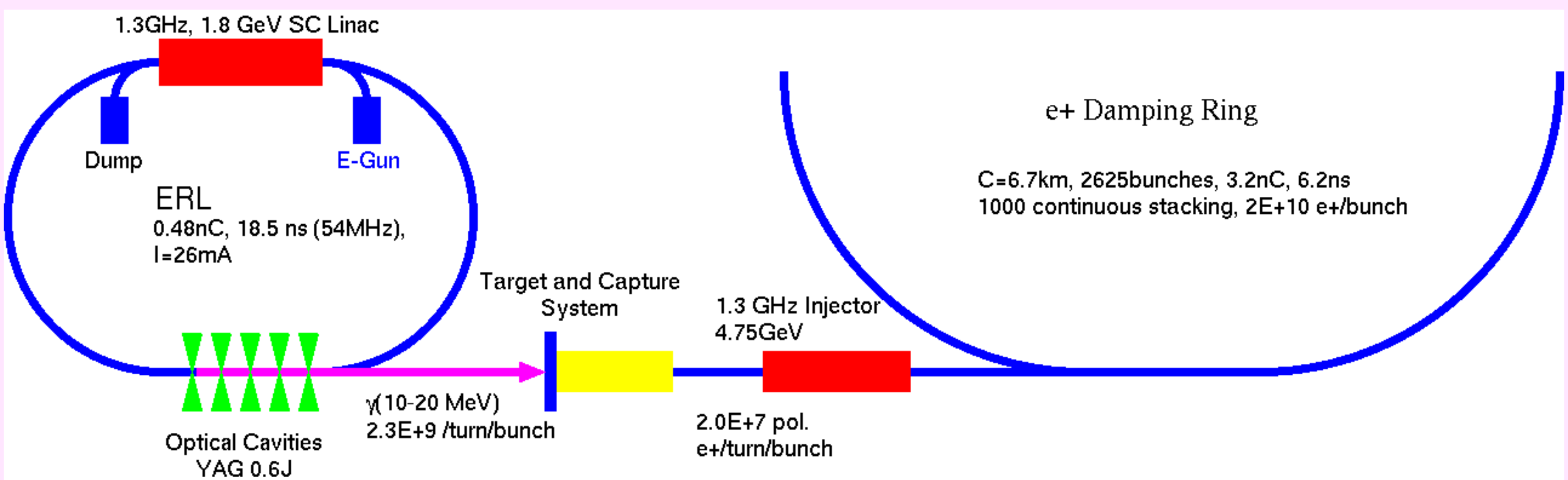
Compton Ring

- A storage ring for electron driver:5.3nC, 6.2ns, 1ps, 1.8GeV, 0.6Jx5CP.
- Positron bunch(Ne+:2.0E+8) is generated.
- 10 bunches are stacked on a same bucket. This process is repeated 10 times with 10ms interval for beam cooling.
- Finally, Ne+:2E+10 is obtained.



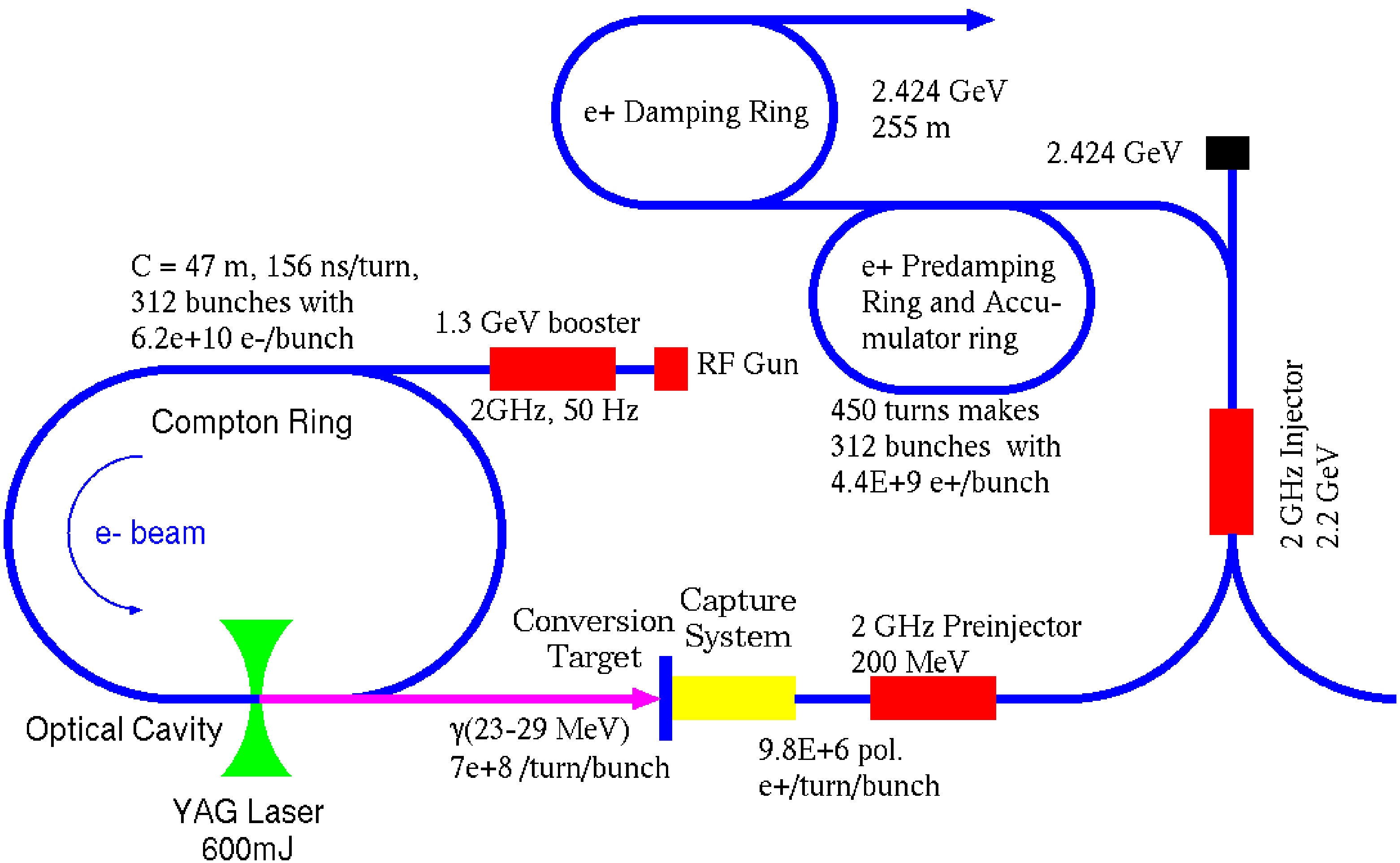
ERL

- ERL(Energy Recovery Linac) is employed as the dedicated electron driver.
  - 0.48nC, 18.5ns (54MHz) ~ 26mA, E=1.8GeV
  - N_γ=2.3E+9 by 0.6 Jx5 CP, N_{e+}=2.0E+7
- By a semi-CW operation (50ms), 1000 times stacking in DR is possible and Ne+=2.0E+10 is obtained.



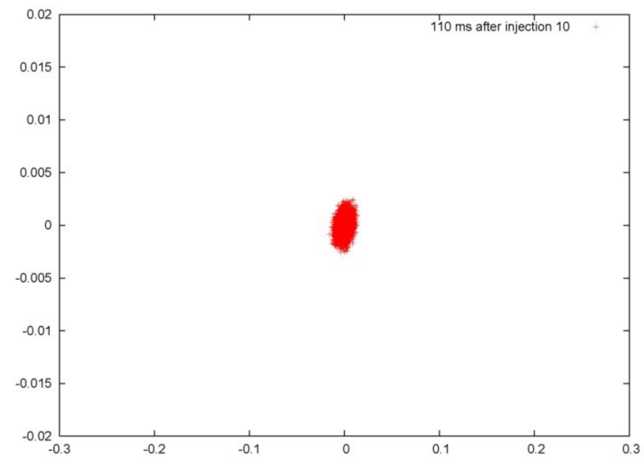
CLIC Compton Scheme

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



Positron Stacking

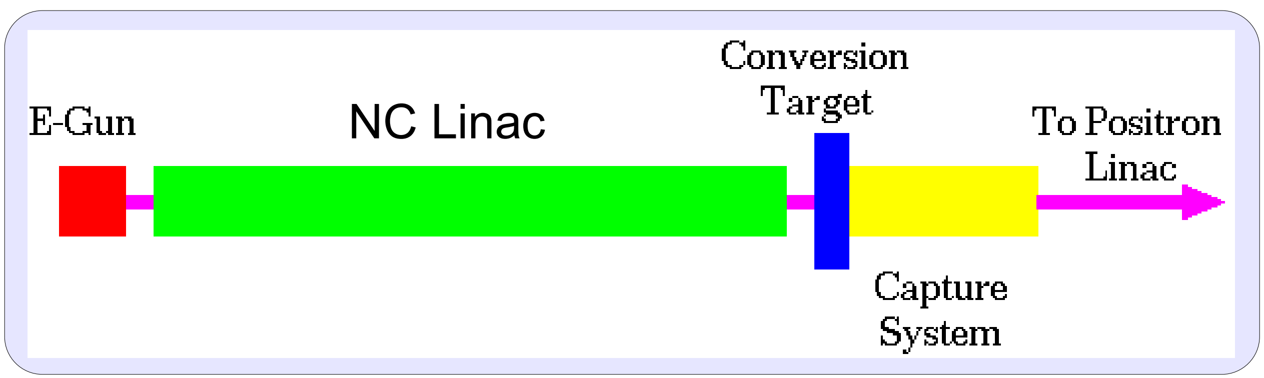
F. Zimmermann



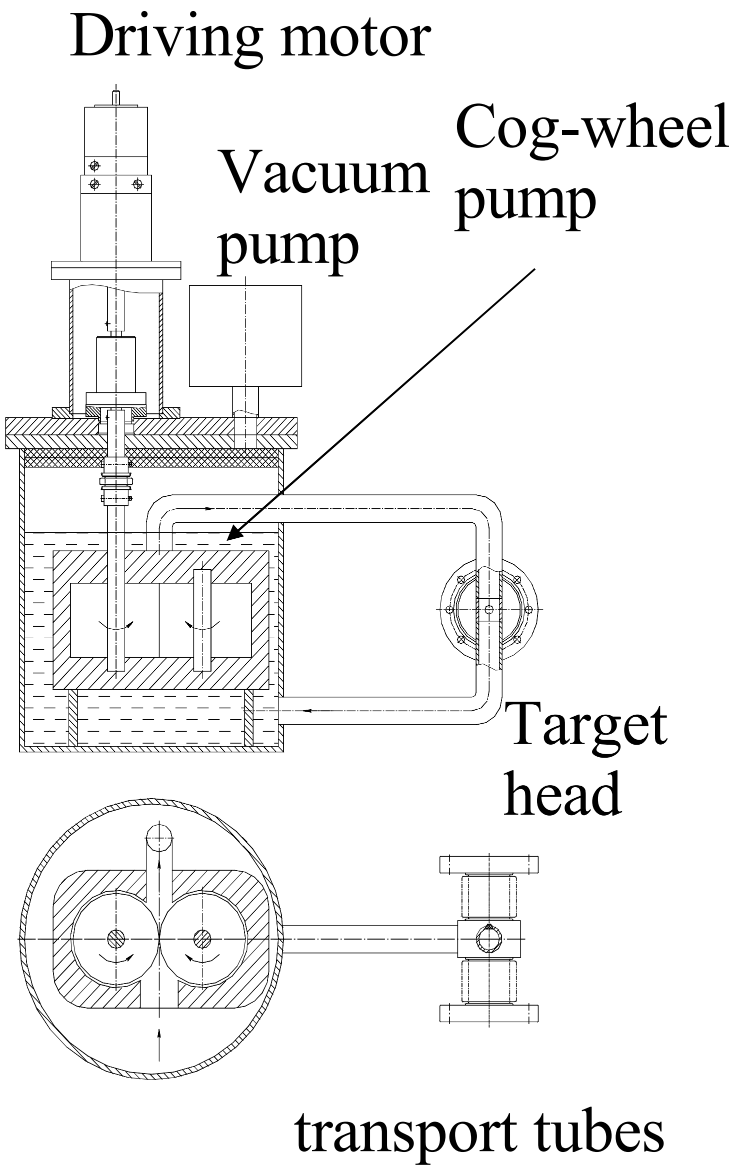
- Except linac scheme, # of positron by a single collision is not sufficient -> need stacking.
- Many bunches are injected to a same bucket in DR.
- Stacking simulation shows 90% efficiency and 10% loss.
- The tolerance of the injection loss would be qualified.

Electron Driven Scheme (1)

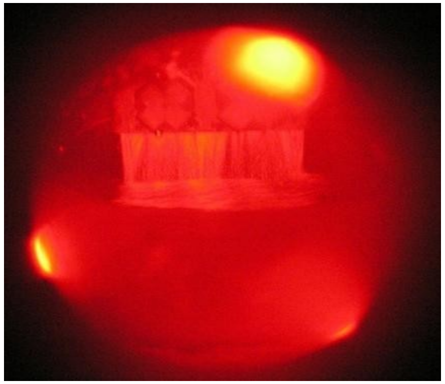
- Electron driven is the most reliable scheme, but possible target damage is an issue.
- Only unpolarized positron.
- Several ideas on target
  - Fast rotating metal target like undulator, but faster.
  - Liquid metal
  - Crystalline



Liquid lead target



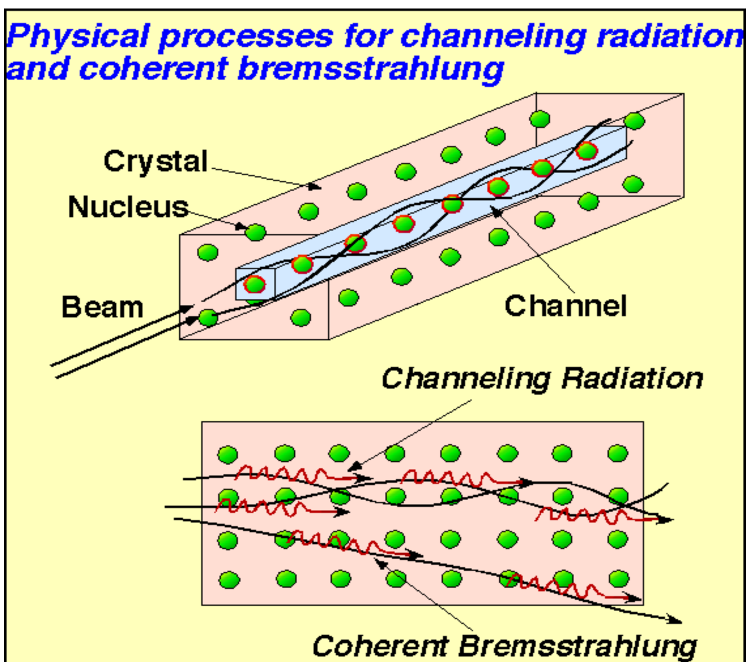
- A prototype in BINP has been operated 20000h without any troubles.
  - Pb 90% Sn 10%, 300°C, Cog-wheel pump.

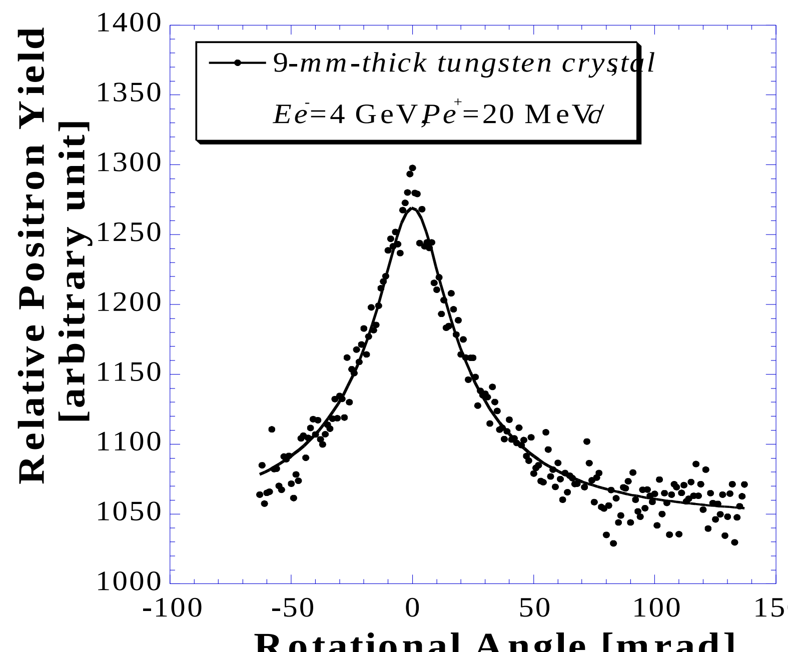


Liquid Pb-Sn jet in vacuum

Crystalline Target (1)

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





Crystalline Target (2)

Positron Generation
Positron Capture
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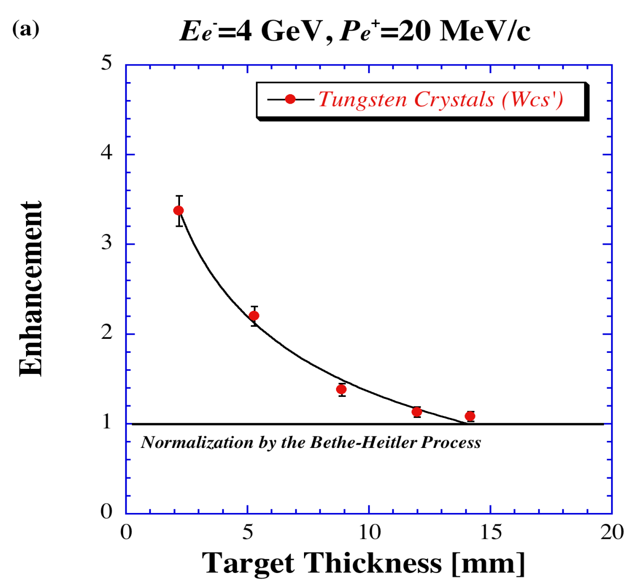
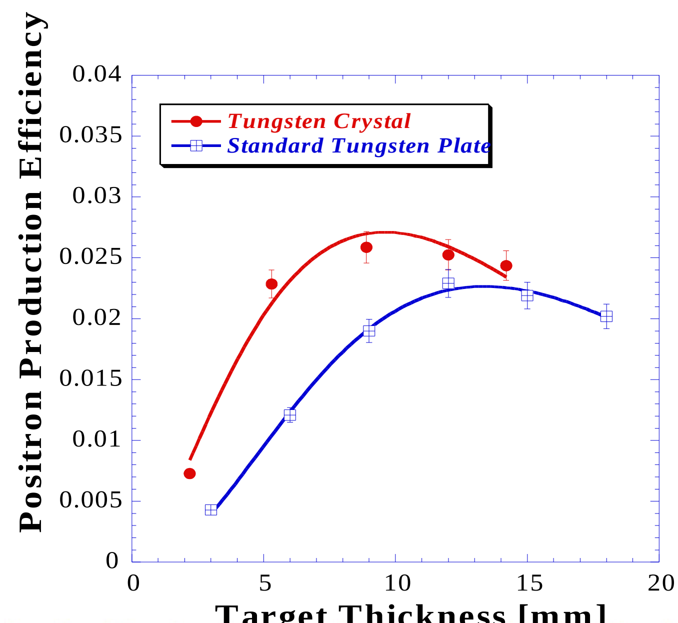
ILC Positron Source
Summary

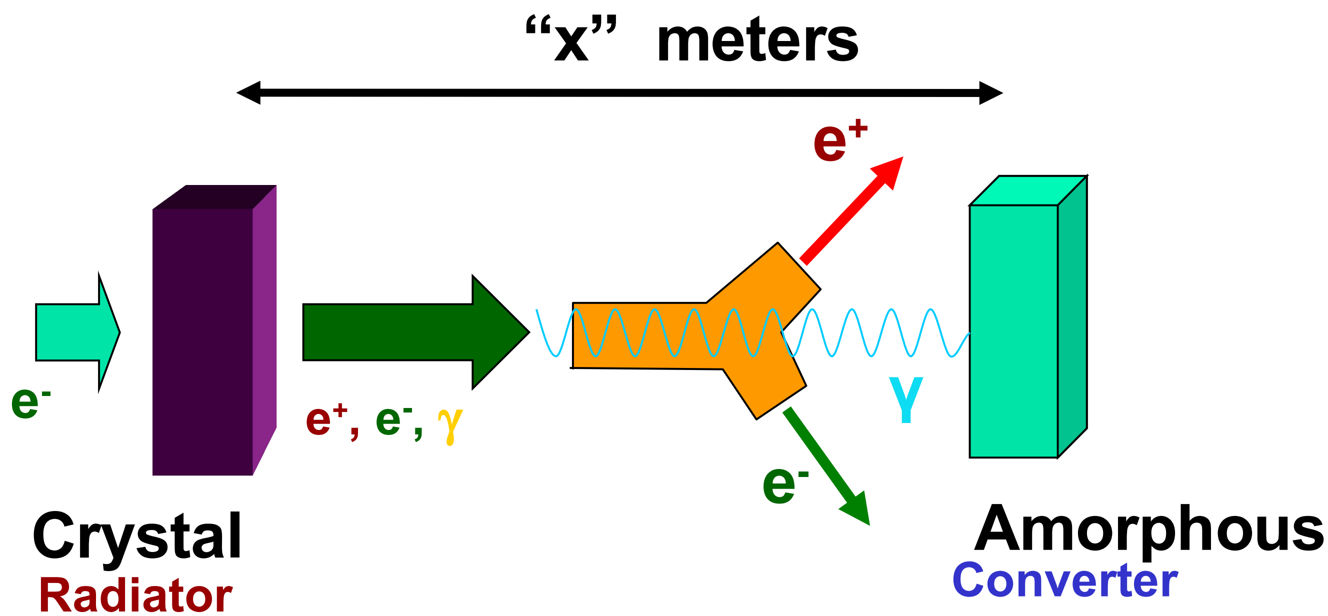
- Positron yield by the crystalline target is enhanced by ~30% with thinner (~9mm) target thickness.
- The heat load becomes almost half compare to the amorphous target.
- The heat load normalized to the generated positron flux is 40% of that by amorphous target. It relaxes the technical limitation very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





Crystalline Target(3)

- By sweeping out charged particles, only the photons are impinging on the converter: that limits the energy deposition in the amorphous target.
- A single target works for CLIC, but multi-target is needed for ILC limited by PEDD.



Summary

Positron Generation
Positron Capture
Positron Source
ILC Positron Source
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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