Positron Production

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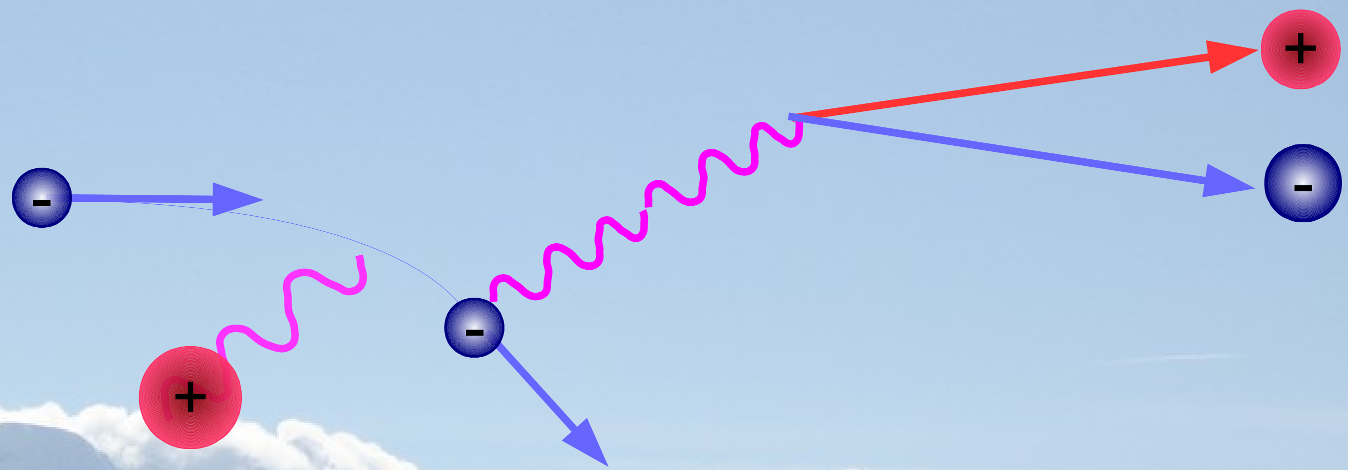
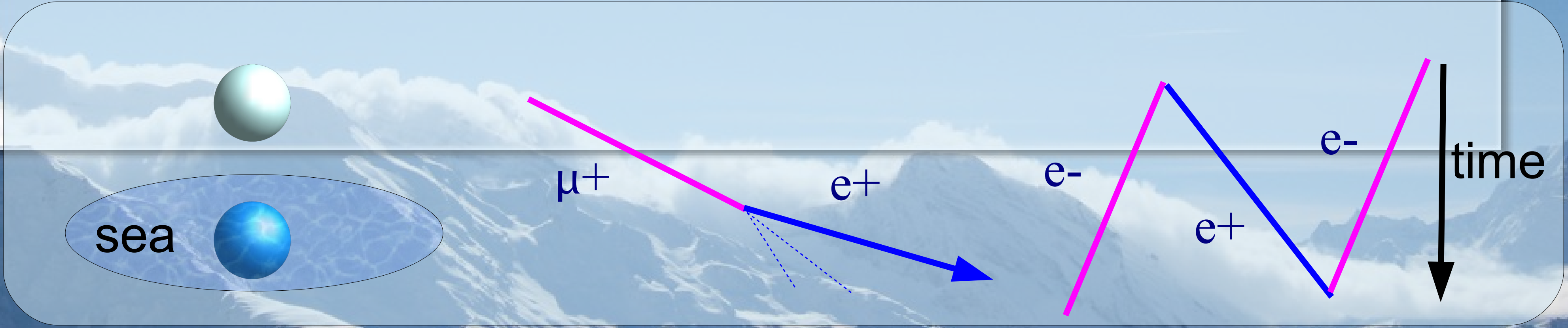


Contents

Introduction

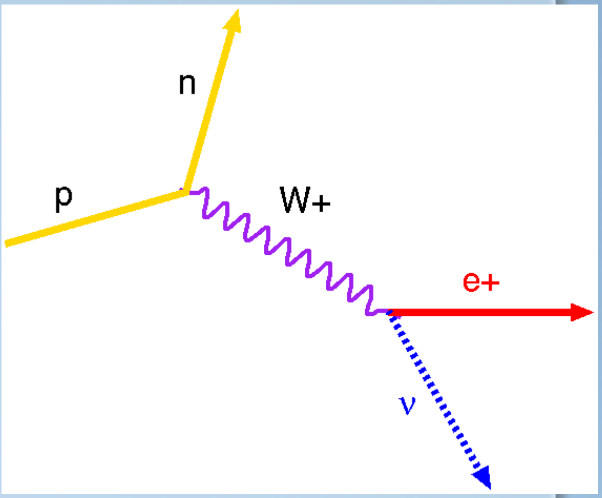
What is Positron?

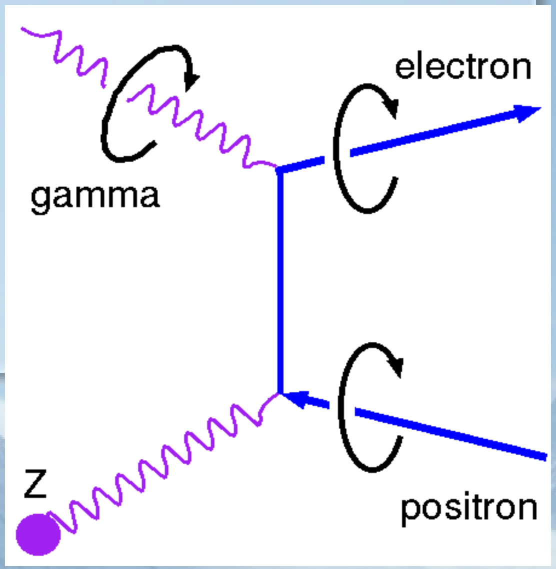
- 1928: Dirac equation suggested electrons with negative energy. Hole hypothesis: "vacuum" is filled with this negative energy electrons to prohibit Klein's paradox. "hole" in the sea of this electrons, acts as positrons.
- 1932:Anderson discovered positrons in cosmic rays with cloud chamber.
- In the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



Positron Production (1)

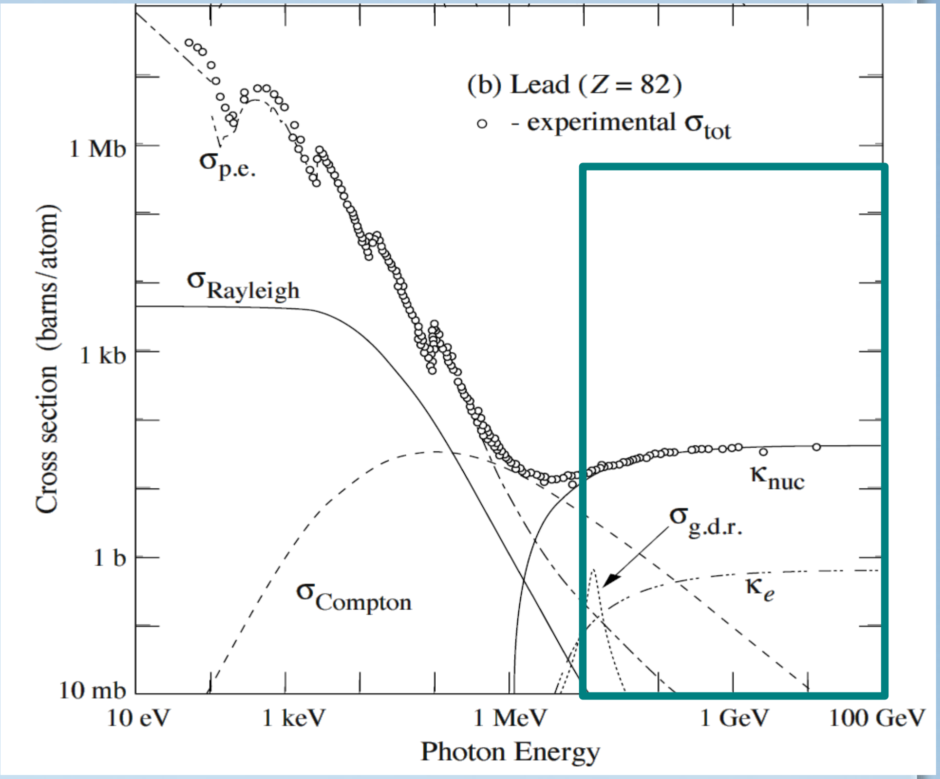
- There is only few positrons in nature. (Nature is not symmetry!)
- Two ways to produce positrons :
  - Create radio-active elements, which β^+ decays; $p \rightarrow n\, e^+\, \nu$.
    - Continous e+ beam.
  - Pair-creation ; $\gamma \rightarrow e+\ e-$.
    - Can be with a time structure.
- All of the positron beam sources with a time structure, employ the pair-creation process.





Positron Production (2)

- 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)

Need Photon?

- We need many photons to create enough amount of positrons through the pair creation.
- How to create the photons?
  - Brems-strahlung, channeling radiation : electron interaction in material. Very effective.
  - Undulator radiation: Synchrotron Radiation. Need very long undulator with very high energy electron.
  - Inverse Compton scattering : Laser and electron interaction. Need very high luminosity.

Positron Generation

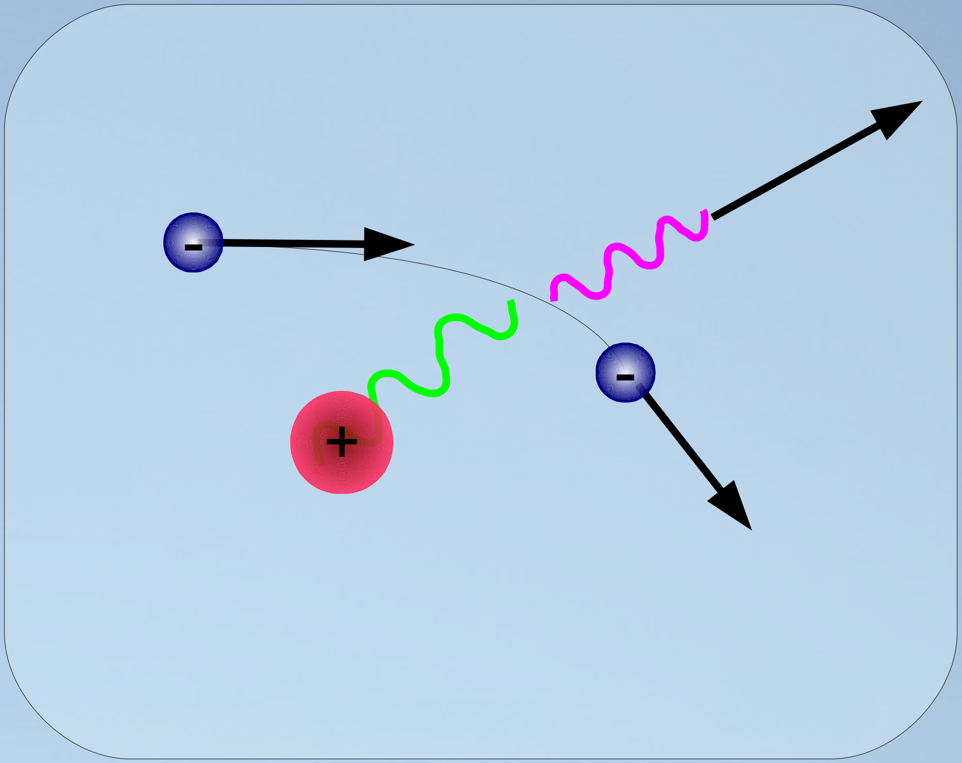
Positron Generation

- Positron beam is generated by the pair-creation process.
- There are several schemes for positron generation, depending on way to generate gamma rays (>10 MeV).
- Electron driven
  - Authentic
  - Channeling radiation
- Direct Pair-creation
  - Undulator
  - Laser-Compton

Electron Driven(1)
Bremsstrahlung(1)

We inject electron beam to a metal target,

- Electron is decelerated by nucleus field.
- Photon is emitted by the energy conservation.
- Gamma rays are obtained with >100 MeV or GeV electrons.



Cascade Shower

In each step, the electron energy becomes ½.

$$E_n = E_0 2^{-n}$$

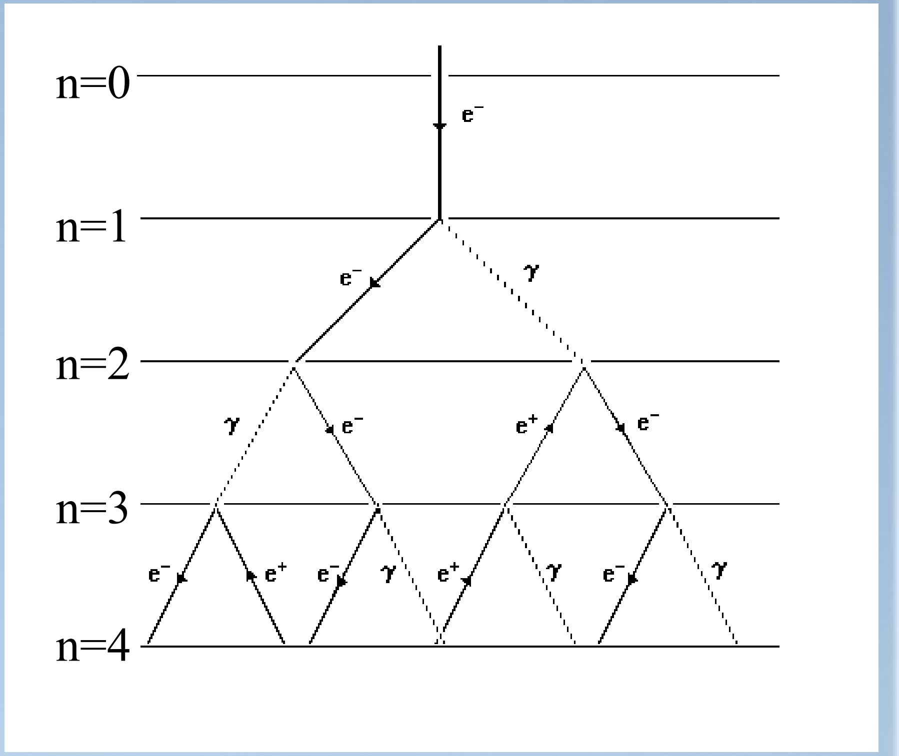
Radiation length X_0:

$$\frac{dE}{dx} = -\frac{E}{X_0}$$

It continues down to $E=E_c$,

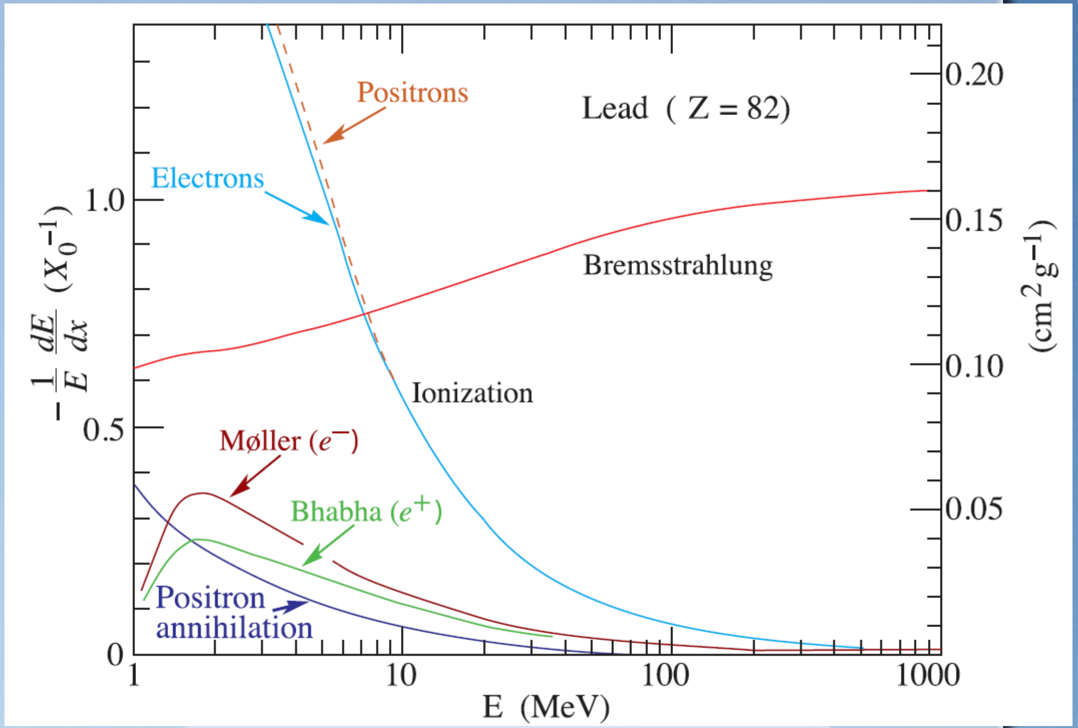
$$x_{max} = nX_0 \ln(2)$$

$$x_{max} = X_0 \ln\left(\frac{E_0}{E_c}\right)$$



What is E_c?

- Bremsstrahlung is dominant in high energy region.
- Below some energy (E_c critical energy) ionization is dominant.
- When high energy electrons are injected into material, electrons loose their energy by Brems-strahlung.
- Below E_c, ionization is dominant. (no growth)



Critical Energy E_c

$$\left(\frac{dE}{dx}\right)_{ion} = \left(\frac{dE}{dx}\right)_{Brems}$$

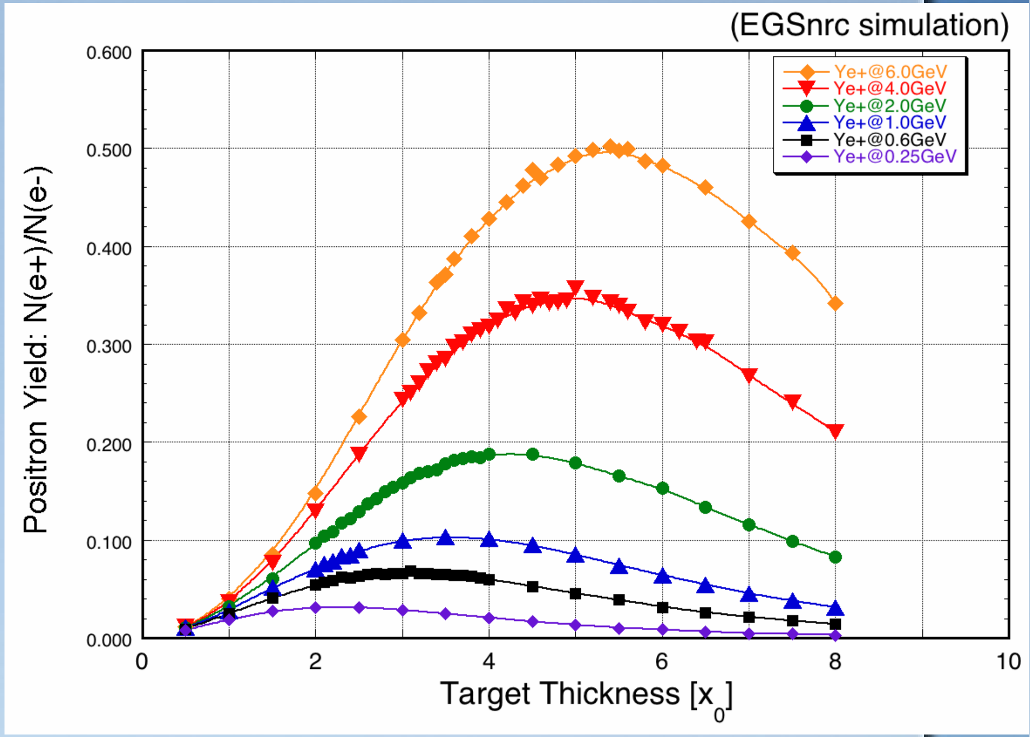
$$E_c[MeV] \sim \frac{800}{Z+1.2}$$

Cascade Shower (2)

- As consequence of the cascade shower by the high energy electron in material, many positrons are generated.
- Number of positron is maximized at shower max determined by X_0, E_0, and E_c.

$$x_{max} = X_0 \ln\left(\frac{E_0}{E_c}\right)$$

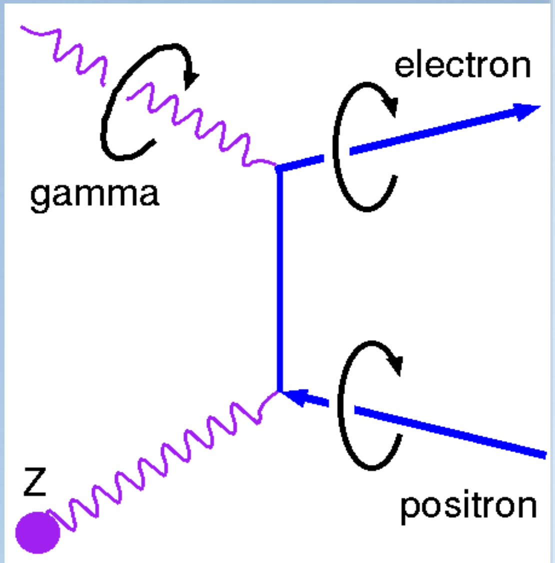
$$X_0 = \frac{716.4[g.cm^{-2}]A}{Z(Z+1)\ln(287/\sqrt{Z})}$$



Courtesy of T.Kamitani

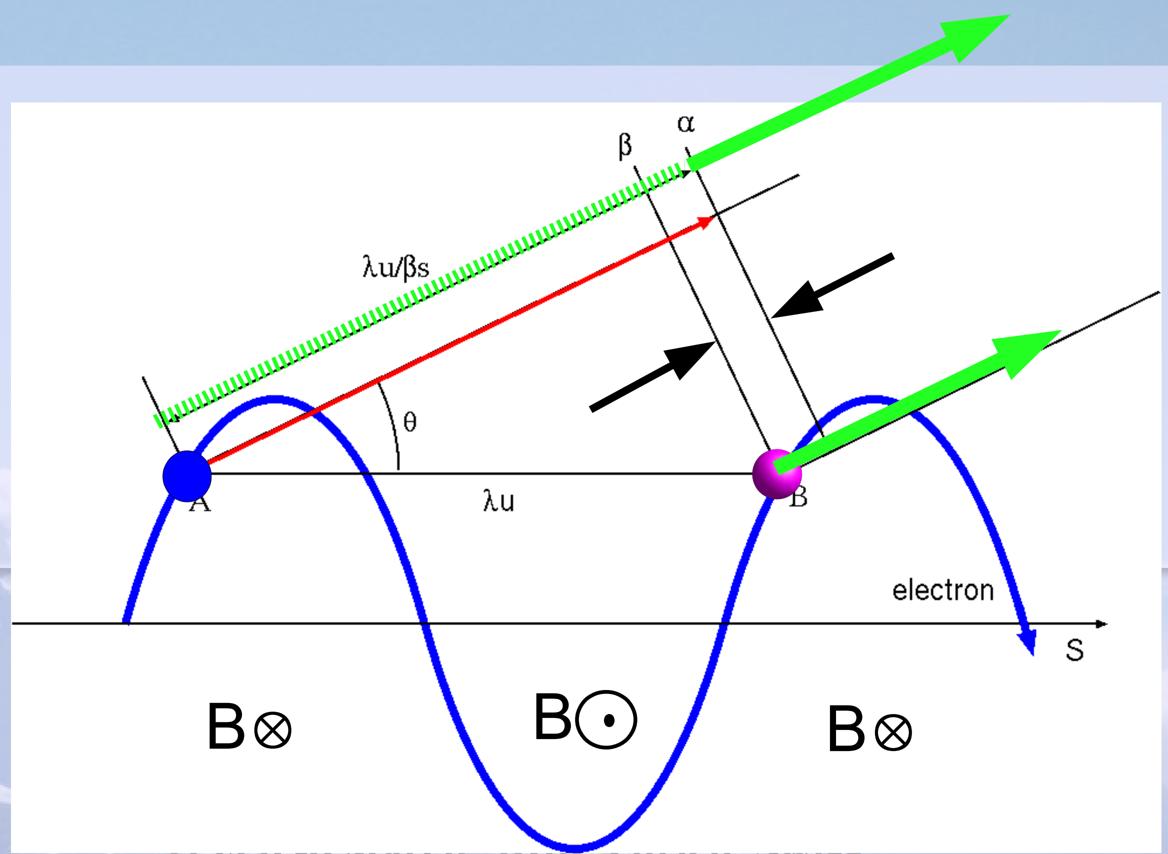
Direct Pair Creation

- 10s MeV photons directly generate positrons through the pair creation process.
- Due to this simplicity, if the photons are polarized, the positrons are also polarized. (Polarized Positron).
- # of particles is not multiplied. Each photon can generate only up to one positron. Because the capture efficiency is much less than the unity, we need many photons.



Undulator Radiation (1)

- In alternate dipole B field(undulator), electron wiggles periodically.
- Electron speed in undulator along the longitudinal axis is less than speed of light due to the zig-zag motion.
- If synchrotron radiation wave-planes from *n*th and *n+1*th period is coherent, it is much enhanced (photon is emittend to this direction.)



Undulator radiation (2)

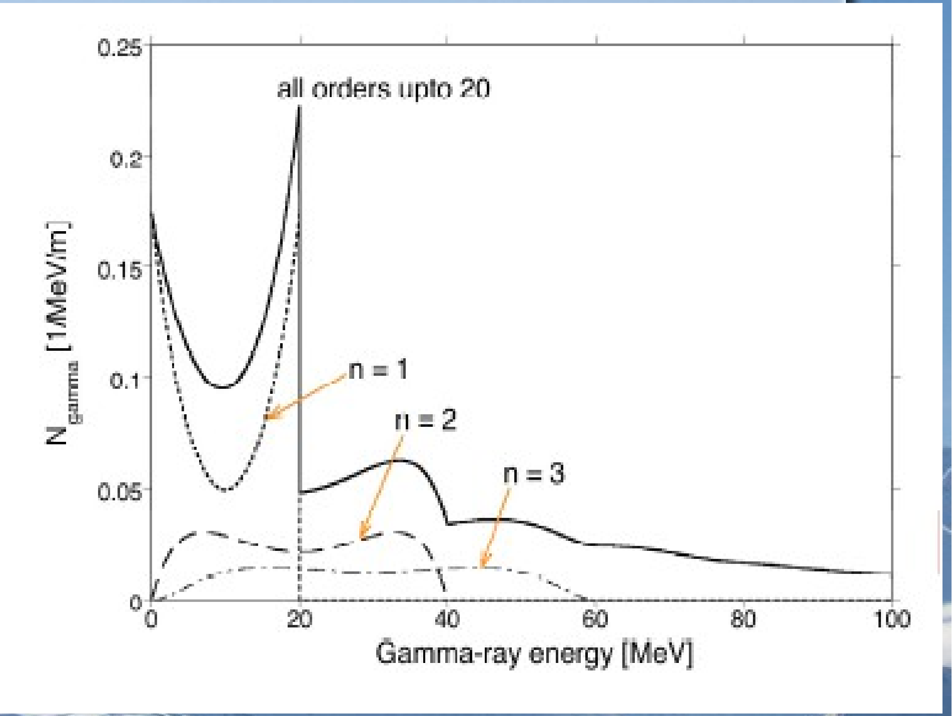
Lienard-Wiechert form (ω photon angular, Ω is solid angle, $\mathbf{n}$ is unit vector to observation)

$$\frac{d^2 I}{d\omega\, d\Omega} = \frac{e^2 \omega^2}{16\pi^3 \varepsilon_0 c} \left| \int_{-\infty}^{+\infty} \boldsymbol{n}\times(\boldsymbol{n}\times\boldsymbol{\beta}) \exp\left[i\omega \left(t - \frac{\boldsymbol{n}\cdot\boldsymbol{r}}{c} \right) \right] \right|^2 \quad (3-8)$$

$$\frac{d^2 N_{ph}}{dEdL} \left[\frac{1}{m.MeV} \right] = \frac{10^6 \mathrm{e}^3}{4\pi\epsilon c^2 h^2} \frac{K^2}{\gamma^2} \left[J_n'(x)^2 + \left(\frac{\alpha_n}{K} - \frac{n}{x} \right)^2 J_n(x)^2 \right] \quad (3-8')$$

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

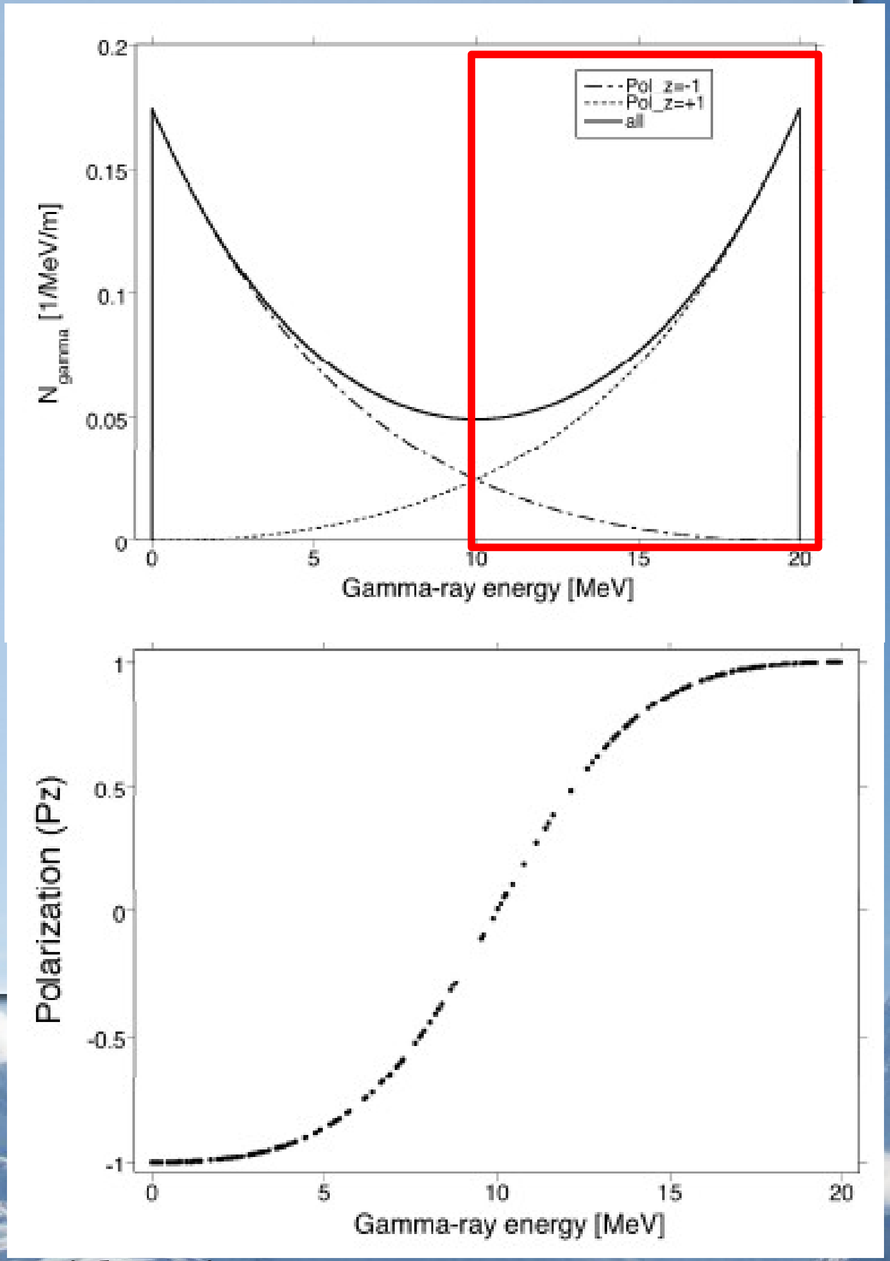
$$\sim 9.50 \frac{nE^2[GeV]}{\lambda_u[m](1+K^2)}$$



Polarized Positron

- Energy, angle, and helicity from undulator radiation are correlated.
- By taking gammas in super-forward direction, gamma rays and positrons are polarized.

T.Kamitani

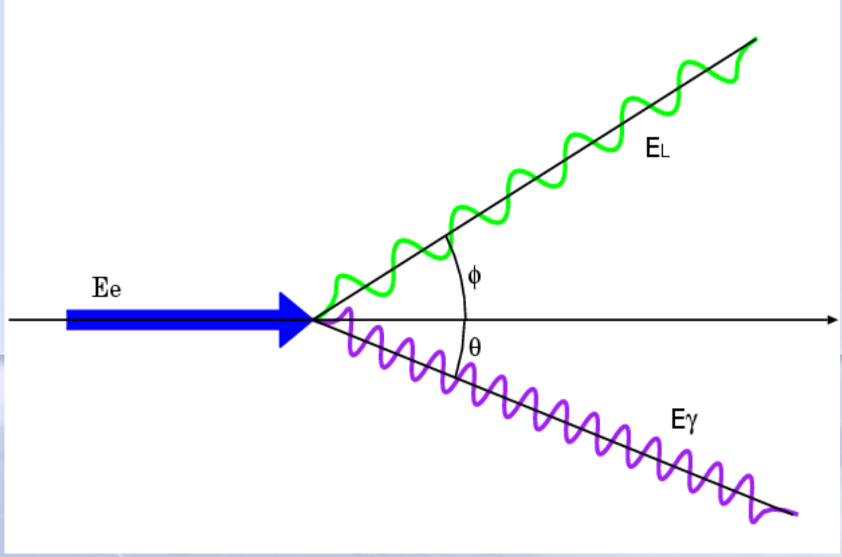


Laser Compton(1)

- Inverse Compton scattering between laser photon and electron beam.
- Laser photon (wavelength is in μm order) is scattered by high energy electron and its energy is boosted.
- As a result, high energy gamma-ray is obtained.

$$E_\gamma \sim \frac{4\gamma^2 mc^2 E_L}{mc^2 + 4\gamma E_L} \qquad (3-16)$$

- E_L : Laser energy 1.2eV @ 1um.
- Electron beam 1GeV, $\gamma=2000$.
- E_γ ~ 16MeV



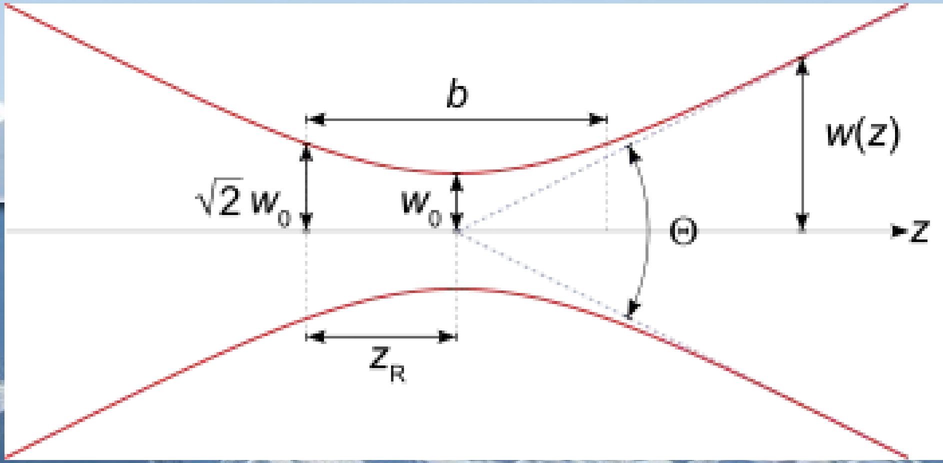
Laser Compton (2)

- Laser acts as a quite short period undulator. The energy from Compton scattering is rewritten as

$$E_\gamma \sim 4\gamma^2 \hbar \frac{2\pi c}{\lambda_L} \qquad (3-17)$$

where λ_L is laser wave length.

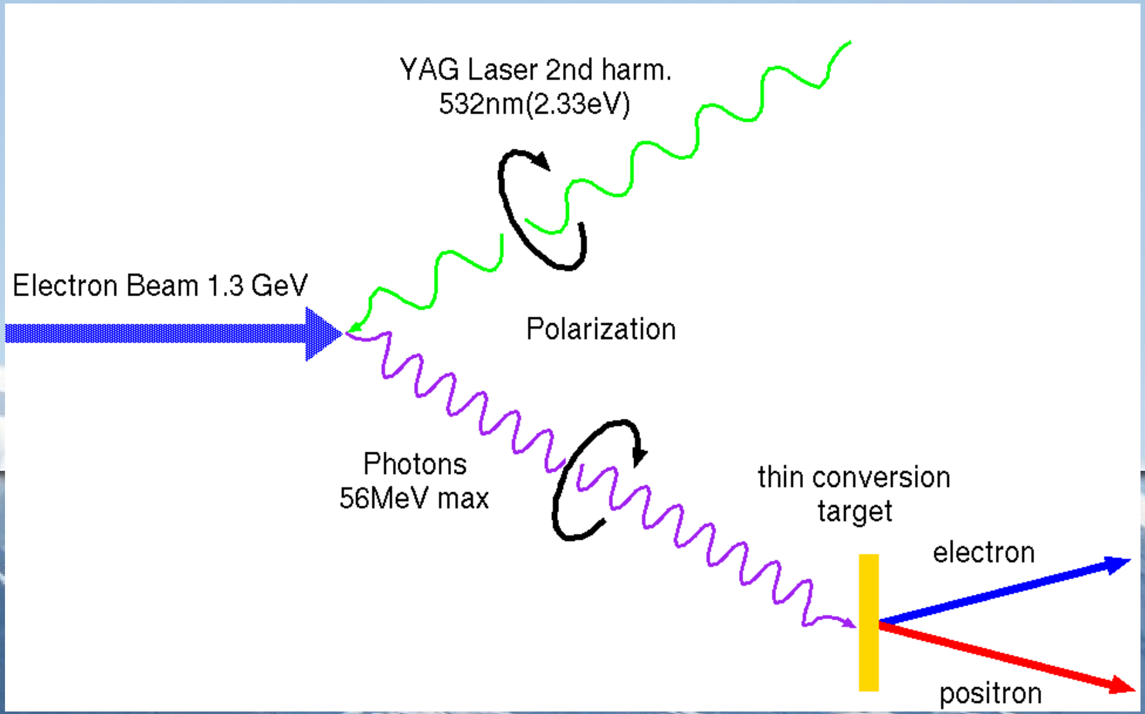
- High energy gamma (several 10s MeV) is obtained with few GeV electron beam.
- Laser focal length is limited to Rayleigh length. It is difficult to make a long “laser undulator”.

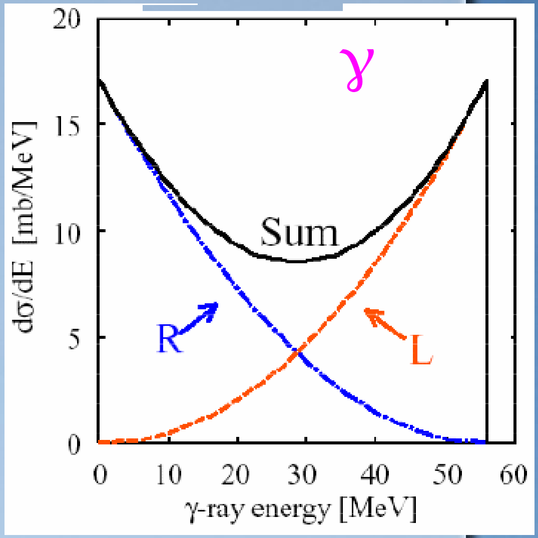


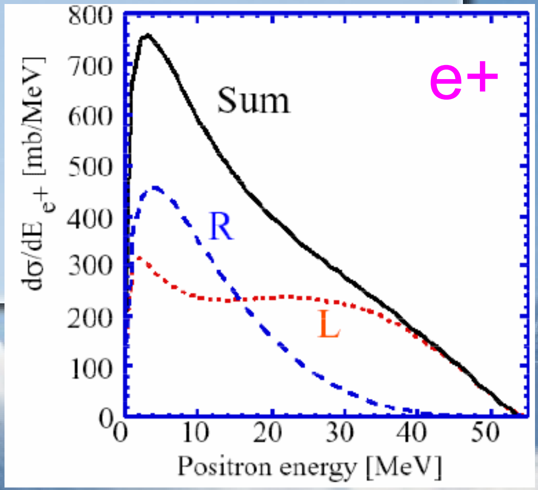
$$2z_R = \frac{2\pi w_0^2}{\lambda}$$

Laser Compton (3)

- By employing circularly polarized laser, the final photon spectrum different for polarization.
- By taking high energy region, the polarized photon is obtained.
- The positron generated from the polarized photon, is also polarized.



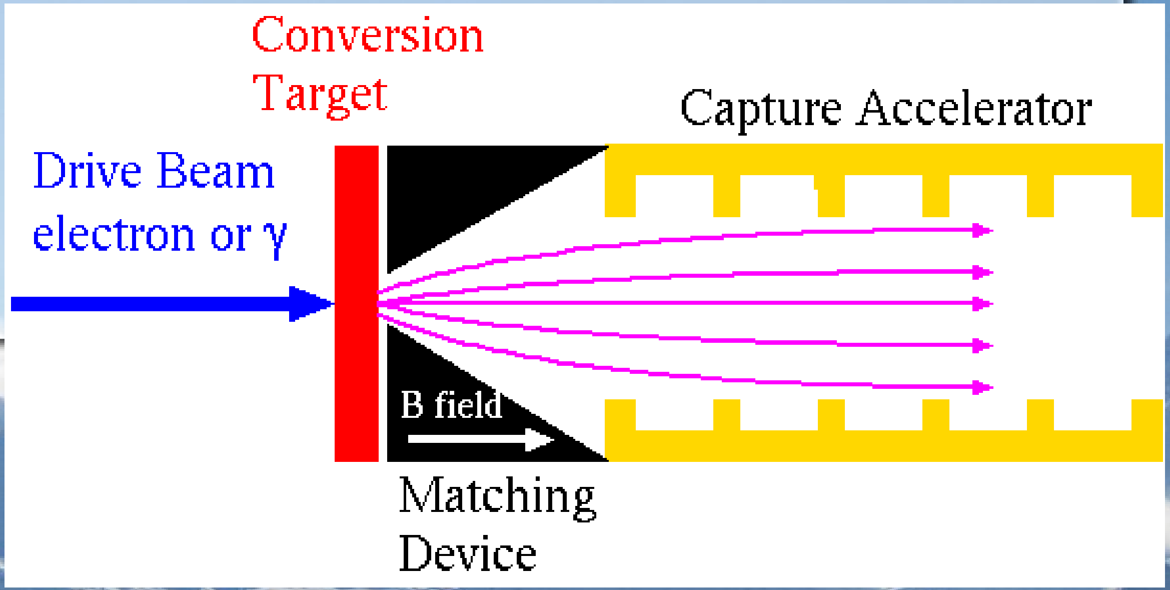




Positron Source

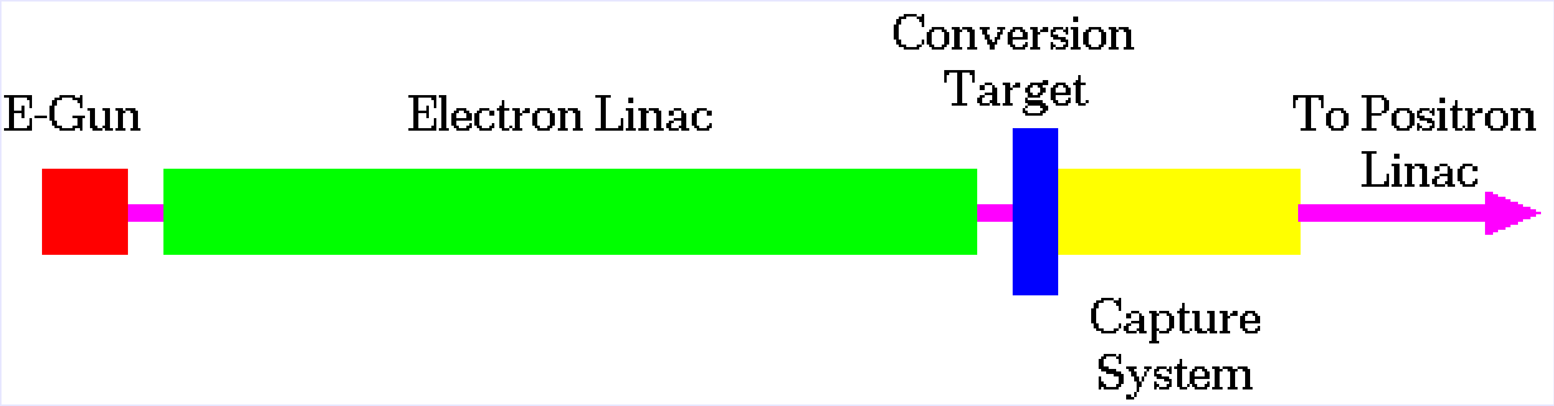
Positron Source

- Positron source is a system, composed from:
  - Drive Beam (Electron or Photon)
  - Conversion target (gamma → e+)
  - Matching Device (p_t supression)
  - Capture Accelerator (Capture in RF bucket)
- Three concepts:
  - Electron driven (conventional),
  - Undualtor,
  - and Laser Compton.



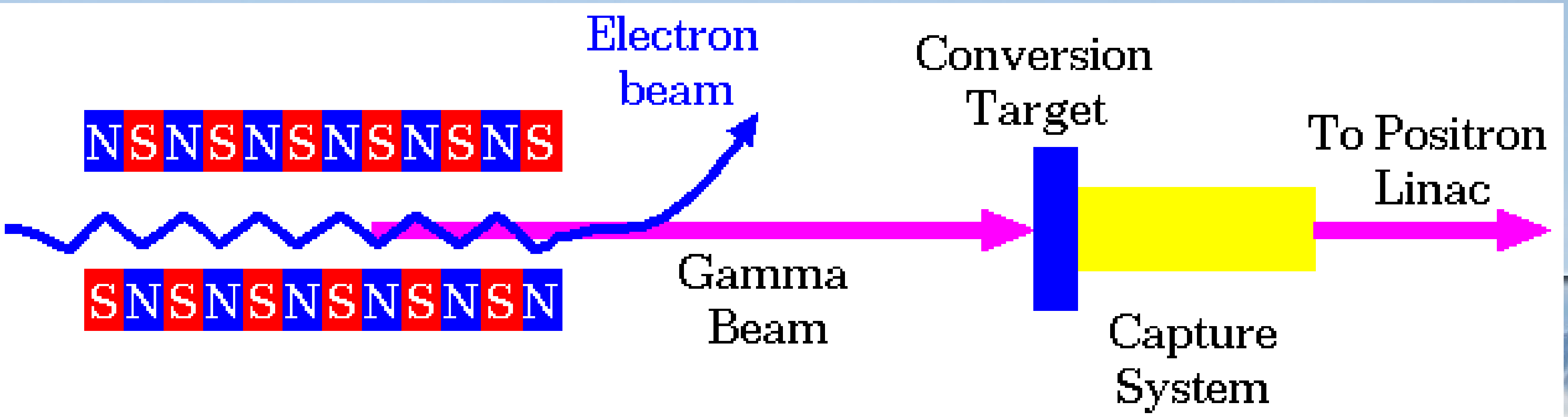
Electron Driven (1)

- Sub or Several GeVs driver electron beam.
- High Density Material for shower development.
- Positron capture by Solenoid, QWT, or AMD.
- NC accelerator tube with solenoid focusing.
- All positron sources based on accelerator every built, is this concept. That is why it is called as “conventional”.



Undulator Scheme (1)

- By passing more than 130 GeV energy electrons through a short period undulator, more than ~10MeV energy gamma rays are generated as synchrotron radiation.
- This gamma ray is converted to positrons in a heavy material.
- With helical undulator, the photon is circularly polarized and polarized positron is generated.

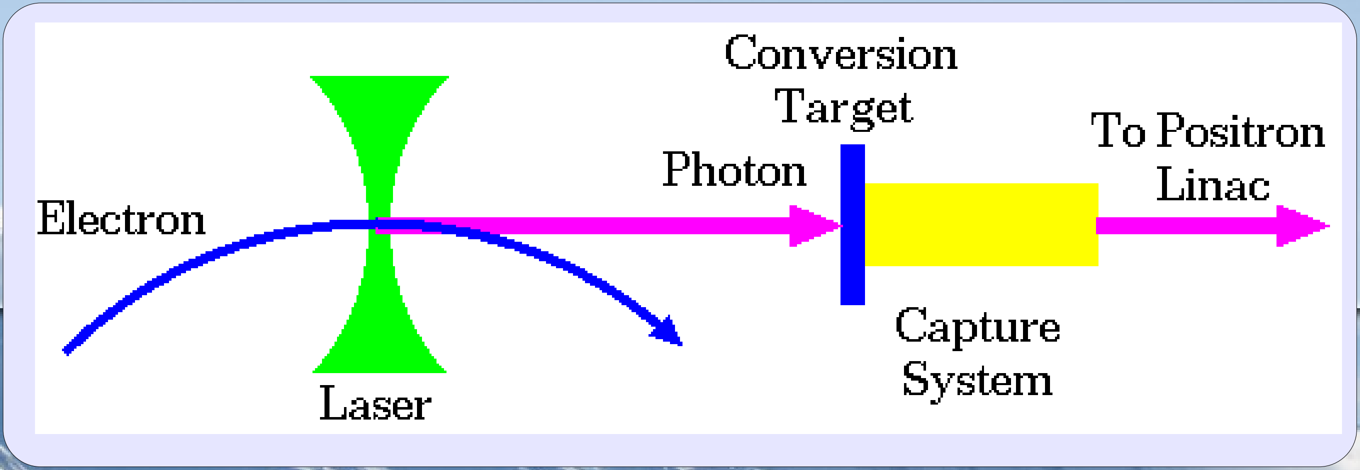


Undulator Scheme (2)

- Constructing a 130 GeV electron linac dedicated to positron generation is not realistic.
- The main electron linac is shared by collision beam and positron generation.
- By employing helical undulator, polarized positron is obtained.

Compton Scheme (1)

- Compton back scattering between several GeVs electron and laser photons generates ~ 30 MeV gamma rays.
- These gamma rays are converted to positrons.
- When the laser photon is circularly polarized, the generated positron is also polarized.
- It is hard to make a long "laser undulator" , because of limitation on the laser focus.



Compton Scheme (2)

- Positron Polarization.
  - Higher degree up to 90 %.
  - Train by train flipping by laser polarity control.
- Dedicated e- beam.
  - No concern for e- beam quality degradation.
  - No inter-system dependence.
    - Simple, easier construction, operation, commissioning, maintenance, high availability.
- To obtain enough amount of positron is a technical challenge, due to the low cross section.

$$Y = \sigma_C N_e N_L f_{rep} G$$

Very small

SLC: The first linear collider

SLC:SLAC Liner Collider

SLAC:Stanford Linear Collider

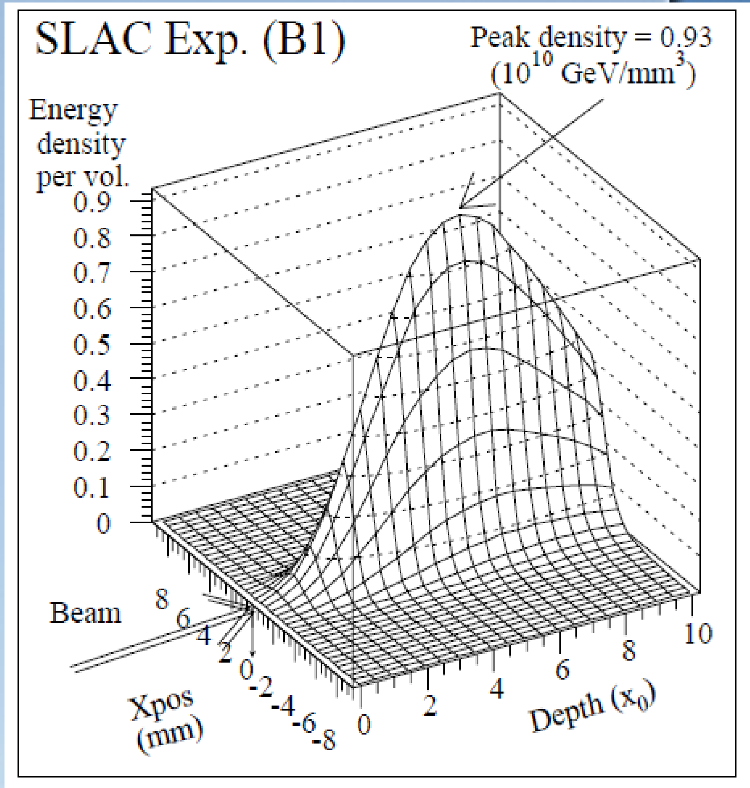
8.0nC/bunch
120 Hz
50 times less

Damage Threshold

SLC positron prodution target (W-Re) had been operated at

$$\rho = 35 [J/g]$$

After the operation, some damage (rough surfaces, small cracks, small holes, etc) was observed. Even there was no diffuculties during the operation, the condition is considered to be a practical limit on the heat load on the target.



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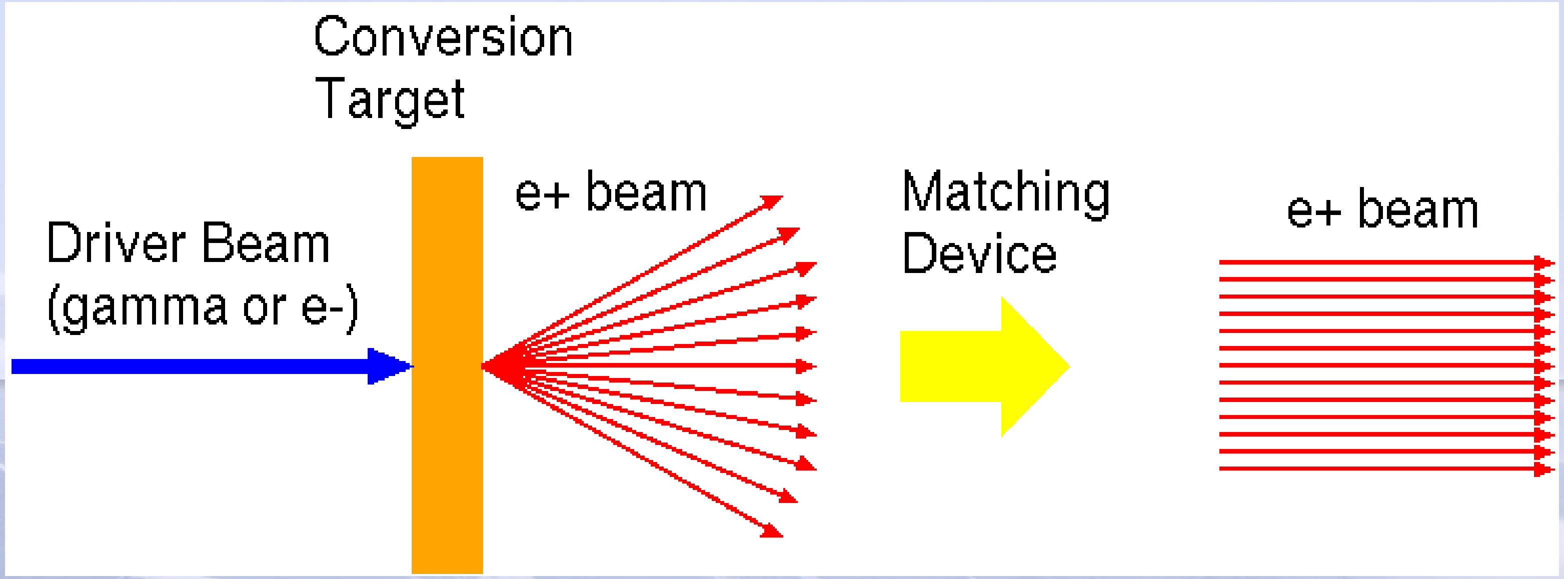
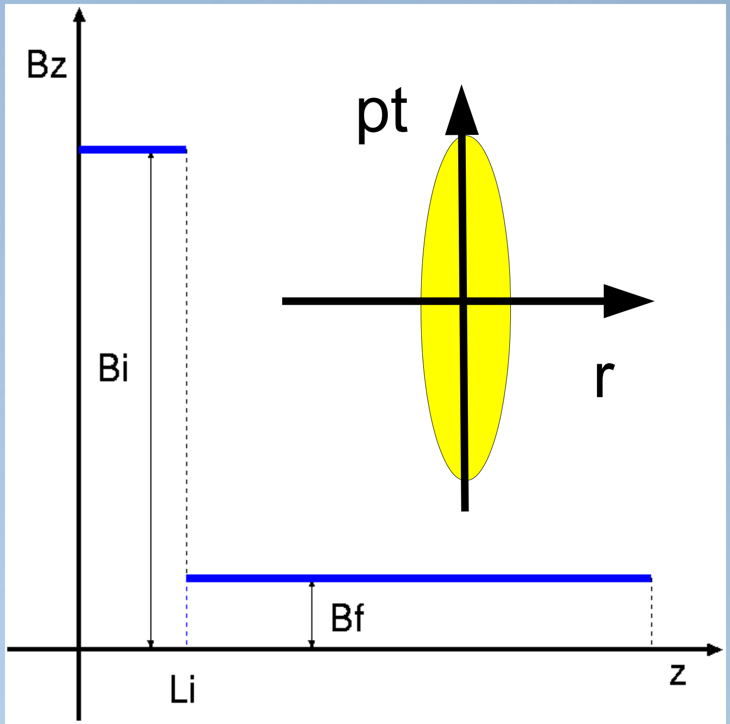
Positron Capture

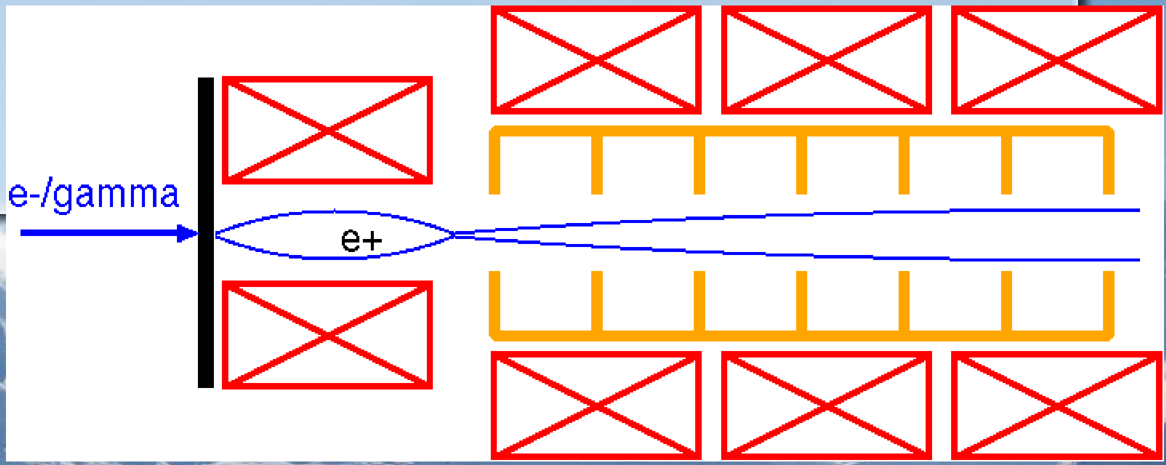
- The generated positrons are distributed in a small spot size and in a large momentum space. To convert it to the parallel beam, a couple of solenoid-like magnetic field with different profile are employed.
  - QWT (Quarter Wave Transformer)
  - AMD (Adiabatic Matching Device)



QWT(1)

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



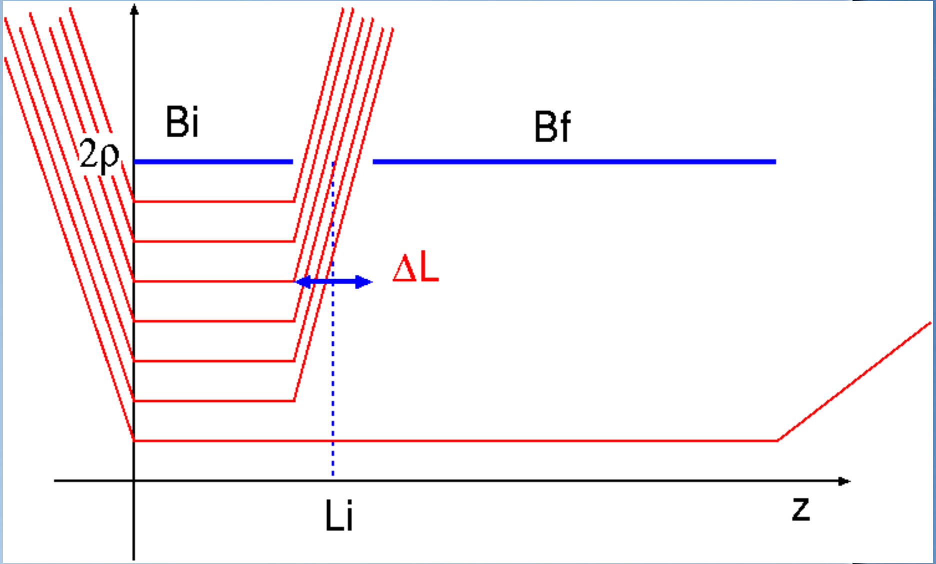


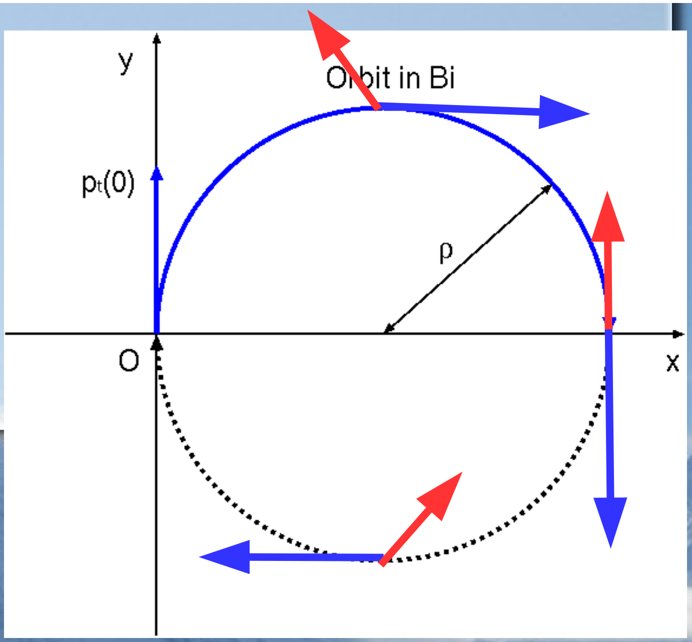
QWT(2)

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

$$\int B_t(z)\,dz = \rho(B_i - B_f)$$

- Positrons are kicked by B_t to θ direction.
- If p_t is parallel to θ direction, p_t is suppressed.
- In othercase, the supression is not ideal.





QWT(3)

Momentum change at the boundary is

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

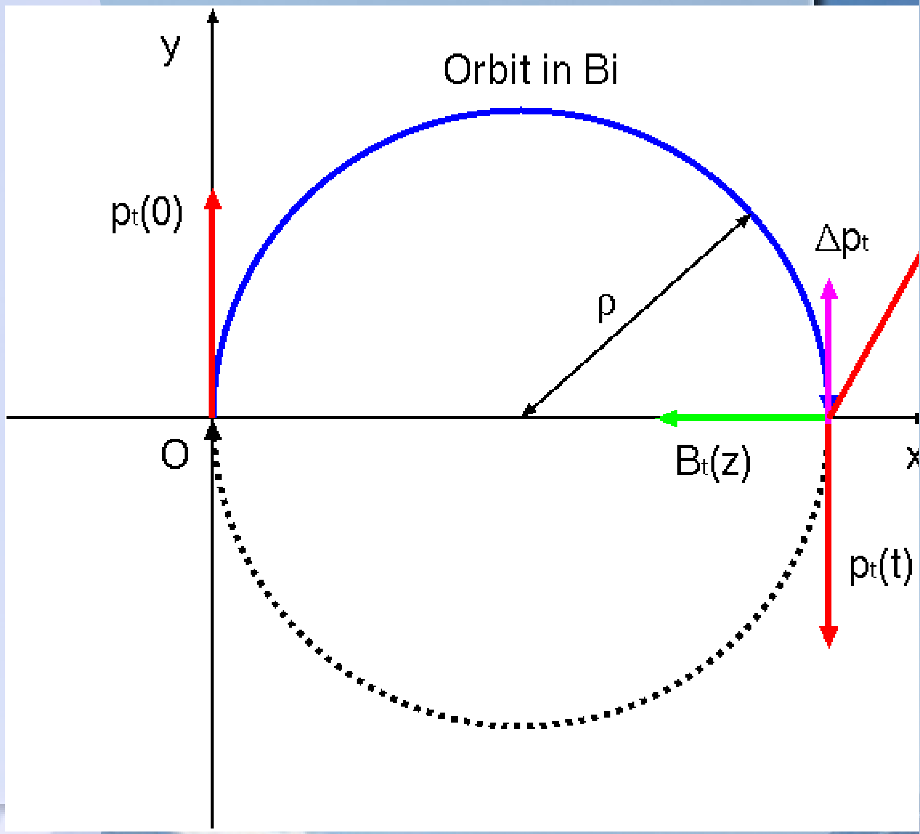
Integrating this equation, total momentum change is

$$\Delta p_t = e v_z \int B_t(z) dt = e v_z \int B_t(z) \frac{dz}{v_z}$$

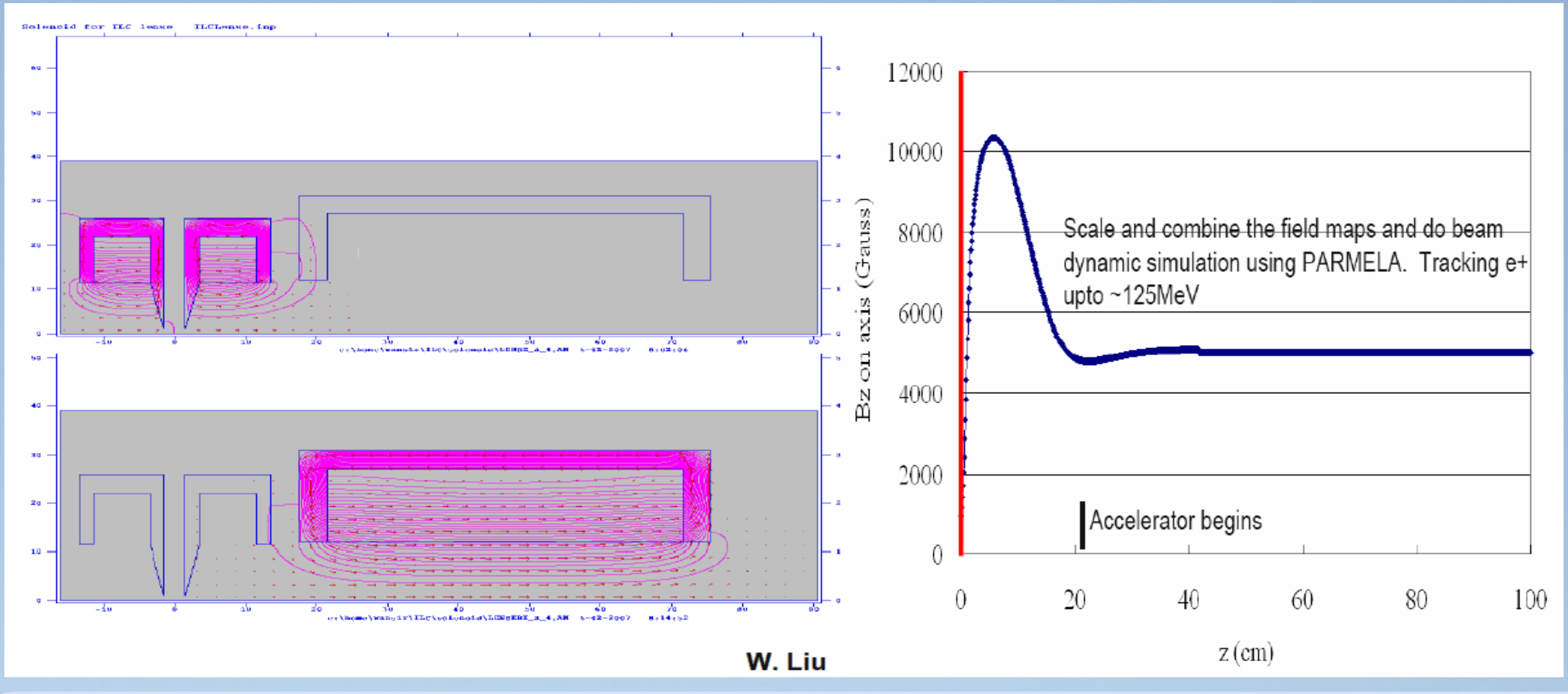
$$= e \rho (B_i - B_f) = \frac{p_{t0}}{B_i}(B_i - B_f)$$

After the kick is

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



QWT(4)

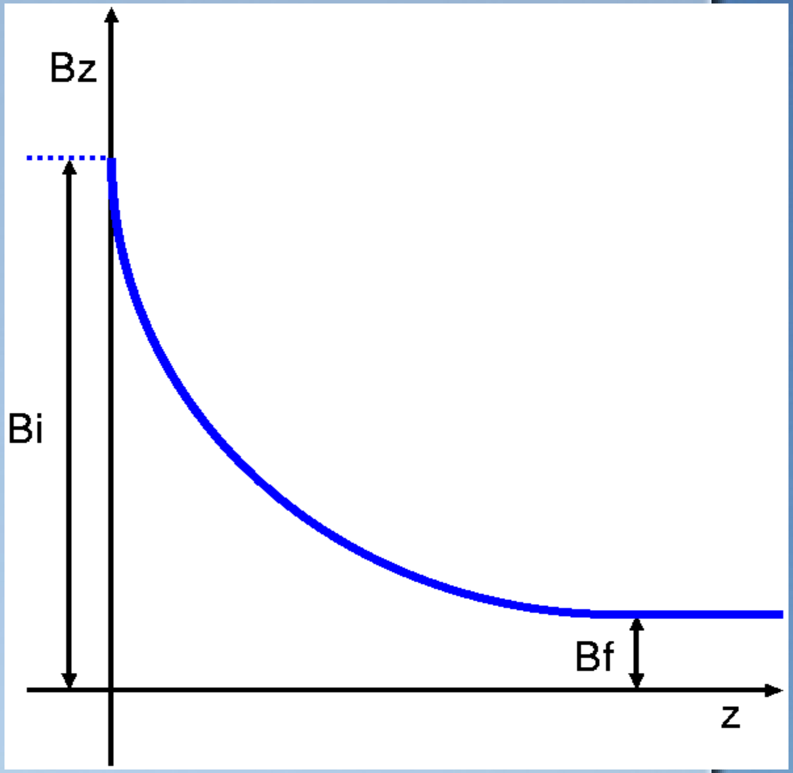


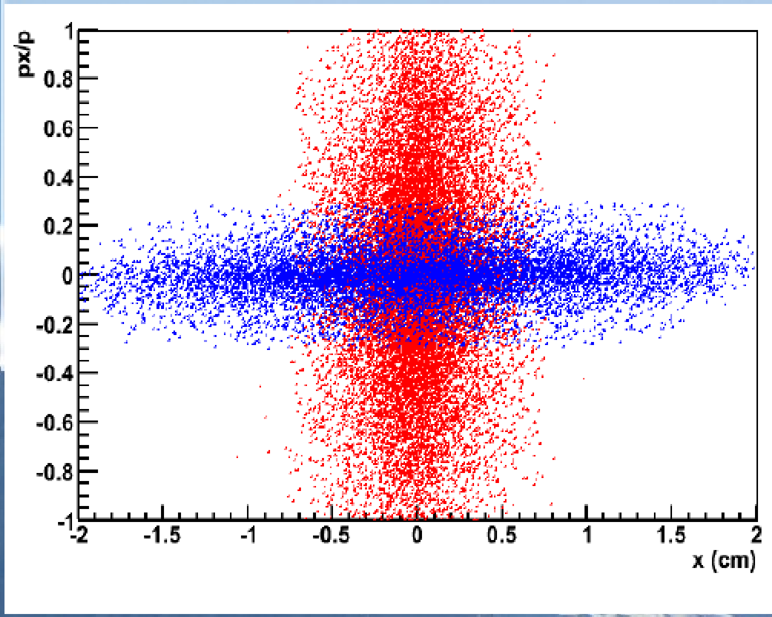
- Two solenoid coils (strong and weak) composes QWT.
- Bucking coil to cancel the strong B field on target.
- B_i and B_f are 1.0 and 0.5 T.
- NC L-band accelerator is placed in B_f region. (Why?)

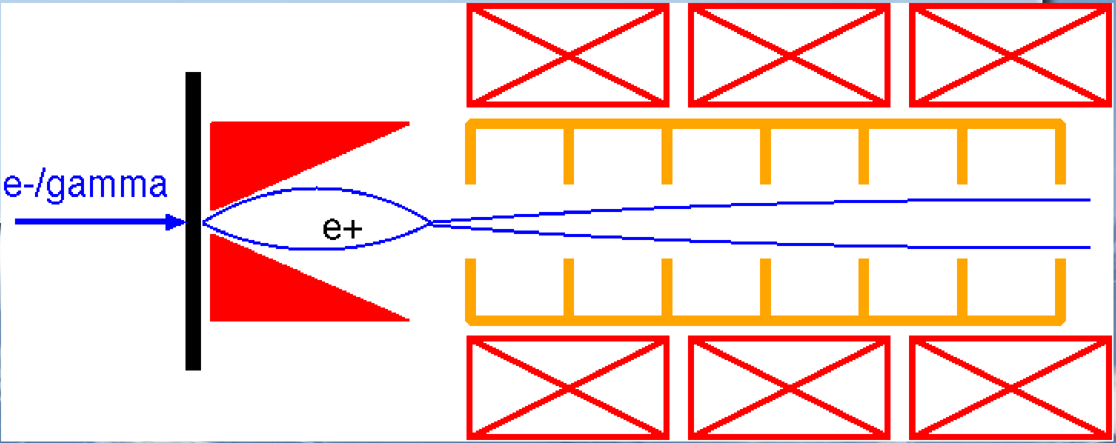
AMD(1)

AMD consists from the initial strong solenoid field along z direction, B_i, which is decreased down to B_f continuously.

$$B(z)=\frac{B_i}{1+\mu z} \qquad (2-18)$$







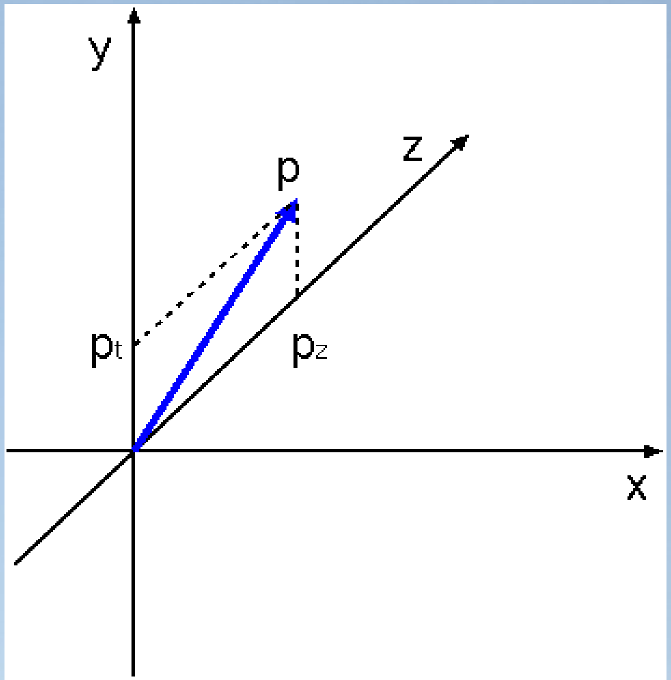
AMD (2)

In xy plane, positrons are circulated with radius ρ(z),

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

If a parameter of the motion is changed slowly compare to the circulating frequency, adiabatic invariant is constant during the motion.

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

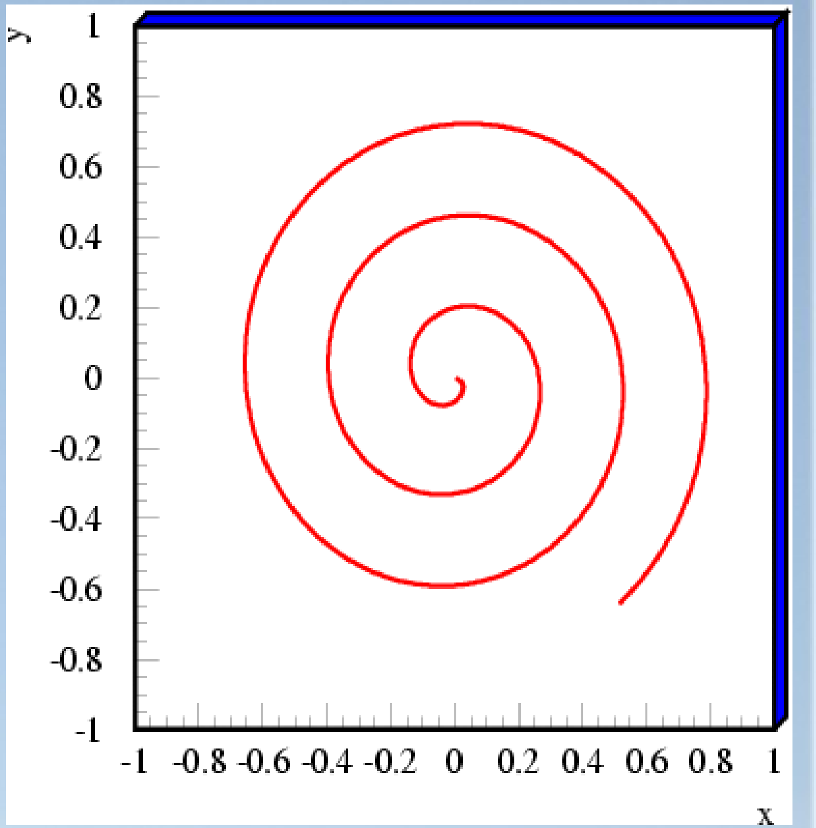


AMD(3)

Due to the adiabatic condition,

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

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



The momentum is suppresed by the square root of the field ratio.

AMD(5)

Pt at the exit of AMD is

$$p_t = \sqrt{\frac{B_f}{B_i}}\, p_{t0}$$

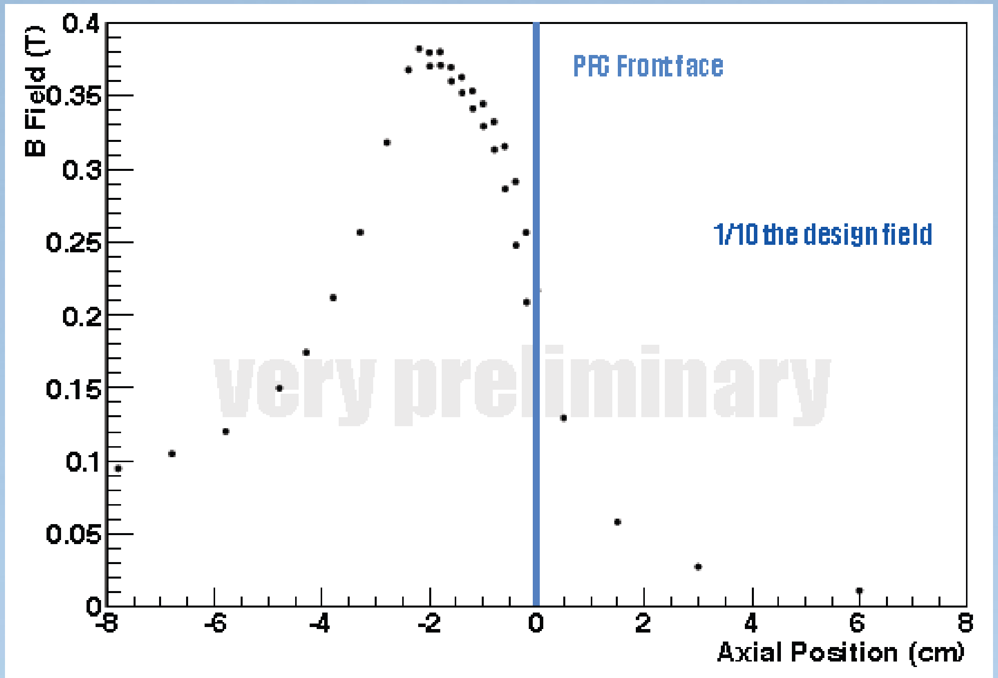
Radius has to be less than aperture (a/2),

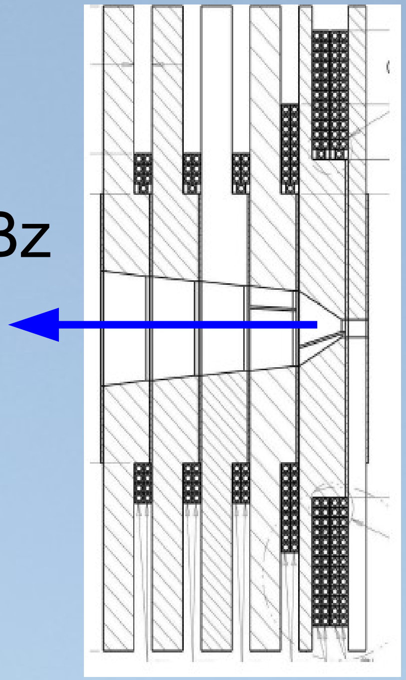
$$\rho = \frac{p_t}{eB_f} < \frac{a}{2} \qquad p_{t0} < \frac{a}{2} e \sqrt{B_f B_i}$$

Acceptance on longitudinal momentum (adiabatic condition)

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

AMD(6)



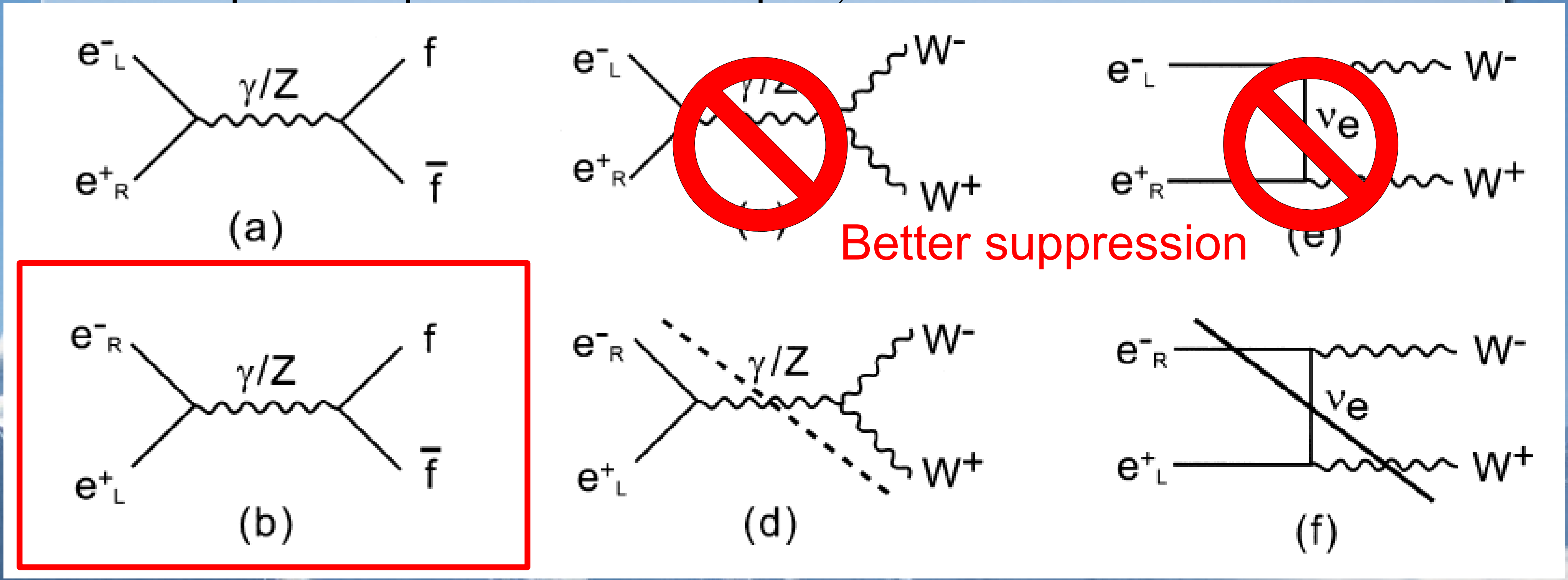


- AMD field is produced by flux-concentrator.
- Primary coil induces eddy current in the inner conductor.
- Because of the tapered shape of the inner conductor, the magnetic field is concentrated.

Positron Source For LC

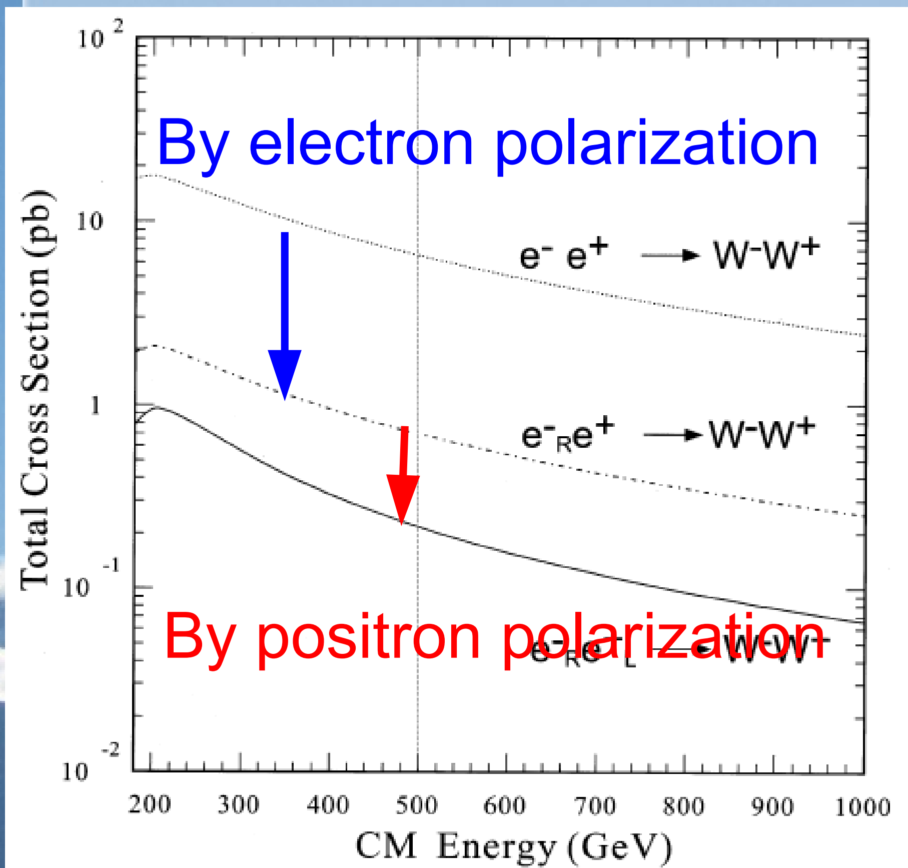
Positron Polarization

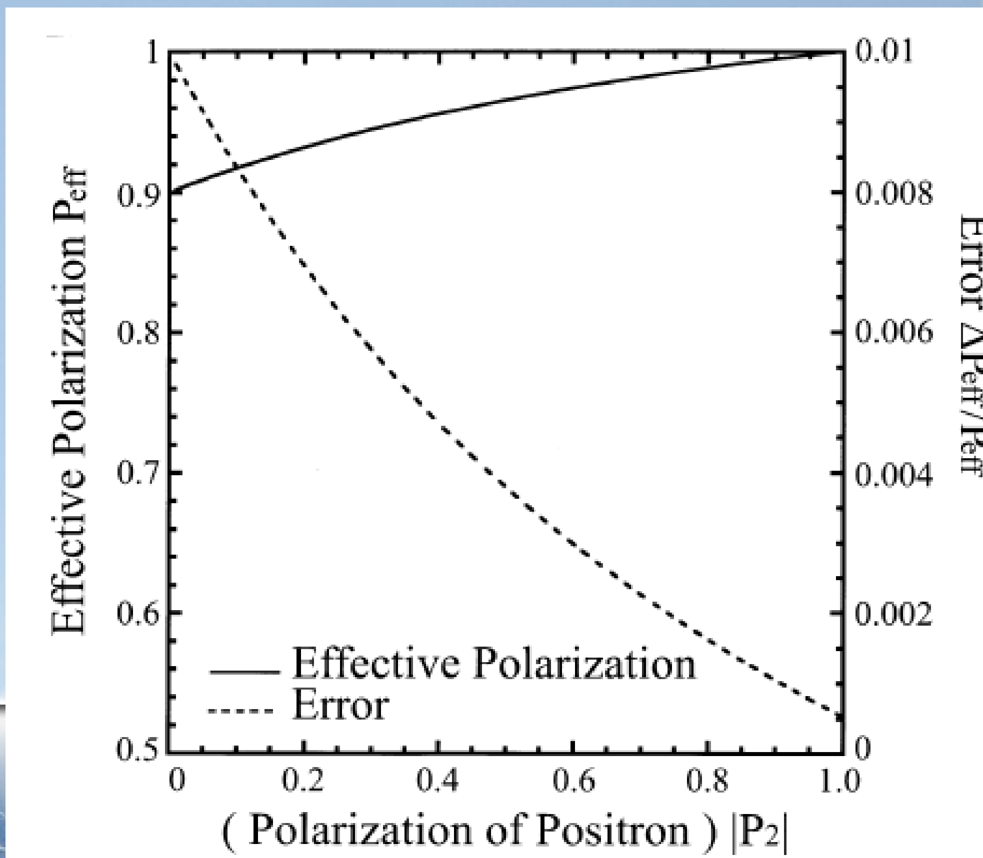
- 90% electron polarization: 95% e^-_L and 5% e^-_R, the small contamination can be suppressed further with a positron polarization.
- The positron polarization is helpful, but not mandate.



Effective Polarization

$$P_{\text{eff}} = (P_- - P_+)/(1 - P_- P_+)$$





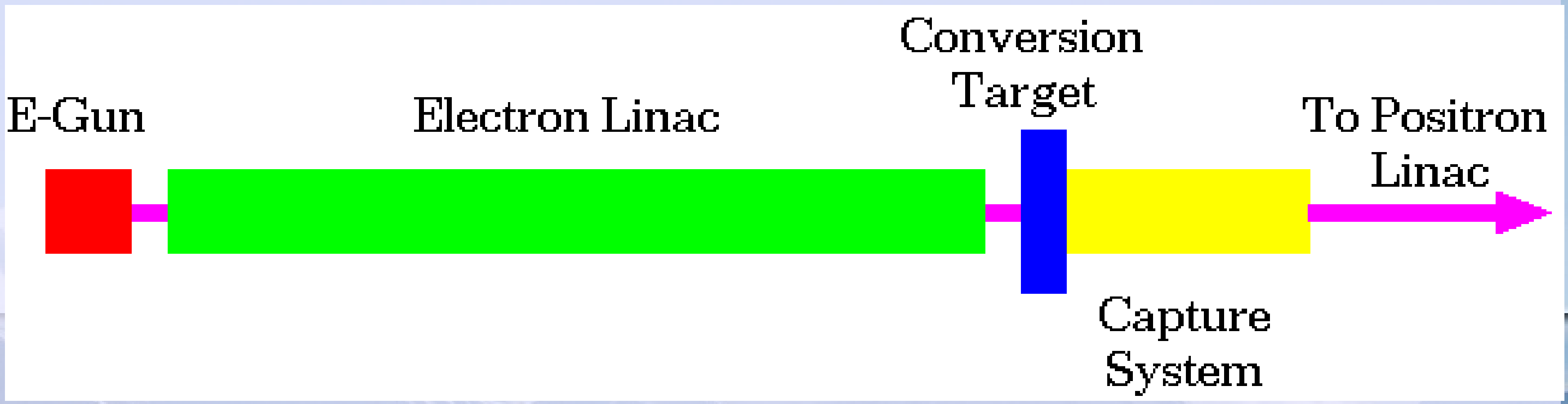
Parameters

Parameter	ILC	CLIC	Unit
Bunch charge	3.20	0.60	nC
Norm. emittance ($\varepsilon x+\varepsilon y$)	0.09	?	m.rad
Bunch separation	559 (670)	0.5	ns
Bunch number in macro pulse	2625(1312)	312	number
Macro pulse length	970(880)	0.16	μ s

- ILC: Large bunch charge, low repetition, low current, long pulse are optimized for SC.
  - Baseline : undulator
  - Reliable Backup : Electron driven
- CLIC: Low bunch charge, high repetition, high current, short pulse are optimized for NC.
  - Baseline: electron driven (channeling),
  - Backup: Laser Compton, undulator.

Electron Driven Scheme

- Electron driven is the only scheme, which is ever been operated, but possible target damage has to be managed.
- Positron polarization is not possible.



Why is it so diffucult?

	N^{e+}/bunch	Reputation(Hz)	N^{e+}/sec
ILC	2.0×10^{10}	5 x 2625	2.6×10^{14}
SLC	4.0×10^{10}	120	4.8×10^{12}

- ILC has to produce 50 times more positron than that of SLC.
- But, number does not matter, PEDD (Peak Energy Deposition Density) does.

$$PEDD \sim \kappa \frac{E(GeV)\,Q(nC)}{V\rho}\,\frac{2r\,N_b}{v t_p}$$

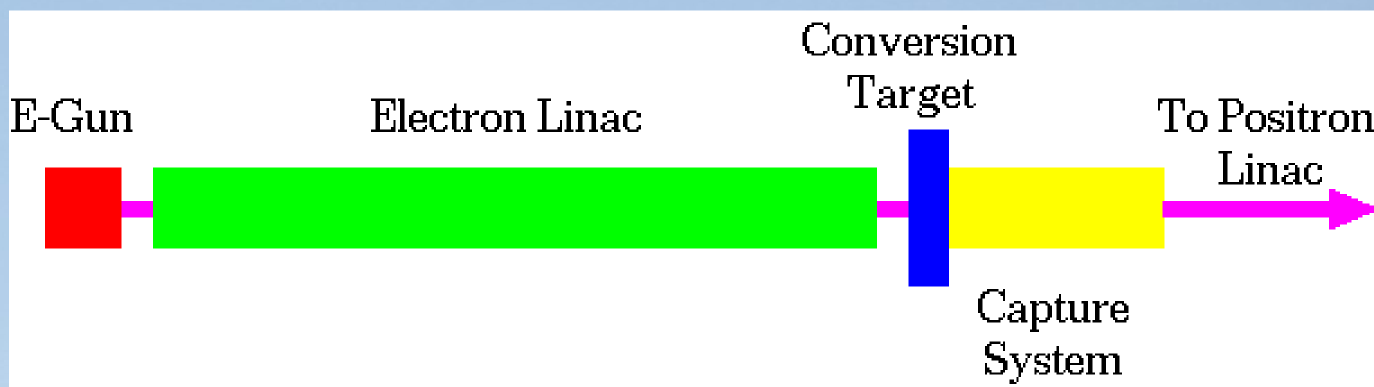
#of bunch

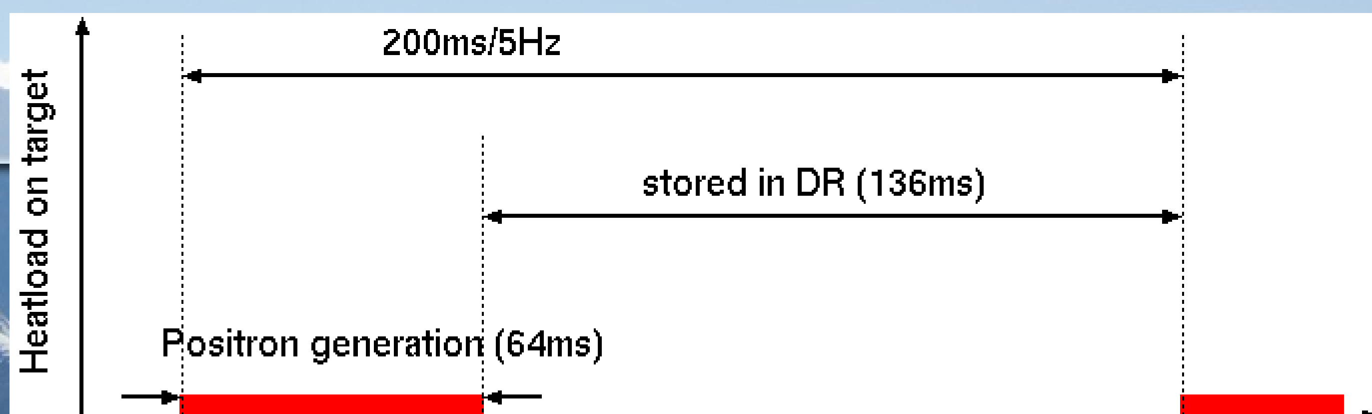
target speed

Pulse duration

Pulse Structure Manipulation

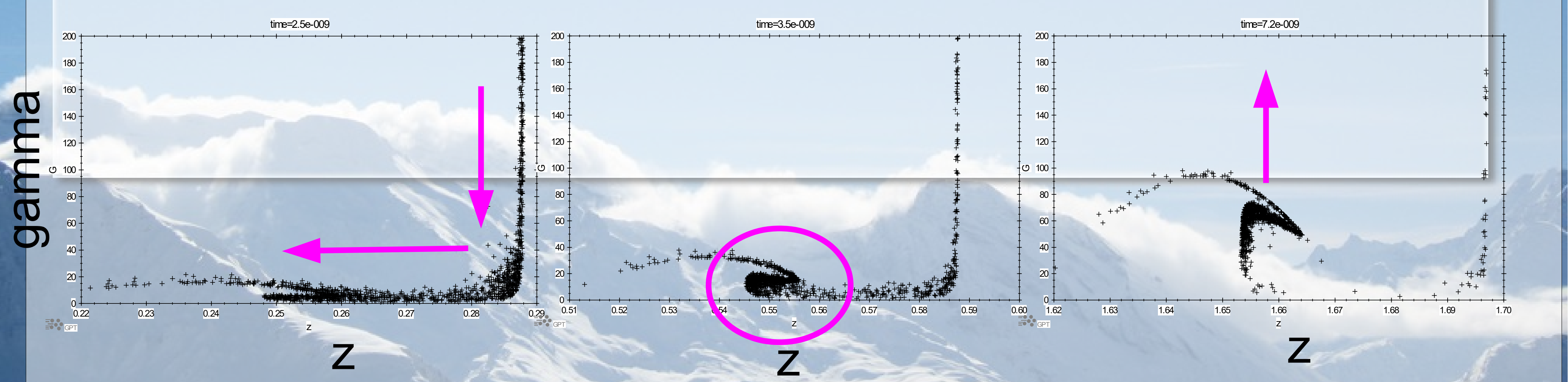
- Several GeV e- beam on W-Re target.
- By manipulating the beam structure (64ms pulses), heat load on the production target is 64 times less.
- 5 m/s target speed is even enough.





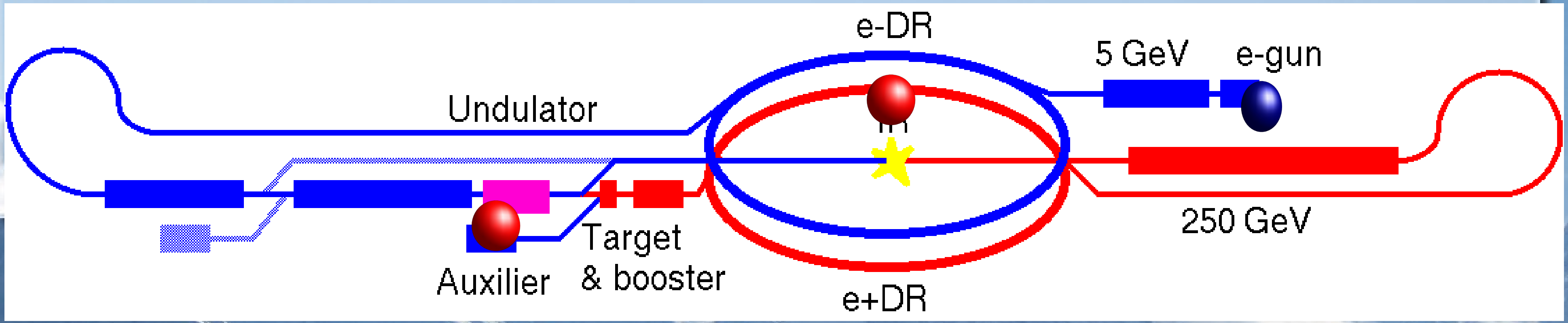
Decceleration Capture

- The positron should be captured in RF bucket at the capture linac.
- The positron peak is on deceleration phase.
- These positrons are slipped down to the acceleration phase where these positrons are captured.

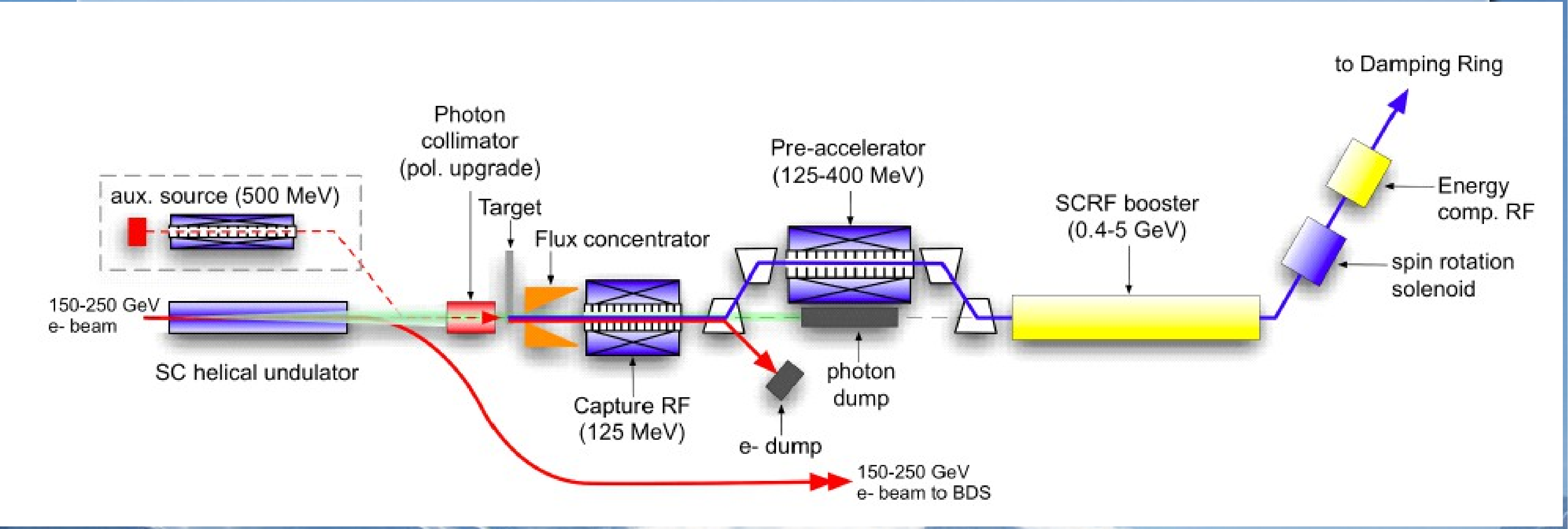


ILC Positron Source

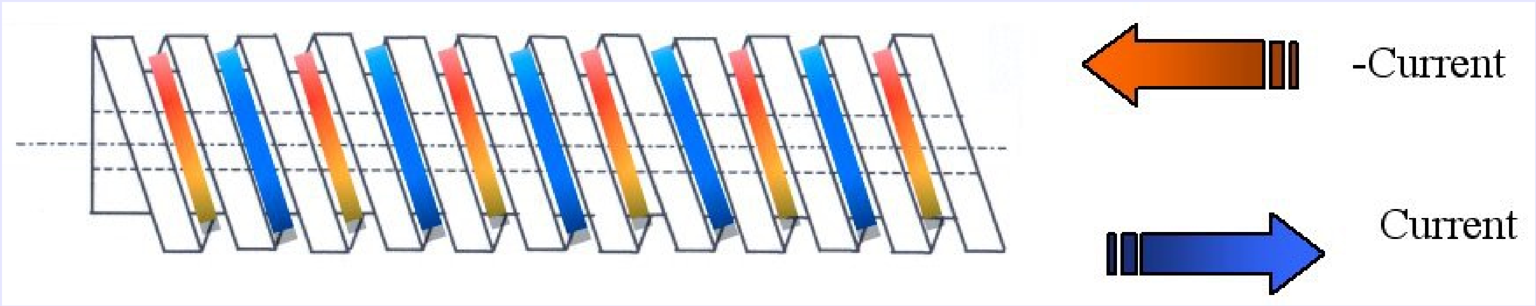
- It is the first undulator based positron source in the world.
- 125-250GeV electrons generate gammas. Linac is shared.
- The generated positron will be used for the next collision. The positron wait 200 ms in the positron DR.

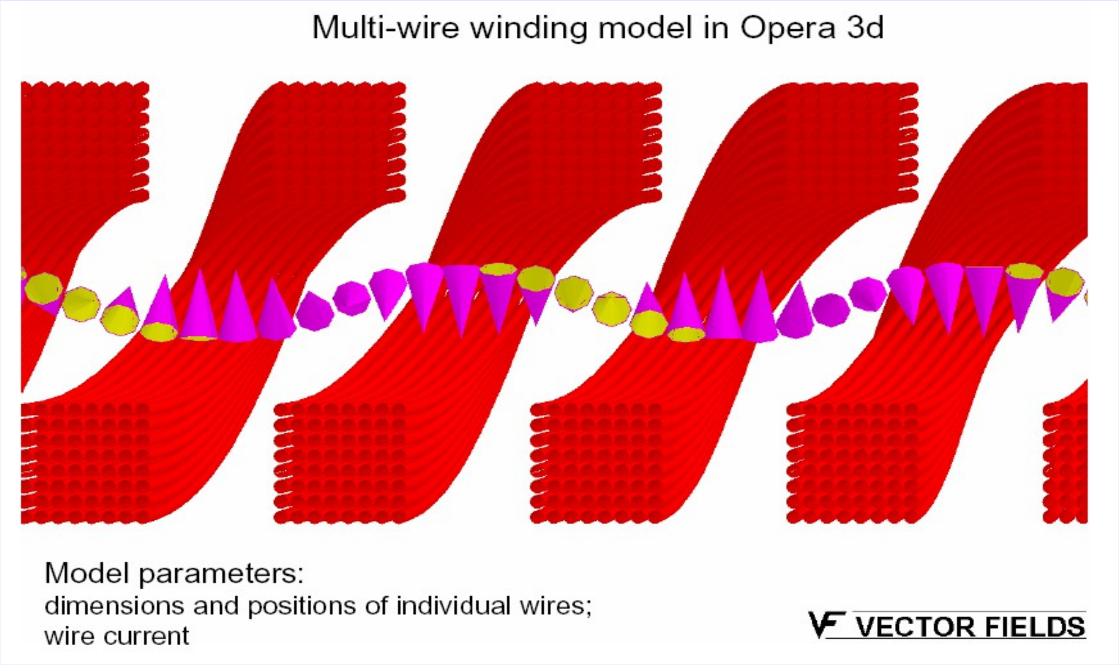


ILC Undulator Positron Source Layout



Helical Undulator



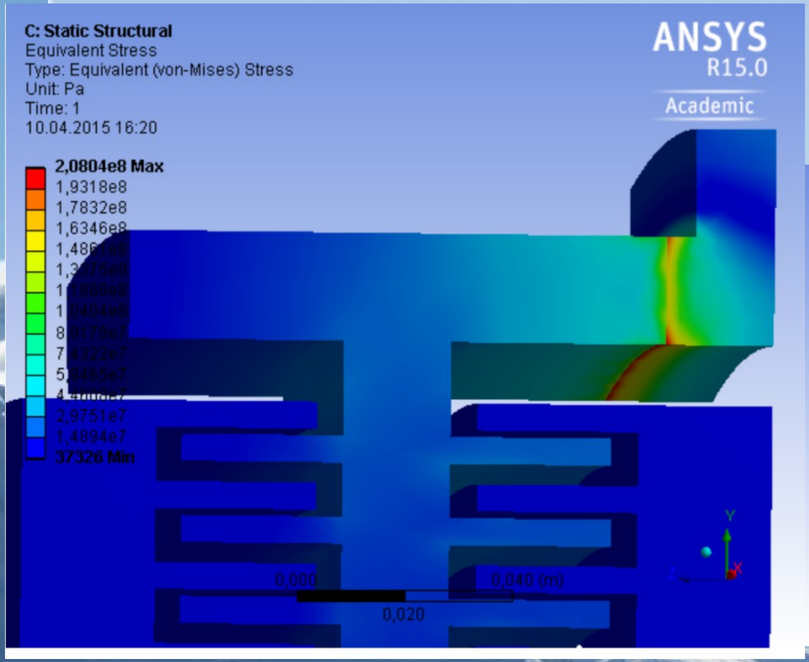


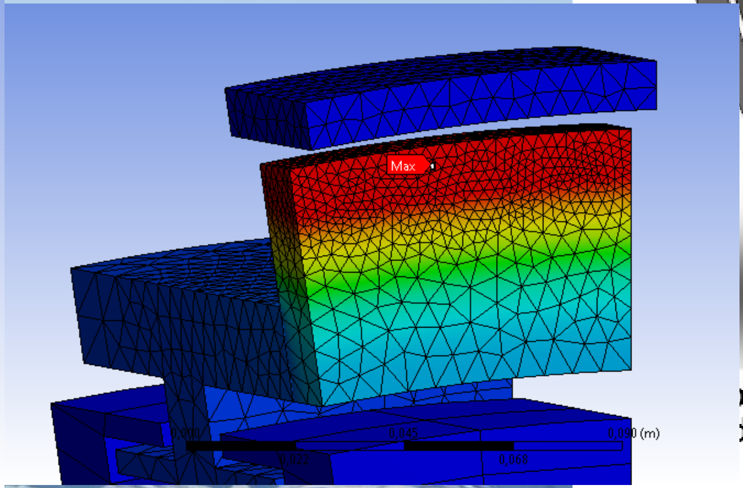
By Yury Ivanyushenkov

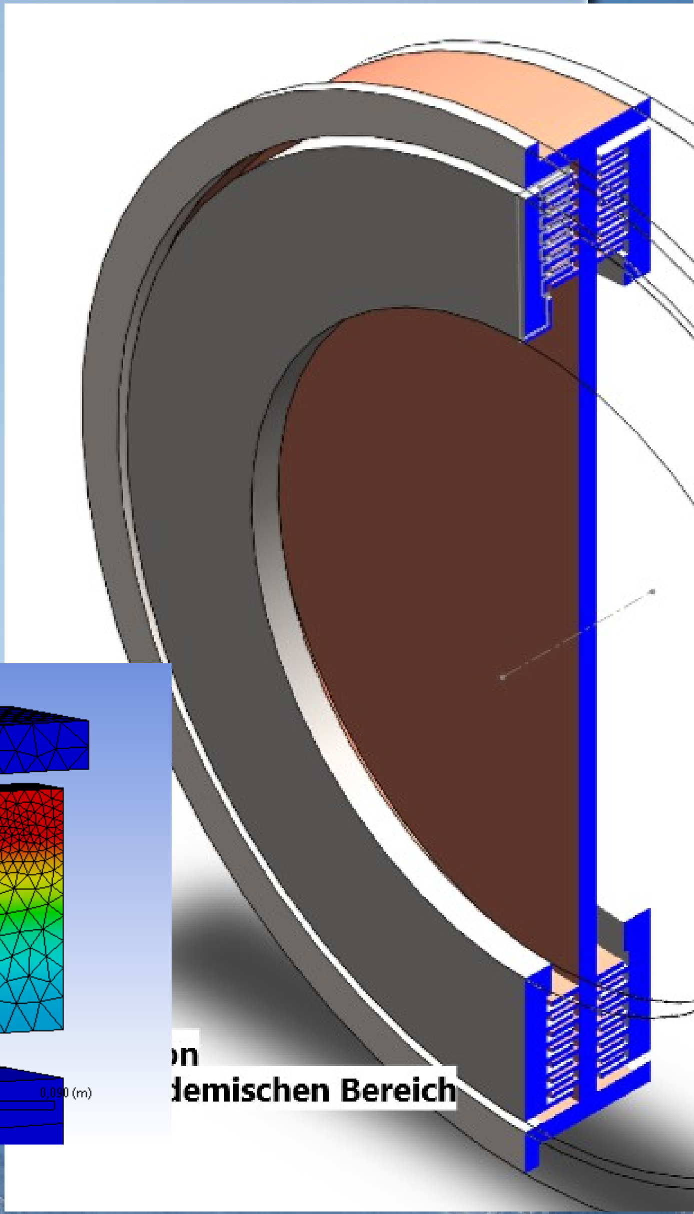
Radiation Cooling Target

- Target : Ti-6% Al-4% V with 0.4 X_0, 15mm.
- Rotating with tangential speed 100 m/s to avoid any damage.
- Heat load by gamma : 5-18 kW
- Thermal heat is removed by radiation .

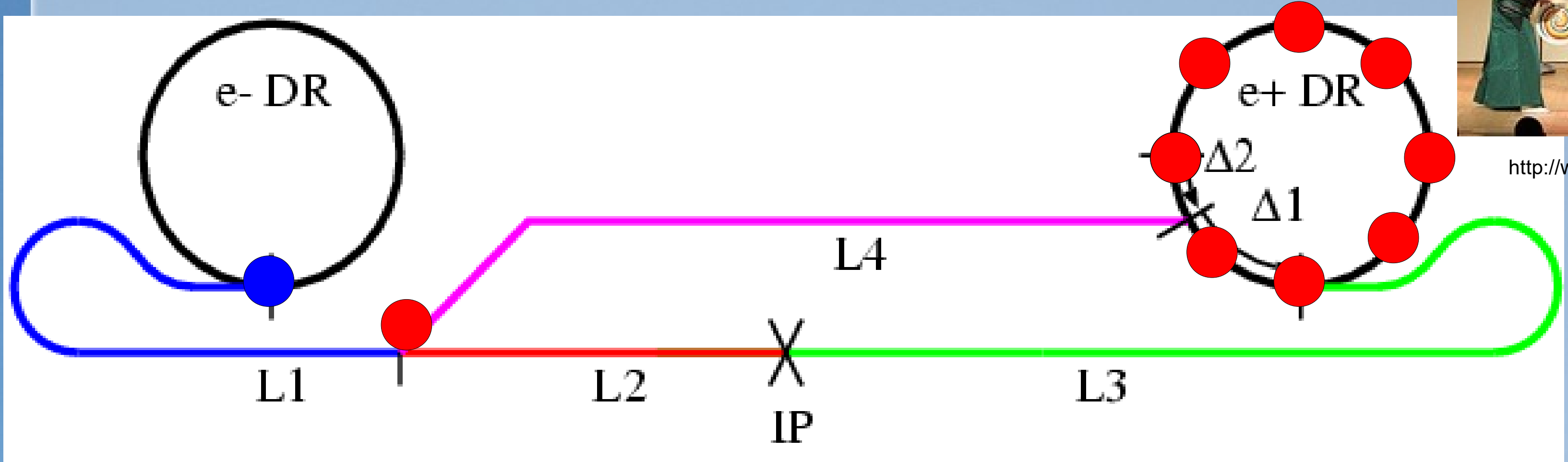
$$P_{rad} = \sigma(\varepsilon_1 T_1^4 - \varepsilon_0 T_0^4)$$







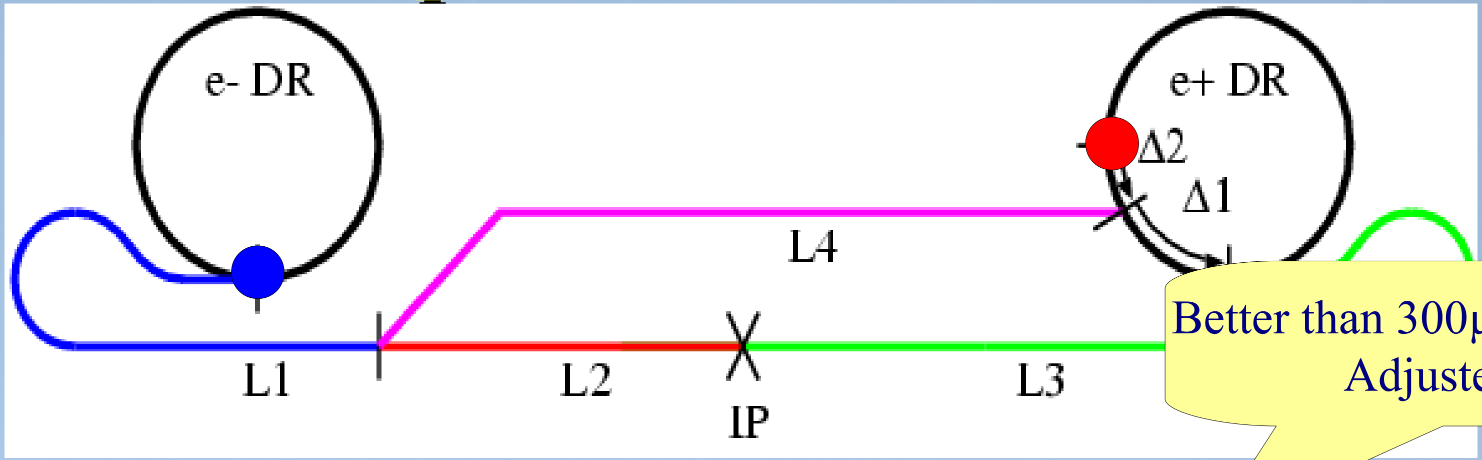
Positron Juggling



http://www.daikagura.org/gigei_nagemono.html

- Positron beam is generated by electron bunch.
- The generated positron will be used in next collision in 200ms.
- Generation and collision are performed simultaneously. The DR bucket must hold the new positron.
- If the path-length satisfy "the self-reproduction condition", the RF bucket is vacant.
- The positron is stored in the DR bucket where the collision partner of the electron which generates the new positron.

Pathlength condtion:
Self-reproduction + collission



Better than 300μm (bunch length)
Adjusted by Δ2.

- Collision condition: $L_1 + L_2 = \Delta_1 + \Delta_2 + L_{3,}$
- Self-reproduction condition: $L_1 + L_4 = \Delta_2 + nC_{DR},$

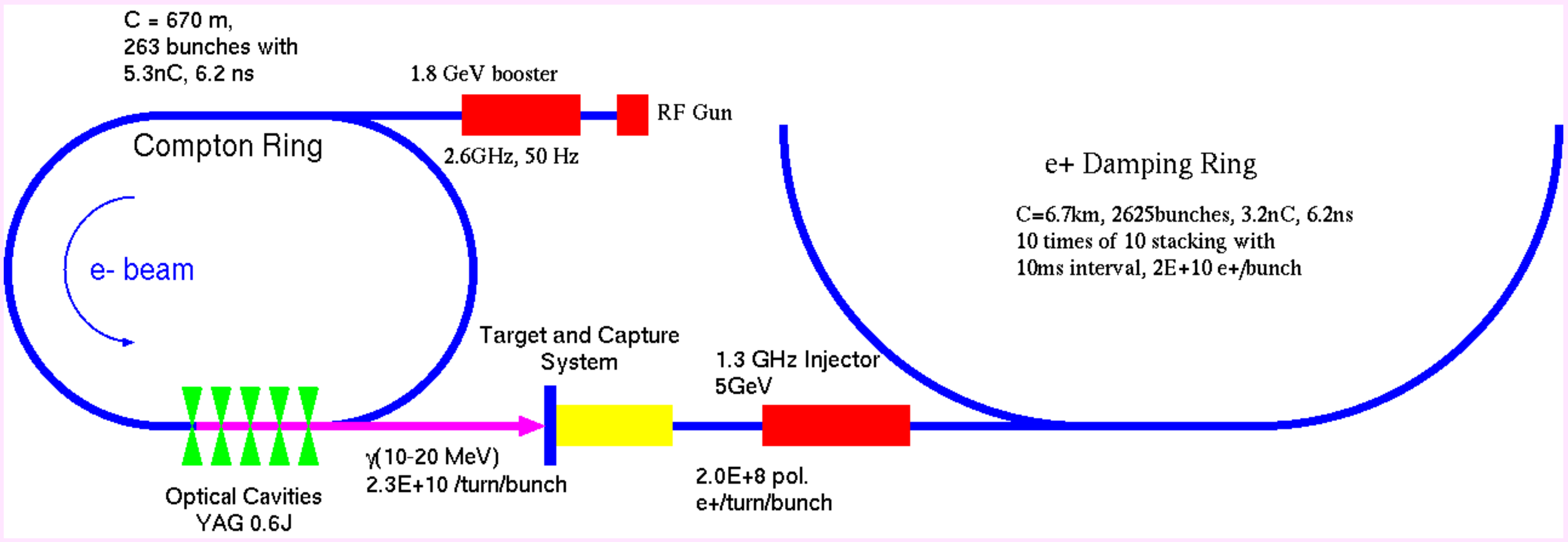
$$L_3 + L_4 + \Delta_1 = L_2 + nC_{DR},$$

Better than RF bucket height (5mm)
Adusted by physical length.

Physical path length has to be adjusted.

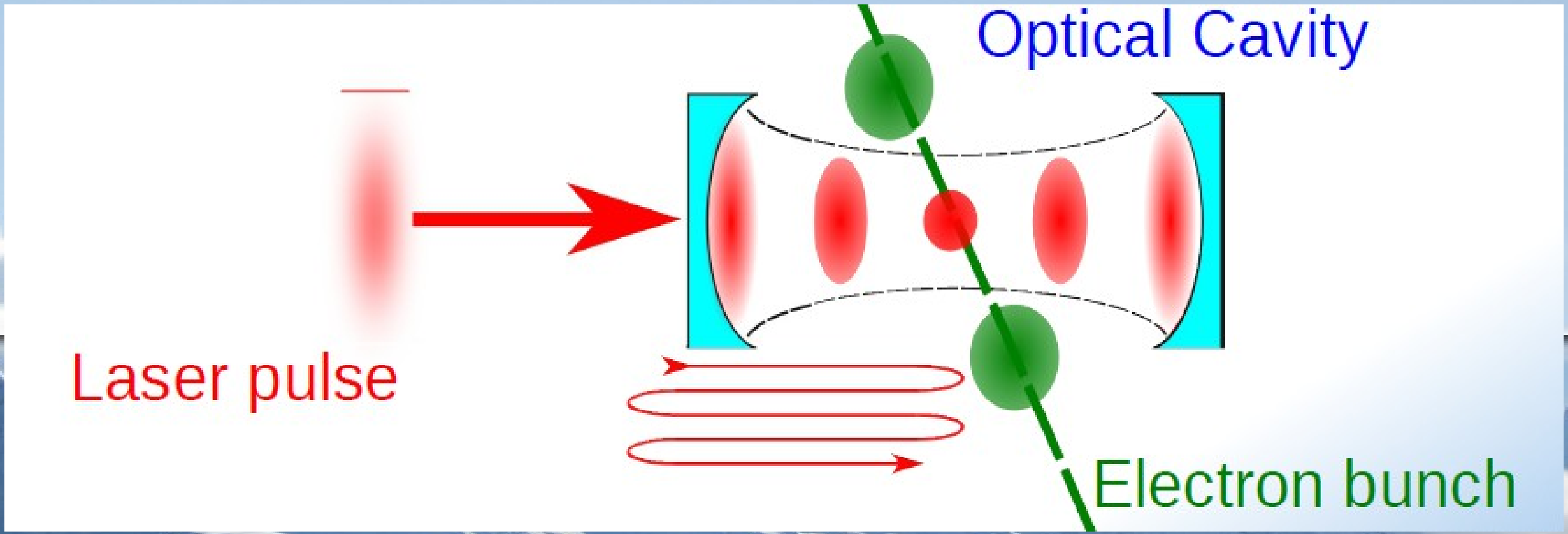
Compton Ring

- A storage ring for electron driver:5.3nC, 6.2ns, 1ps, 1.8GeV.
- Laser pulse is stored in optical cavity, 0.6Jx5.
- 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.



Pulse Stacking Cavity

- Many laser pulses are stored and the power is enhanced by the pulse stacking.
- Pulsed laser is stacked when appropriate conditions of the external cavity are satisfied simultaneously for
  - Laser wave length $L_{cav} = m \frac{\lambda}{2}$
  - Mode-locking frequency $L_{cav} = n L_{rep}$



Comparison

	Electron driven	Undulator	Laser Compton
Electron Driver	3.0-6.0 GeV NC Dedicated	150-250GeV SC Common, alternate	1.8 GeV Ring/ERL Dedicated
Radiator	W-Re target	Undulator λ=0.8cm	Laser λ=1.0μm
Converter	W-Re target 1 m/s	Ti-alloy 100 m/s	W target 1 m/s
Matching Device	SC DC solenoid/Pulsed FC	QWT/Pulsed FC	SC DC solenoid
E+ booster	NC	SC	SC
Path length adjustment	NO	YES	NO
Polarization	NO	30-60%	0-90%

Summary

- Fundamentals of positron generation are explained .
- 3 Positron Source Conepts
  - Electron driven
  - Undulator
  - Laser Compton
- To realize the required performance, the state-of-the-art of the technology should be integrated.
- Target is strongly activated. The target should be remotely maintained (exchange) with a high reliablity.