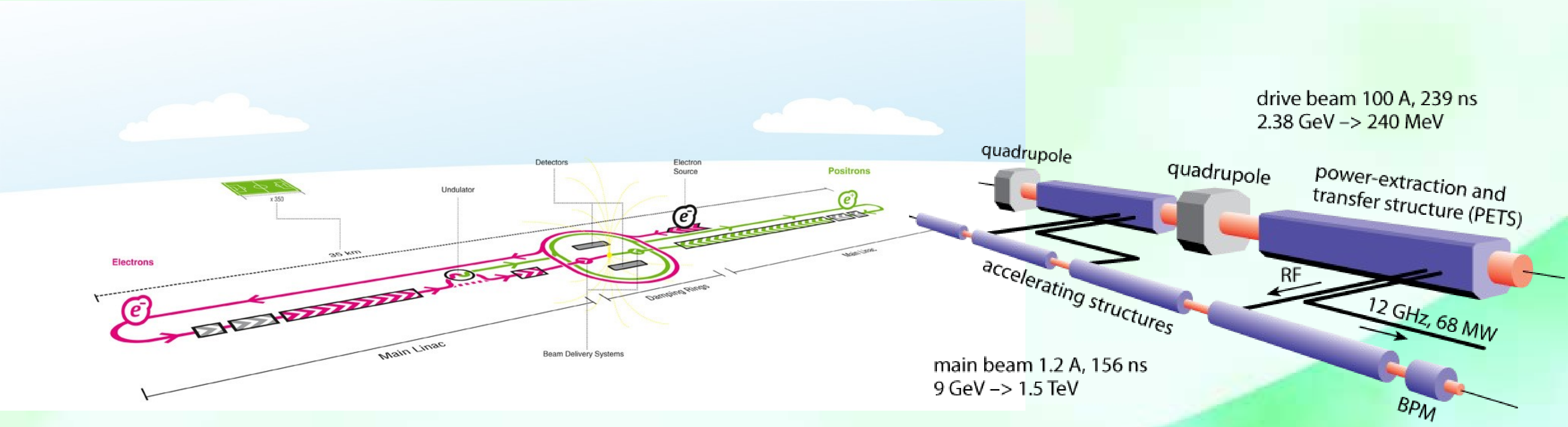
# Positron Source for Linear Colliders

## KURIKI Masao (Hiroshima/KEK)



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Summary

# Positron Generation

# What is Positron?

Positron Generation
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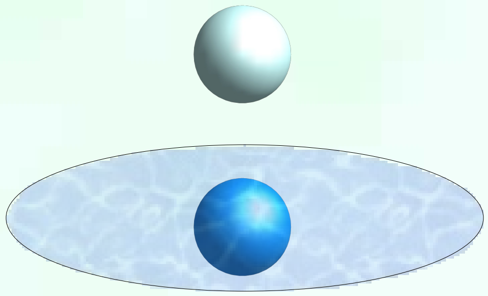
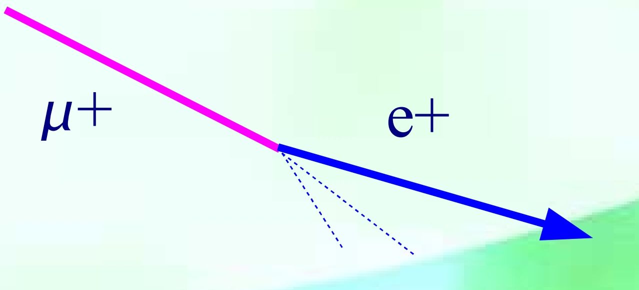
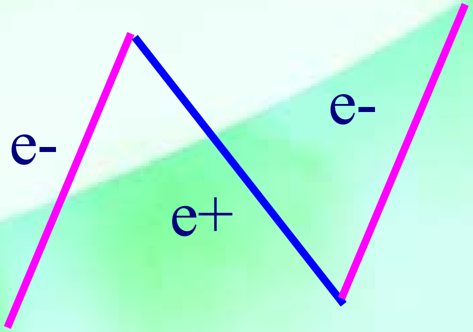
Summary

- 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**
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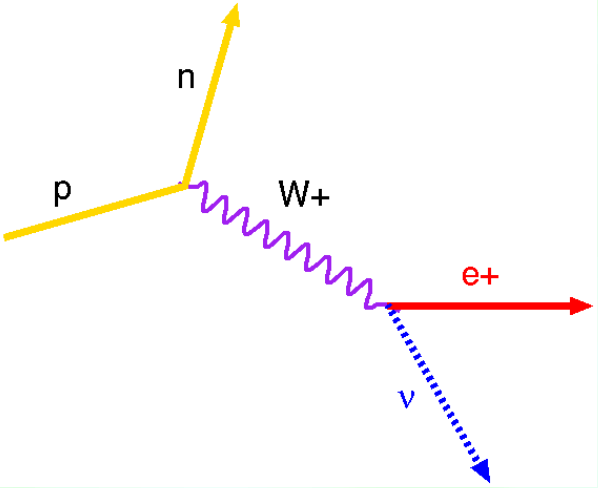
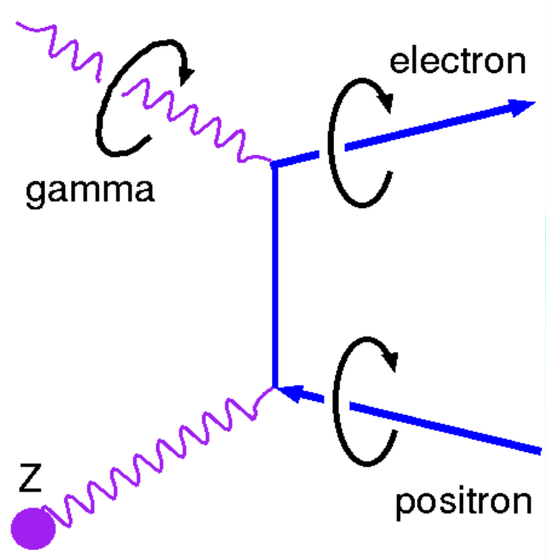
Positron Capture
LC Positron Source
Summary

- 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 with a time structure, employ the pair-creation process.

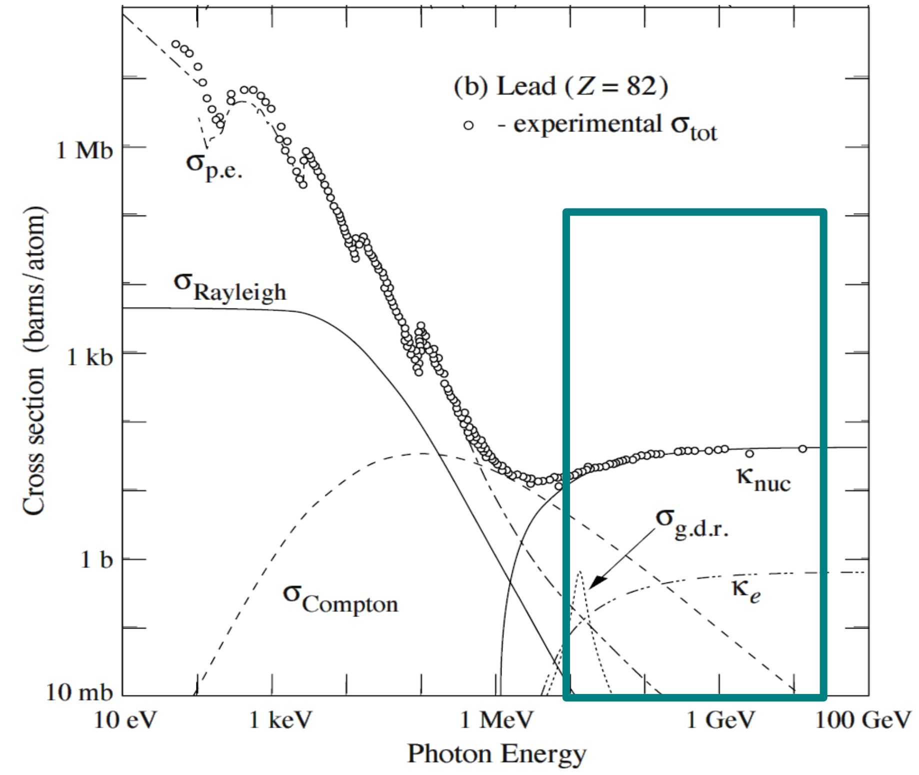




# Positron Production (2)

**Positron Generation**
Positron Source
Positron Capture
LC 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
$\kappa_{nuc}$, $\kappa_e$: pair creation
(from Particle Data Group, http://pdg.lbl.gov)

# Need Photon?

- We need many photons to create enough amount of positrons for LC
  - Typical capture efficiency is only 0.2%.
  - 3.2nC (2.0E+10 positron/bunch) for ILC.
  - 0.6nC(4.4E+9 positron/bunch) for CLIC.
- How to create the photons?
  - Brems-strahlung, channeling radiation.
  - Undulator radition (Synchrotron Radiation).
  - Inverse Compton scattering.

# Bremsstrahlung

- **Positron Generation**
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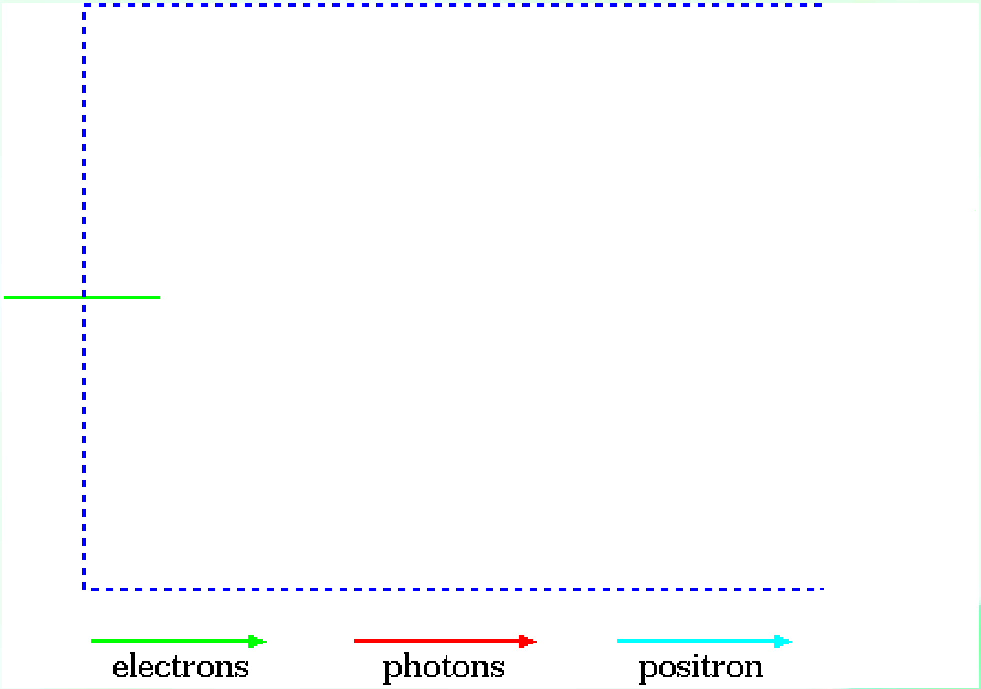
- Summary

- When high energy electron (typically >100MeV) impinges on a material,it interacts through various processes;
  - Bremsstrahlung(BS)
  - Electron excitation
- Photons generated by BS, interact through
  - Pair-creation
  - Compton scattering
- As consequences, EM shower (mixture of electrons, positrons and gammas) is developed.



Extract these positrons from the EM shower.

# EM Shower (1)

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

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

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

# EM Shower (2)

**Positron Generation**
Positron Source
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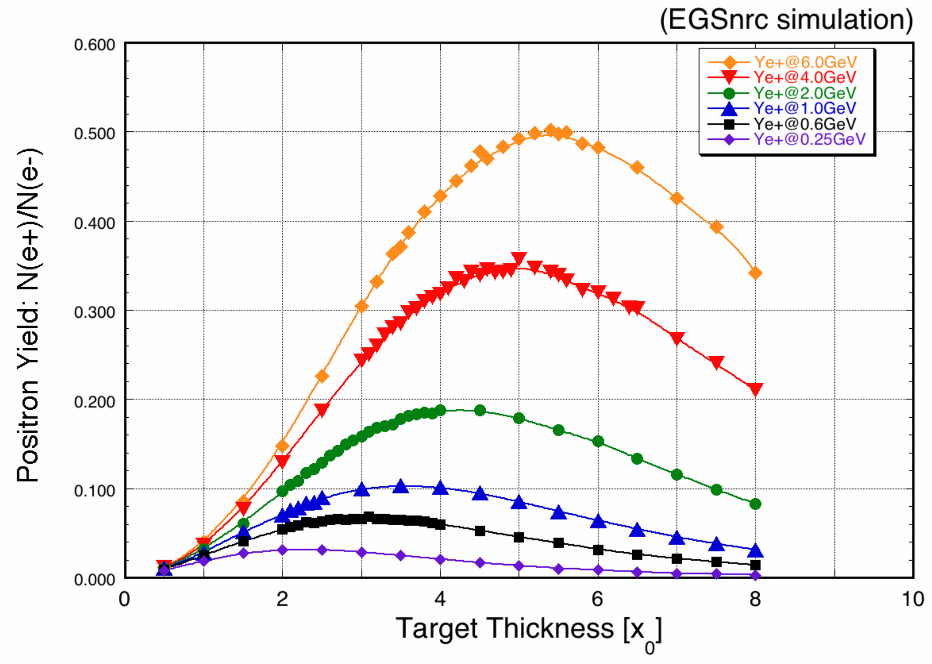
LC Positron Source
Summary

- # 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.
- Empirical expression for the shower max length in $X_0$;

$$T_{max} = 1.01\left[\ln\left(\frac{E_0}{\epsilon_0}\right) - 1\right] \quad (1-2)$$

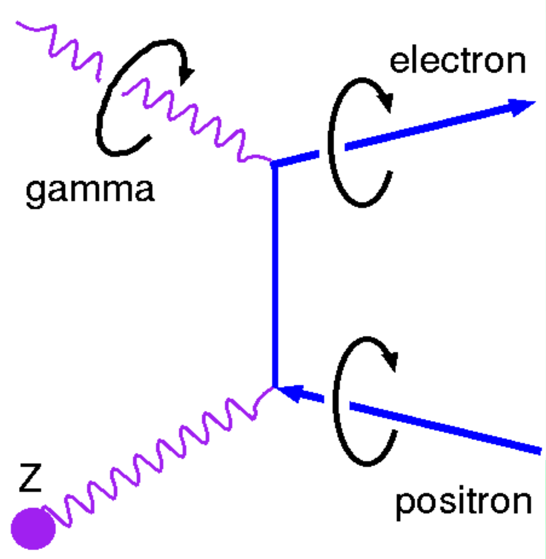
  - $E_0$: Electron energy
  - $e_0$: critical energy
- # of positron is also peaked at the shower max. It determines the target thickness.



Courtesy of T.Kamitani

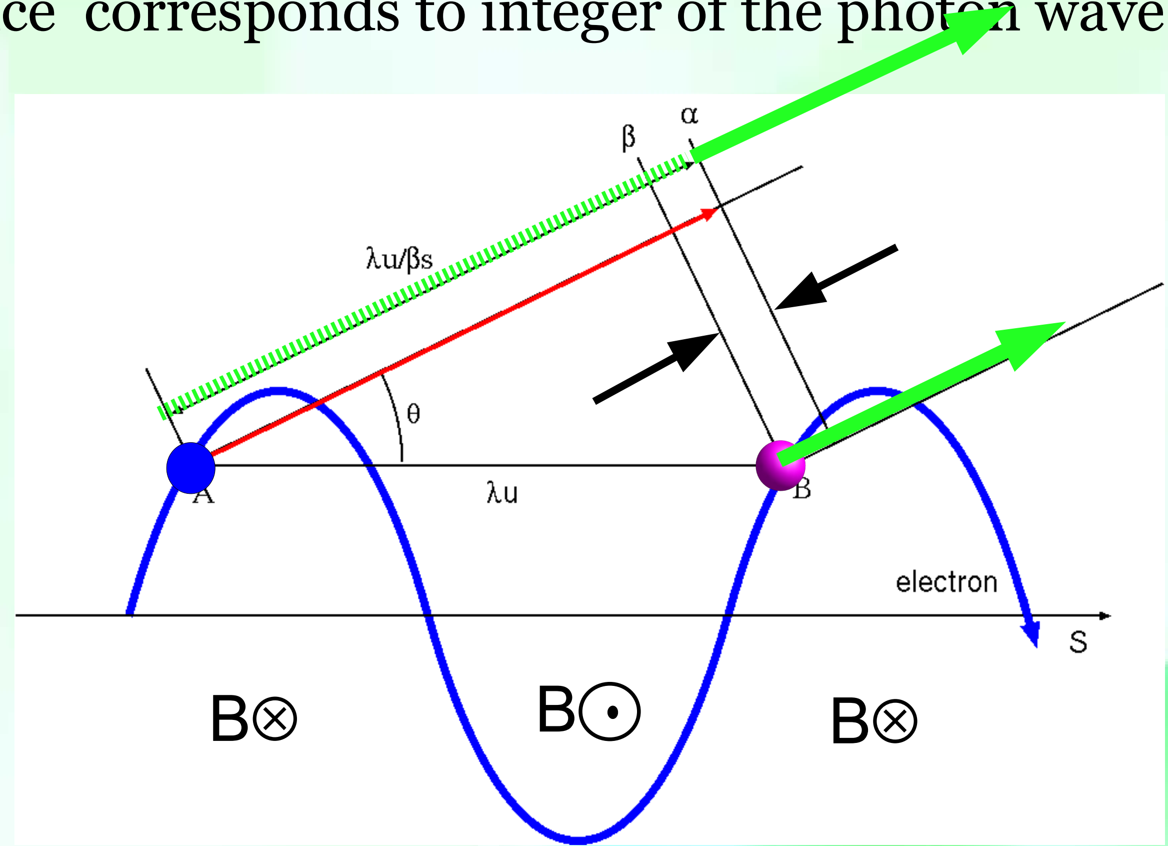
# Photon Driver

- With 10s MeV photons, photons directly generate positrons through 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. 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 zig-zag motion.
- Photons are emitted to the direction where wave-plane distance corresponds to integer of the photon wave length.



# Undulator radiation (2)

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Summary

The radiation spectrum is given by Lienard-Wiechert form

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

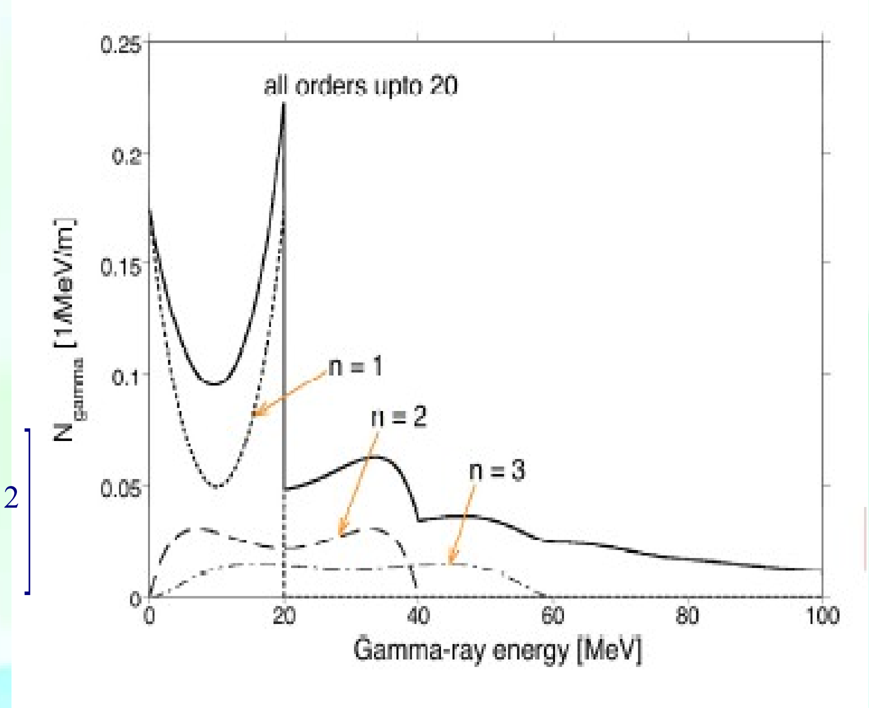
ω is angular frequency of photon, Ω is solid angle, **n** is unit vector to observation. The photon cut off energy is

$$\lambda_1=\frac{\lambda_u}{2\mathrm{n}\gamma^2}\left(1+K^2+\theta^2\gamma^2\right)$$

$$E_1[eV]=9.50\frac{nE^2[GeV^2]}{\lambda_u[m](1+K^2+\theta^2\gamma^2)}$$

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

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



# Undulator Radiation (3)

- The cut off photon energy from undulator is rewritten as

$$E = \frac{2n\gamma^2 \hbar \omega_0}{1+K^2} \qquad (3-12)$$

$$\omega_0 = \frac{2\pi\beta c}{\lambda_u} \qquad (3-13)$$

where ħωₒ is photon energy.

- The undulator radiation = electron and photon scattering.
  - Photon wave length = undulator period.
  - The photon energy is boosted by $\gamma^2$.
- Because the undulator period is long, we need high $\gamma^2$.
  - 130 GeV for e+ generation.
  - A dedicated electron linac is unrealistic.

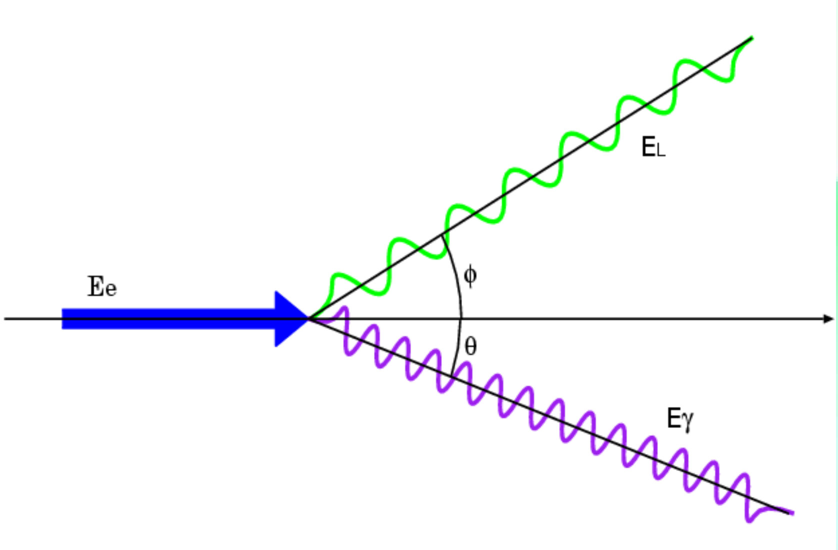
# Laser Compton(1)

- **Positron Generation**
- Positron Source
- Positron Capture
- LC Positron Source
- Summary

- Inverse Compton scattering between laser photon and electron beam.
- Laser photon (wavelength is μm order) is scattered by high energy electron and its energy is boosted.
- As as 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.
- $E_\gamma$ ~ 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 $\lambda_L$ is laser wave length. The laser photon is boosted by electron with factor $4\gamma^2$.

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

# Laser Compton (3)

**Positron Generation**
Positron Source
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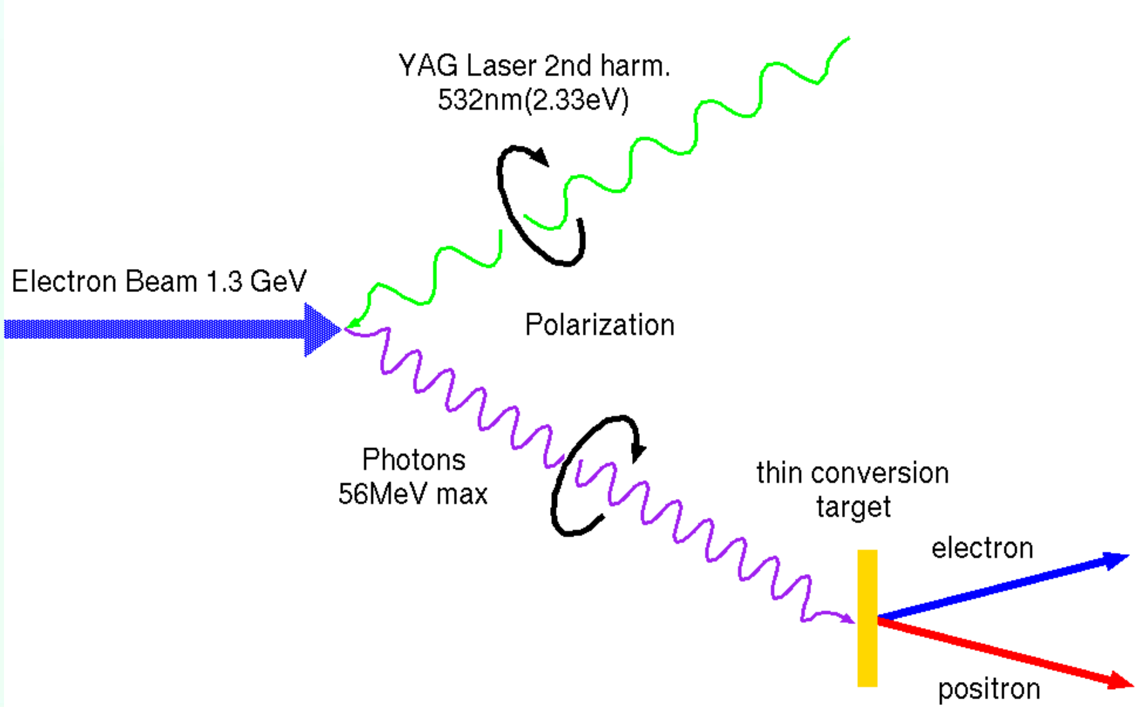
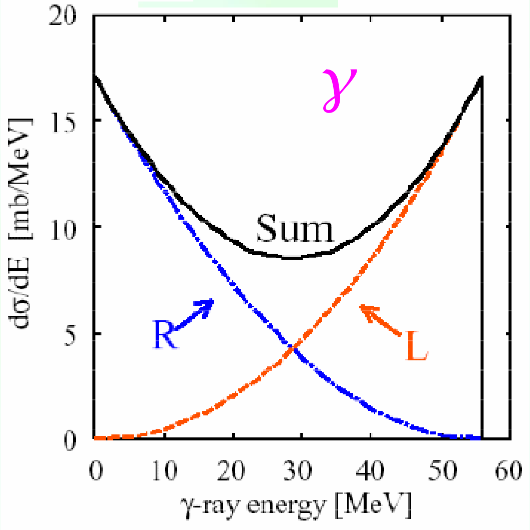
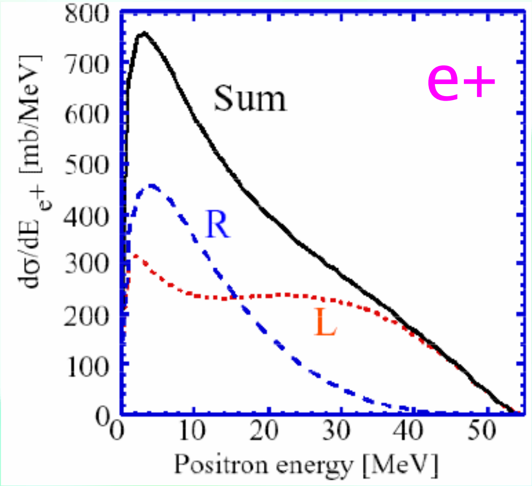
LC Positron Source
Summary

- 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.

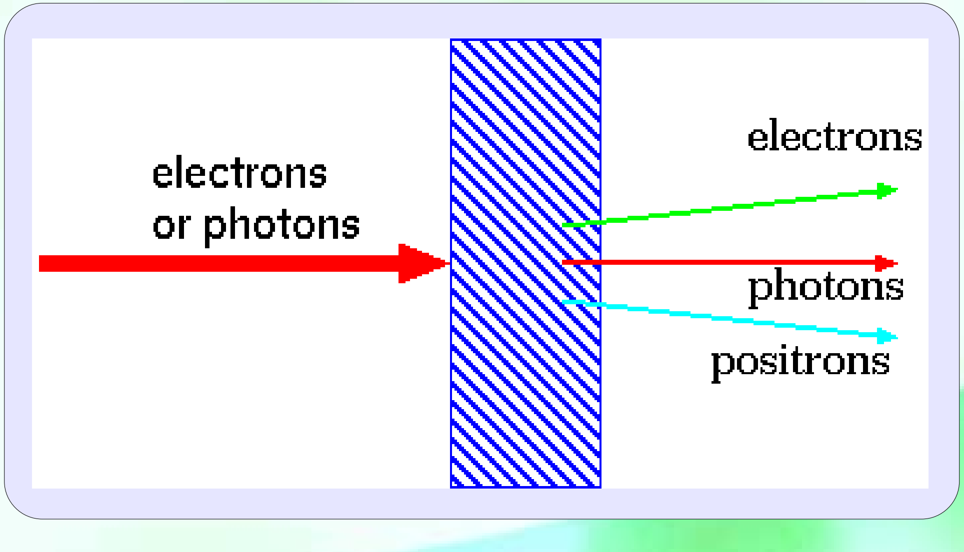






# Summary for Positron Generation

- Positron is generated through pair-creation process.
- Driver beam (electron >100s MeV or photon > 10 MeV) impinges on the converter and positron is obtained as a mixed flux of e+, e-, and photon.
- high multiplication and no polarization for electron (EM-Shower)
- No multiplication and possible polarization for photon.



Positron Generation
**Positron Source**
Positron Capture
LC Positron Source
Summary

# Positron Source

# Positron Source

- Positron source is a system, composed from:
  - Drive Beam (Electron or Photon)
  - Conversion target
  - Matching Device
  - Capture Accelerator
- Three concepts of positron source have been proposed.
  - Electron driven (conventional), undualtor, and laser compton.

Positron

Drive Beam

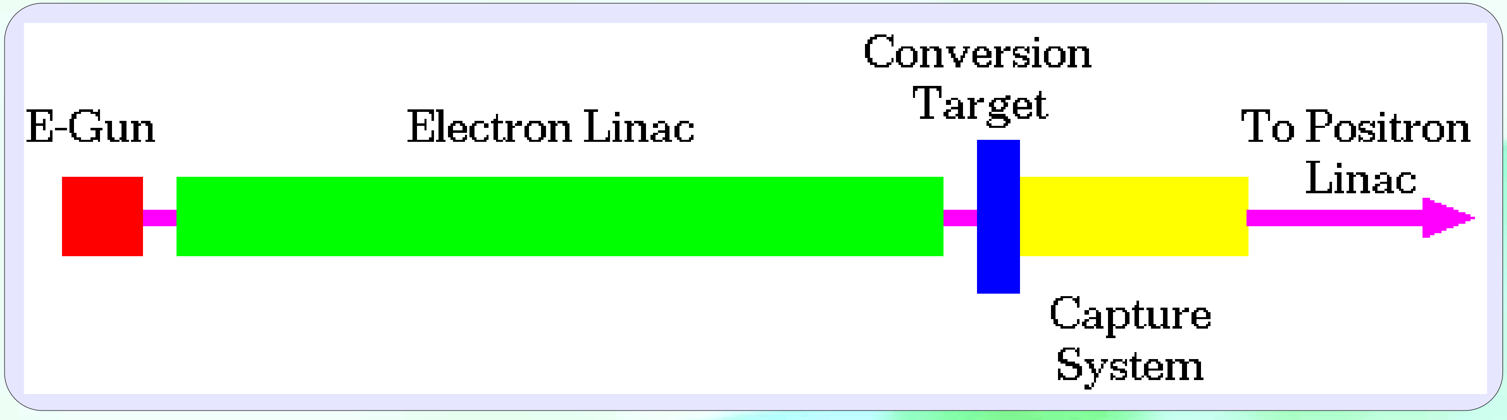
Conversion Target

Matching Device

Capture Accelerator

# Electron Driven (1)

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



# Electron Driven (2)

Positron Generation
**Positron Source**
Positron Capture
LC Positron Source
Summary

For each drive electron energy, positron yield is optimized with target thickness, which corresponds to the shower max,

$$T_{max} = 1.01\left[\ln\left(\frac{E_0}{\epsilon_0}\right) - 1\right] \qquad (3-1)$$

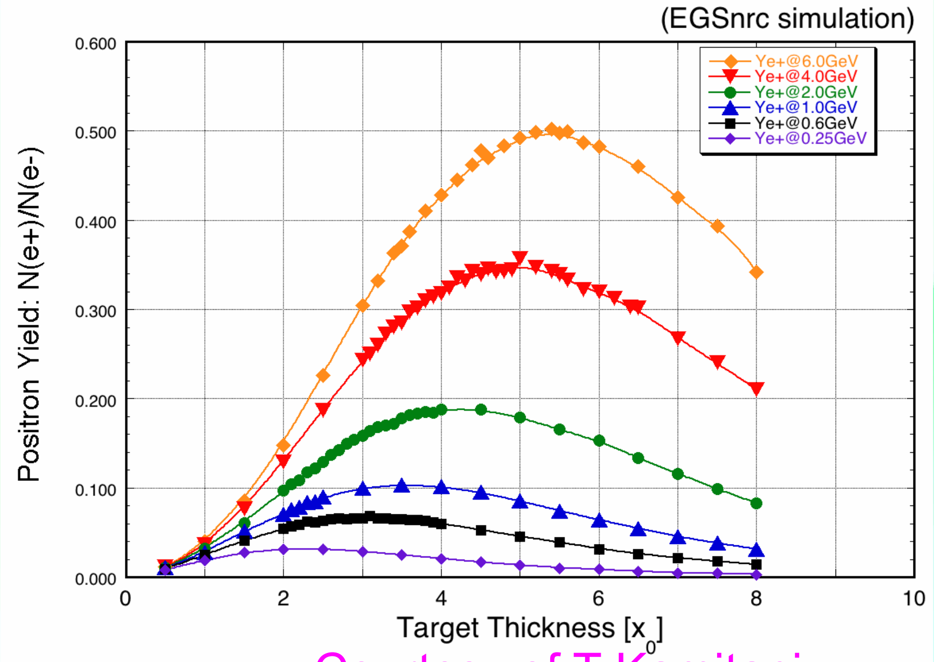
where $E_0$ is electron energy, $\varepsilon_0$ is critical energy.

The positron yield is

$$\eta = \frac{N_{pos}}{N_{ele}} \qquad (3-2)$$

$$\eta_n = \frac{N_{pos}}{N_{ele} E_{ele}} \qquad (3-3)$$

where η is simple yield and $\eta_n$ is the normalized yield.



Courtesy of T.Kamitani

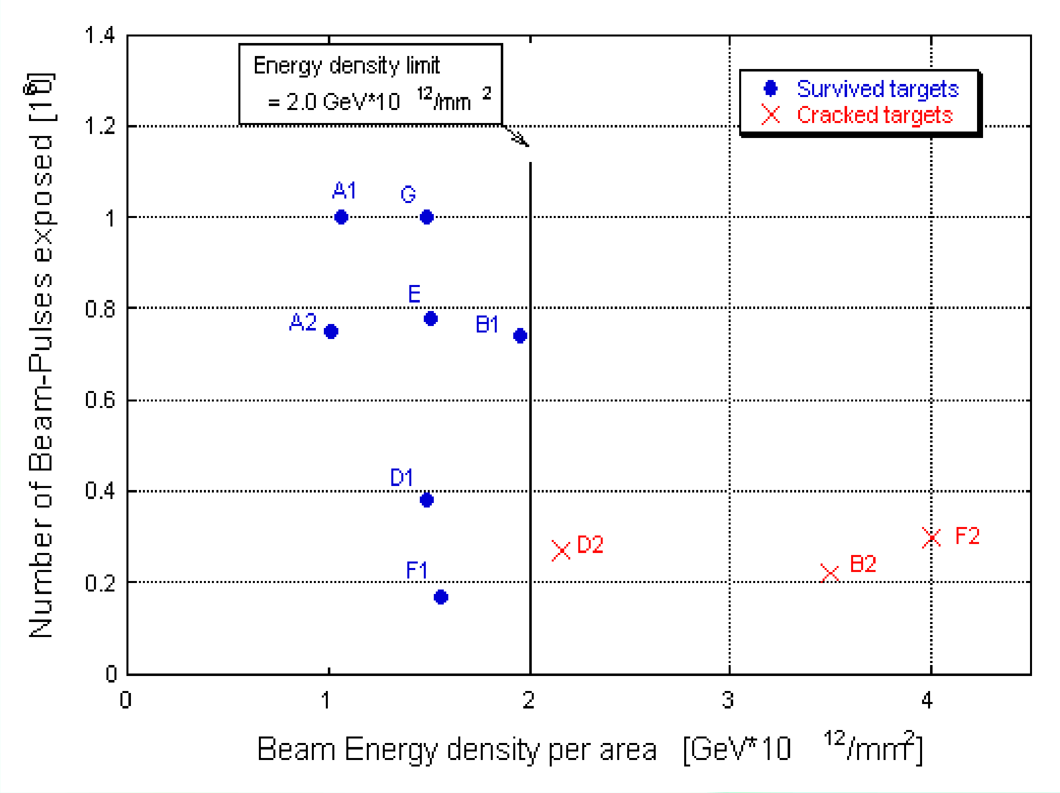
# Electron Driven Scheme (3)

- 20-30% of electron energy is deposited in the target as thermal energy.
- Actual limit on the electron driven scheme is given by the target destruction with this thermal energy.
- The destruction can be occurred several processes,
  - Melting,
  - Fatigue,
  - Destruction by thermal shock wave, etc.
- Several novel ideas are proposed to solve this issue.

# Damage Threshold (1)

Positron Generation
Positron Source
Positron Capture
LC Positron Source
Summary

- Damage threshold for positron production target (W-Re) is examined at SLAC.
- Single bunch beam is injected to target repeatedly in 120Hz.
- The damage depends only on beam energy density, not for number of shots.
- Threshold is 2.0 GeV $10^{12}/\mathrm{mm}^2$ or $320\mathrm{J}/\mathrm{mm}^2$ .



S. Ecklund, SLAC-CN-128

# Damage Threshold (2)

Positron Generation
Positron Source
Positron Capture
LC Positron Source
Summary

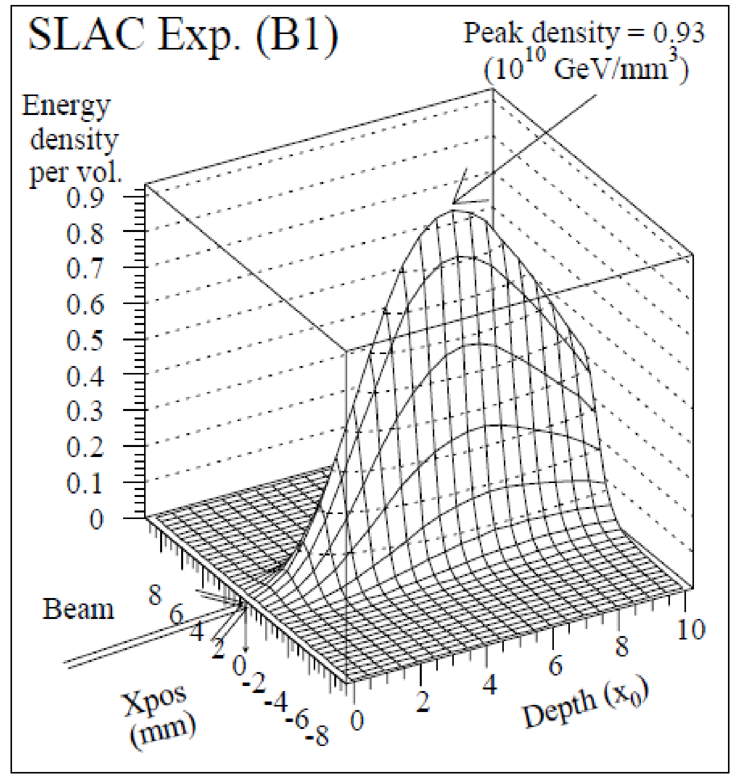
To evaluate the universal damage threshold, the energy deposited density in the SLAC experiment is evaluated as

$$\rho = 0.93\times10^{10}\ \left[GeV/mm^3\right]$$

$$\rho = 76\ \left[J/g\right]$$

Although SLC had been operated below this limit, a significant damage is observed at the production target. The actual limit is now considered to be the condition of SLC,

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



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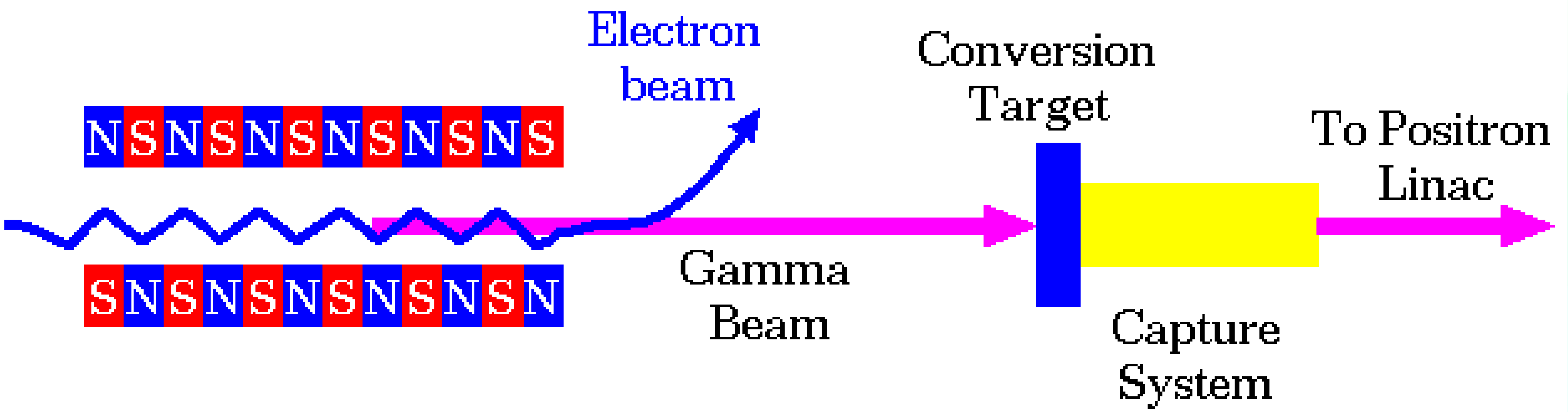
# Undulator Scheme (1)

Positron Generation
**Positron Source**
Positron Capture
LC Positron Source
Summary

- By passing more than 100 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)

- 130GeV>E electron driver is required to generate 10 MeV>E gamma for positron generation.
- Electron beam for collision is used for the positron generation, because a dedicated electron beam is not realistic.
- The electron and positron linacs in LC are not independent anymore. Many system constraints.
- In low energy operation, the positron yield becomes very low. It could be solved by deceleration or alternate-pulse operation.
- By employing helical undulator, polarized positron is obtained.
- Low positron yield can be recovered by making the undulator as long as required, 231m for ILC.

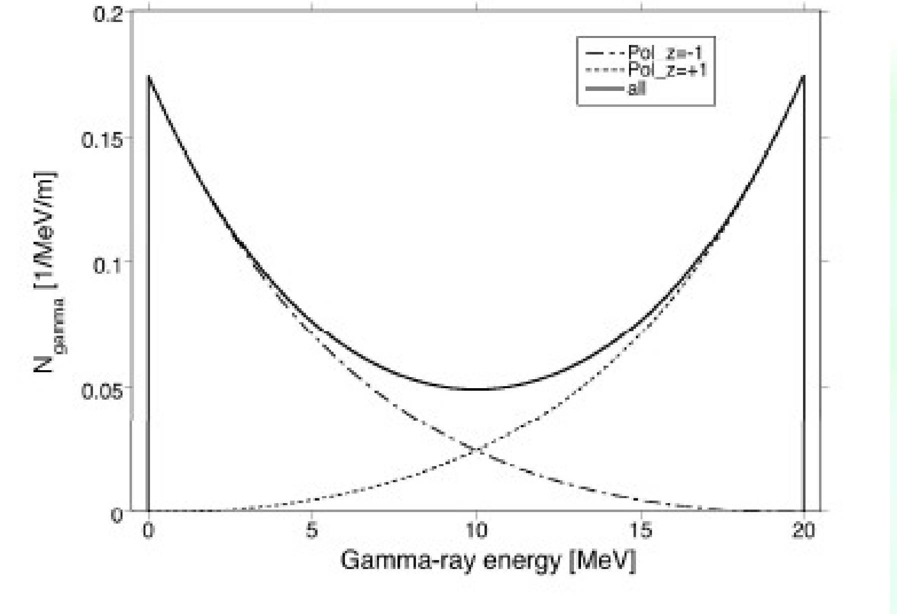
# Polarized Positron

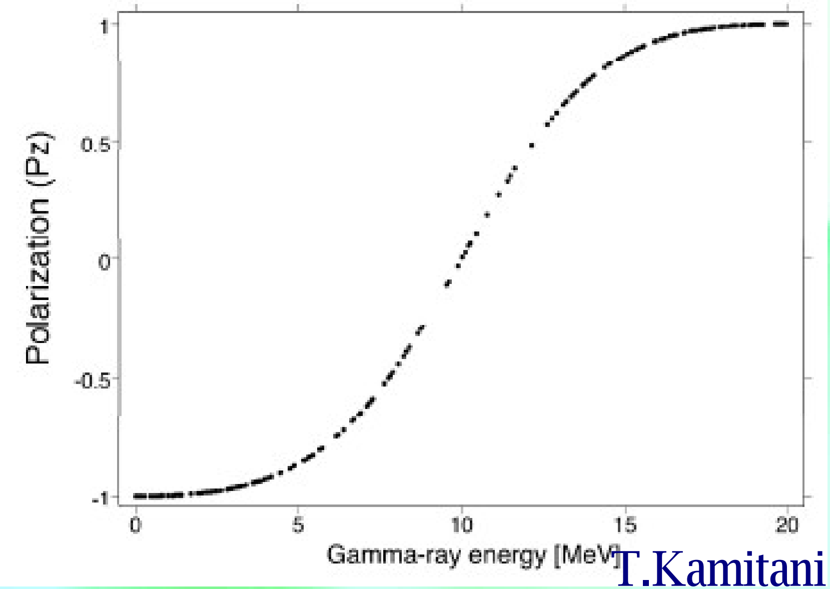
Positron Generation
Positron Source
Positron Capture
LC Positron Source
Summary

- 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.

$$\frac{dN_n}{dE}\left[\frac{1}{MeV}\right]=\frac{10^6 e^3 L}{4\pi\epsilon c^2 h^2}\frac{K^2}{\gamma^2}\left[J_n'(x)^2+\left(\frac{\alpha_n}{K}-\frac{n}{x}\right)^2 J_n(x)^2\right] \quad (4-1)$$

$$\theta=\frac{1}{\gamma}\sqrt{n\frac{\omega_n(1+K^2)}{\omega}-1-K^2} \quad (4-2)$$





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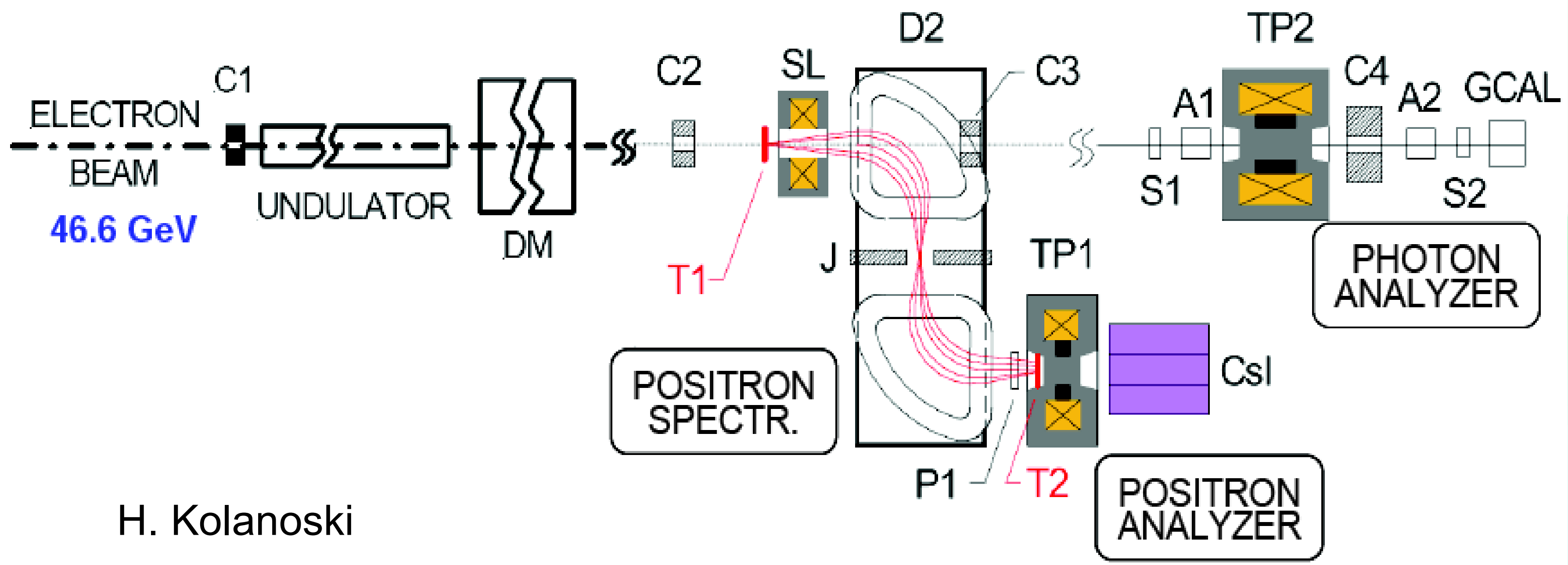
# E166 (1)

Positron Generation
**Positron Source**
Positron Capture
LC Positron Source
Summary

- E166 is an experiment, which was carried out at SLAC to demonstrate the polarized positron production with helical undulator.
- 46.6 GeV electron beam passes through 1m undulator, K=0.17 (0.71T, $\lambda_u$=2.54mm).
- γ and positron polarization is analyzed by transmission method.

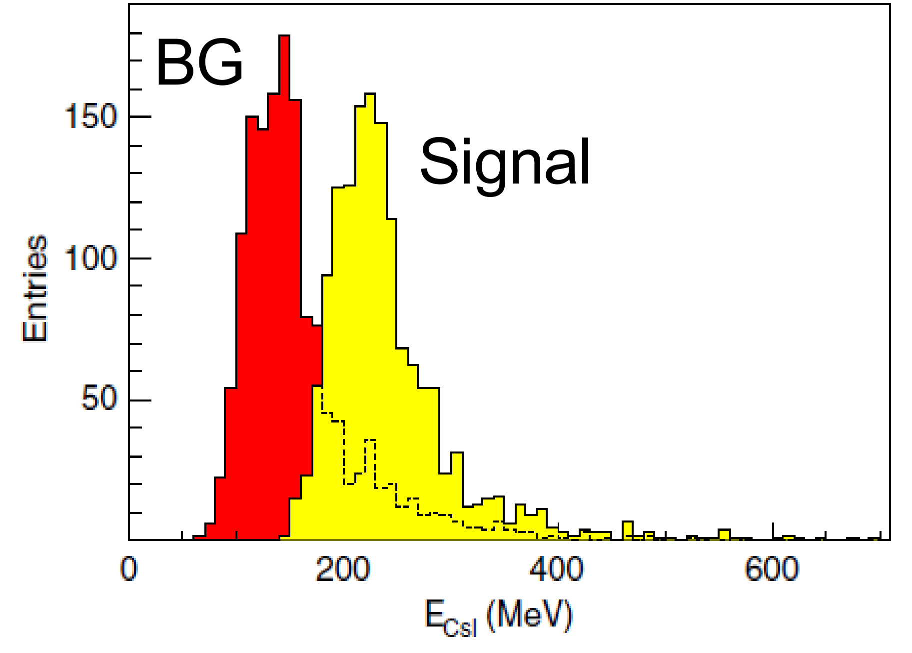


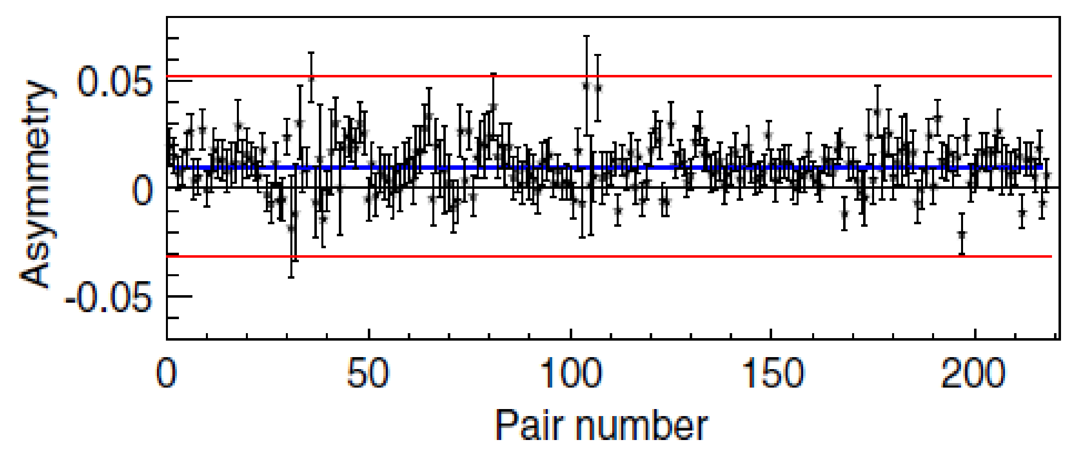
H. Kolanoski

# E166 (2)

- The signal is observed undulator on and off to subtract background contribution.
- The asymmetry is calculated with each pair of data with opposite magnetization of the polarimeter.

$$\delta_\gamma = \frac{S^-_{CsI} - S^+_{CsI}}{S^-_{CsI} + S^+_{CsI}} \qquad (3-14)$$





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# E166 (3)

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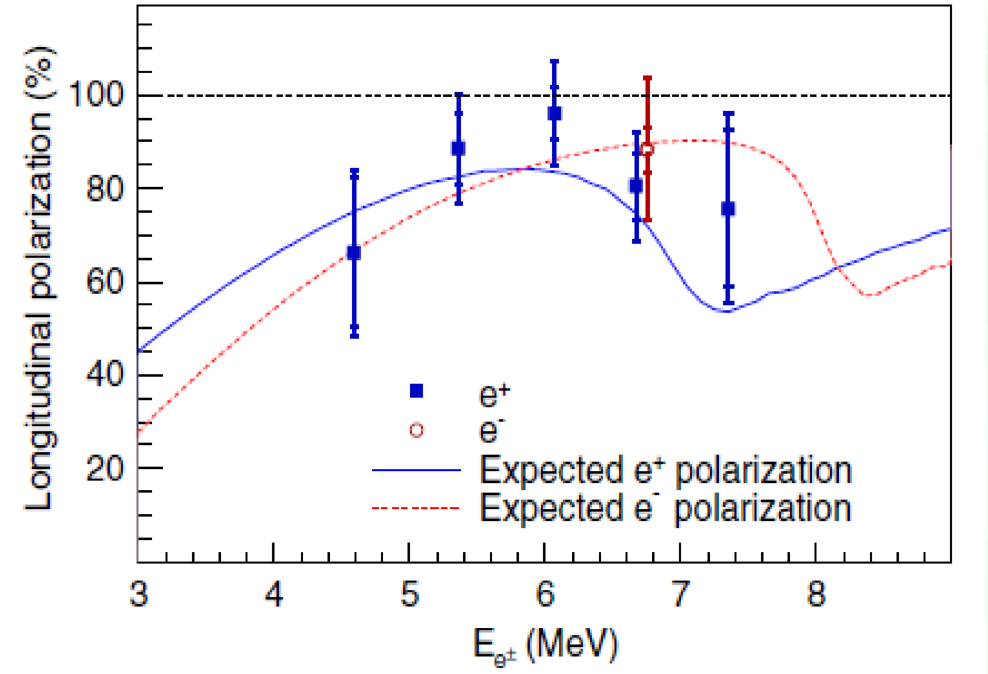
- Summary

From the asymmetry from the polarimeter, the positron asymmtery is extracted as

$$P_{e+} = \frac{\delta_{\gamma}}{A_{e+} P_{e-}^{Fe}} \qquad (3-15)$$



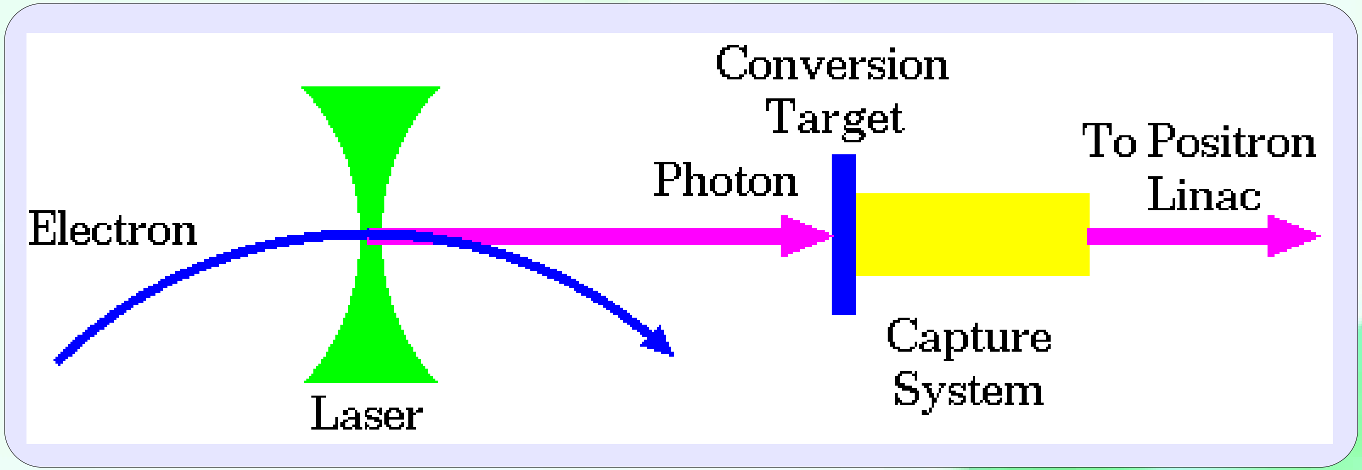
~80% positron polarization is obtained, which is consistent with expected value.

| $E_{e^\pm}$ | $\delta \pm \sigma_\delta(\text{stat})$ | $A$ | $P \pm \sigma_P(\text{stat}) \pm \sigma_P(\text{syst})$ |
|---|---|---|---|
| 4.6 ($e^+$) | 0.69 ± 0.17 | 0.150 | 66 ± 16 ± 8 |
| 5.4 ($e^+$) | 0.96 ± 0.08 | 0.156 | 89 ± 8 ± 9 |
| 6.1 ($e^+$) | 1.08 ± 0.06 | 0.162 | 96 ± 6 ± 10 |
| 6.7 ($e^+$) | 0.92 ± 0.08 | 0.165 | 80 ± 7 ± 9 |
| 6.7 ($e^-$) | 0.94 ± 0.05 | 0.153 | 88 ± 5 ± 15 |
| 7.4 ($e^+$) | 0.89 ± 0.20 | 0.169 | 76 ± 17 ± 12 |

G. Alexander

# 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 Generation
**Positron Source**
Positron Capture
LC Positron Source
Summary

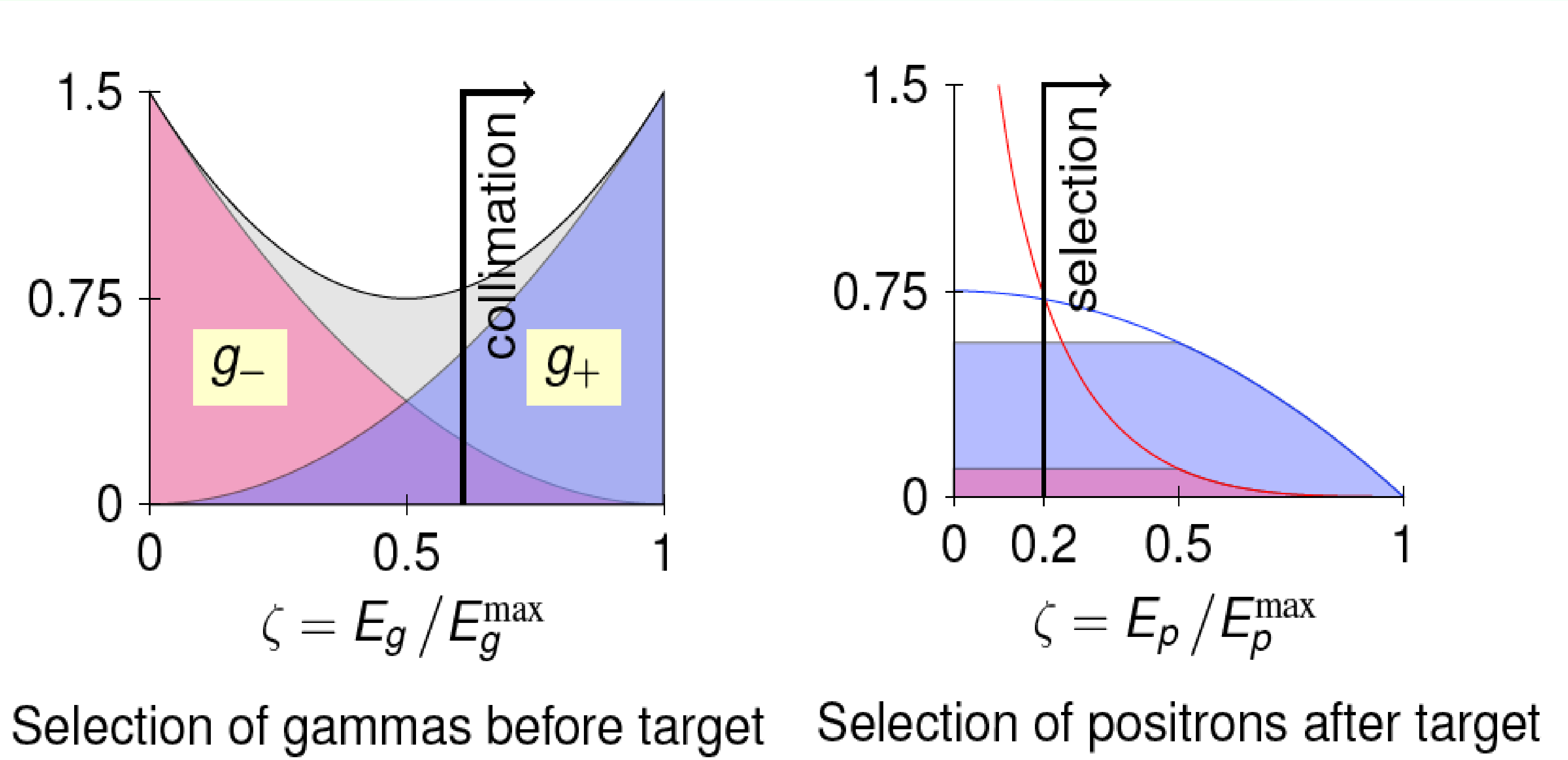
- Positron Polarization.
  - **Higher degree up to 90 %.**
  - **Train by train flipping (5Hz) by laser polarity control.**
- Dedicated e- beam.
  - No concern for e- beam quality degradation.
  - No inter-system dependence.
    - **Simple, easier construction, operation, commissioning, maintenance, high availability.**
- No problem on low energy operation.

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

- To obtain enough amount of positron is a technical challenge.
- Three variations on the electron driver: Linac, Storage ring, ERL(Enegy Recovery Linac)

# Compton Scheme (3)

- Polarized gamma is obtained by collimation (pre-selection).
- The positron polarization is enhanced by the energy selection (post selection).

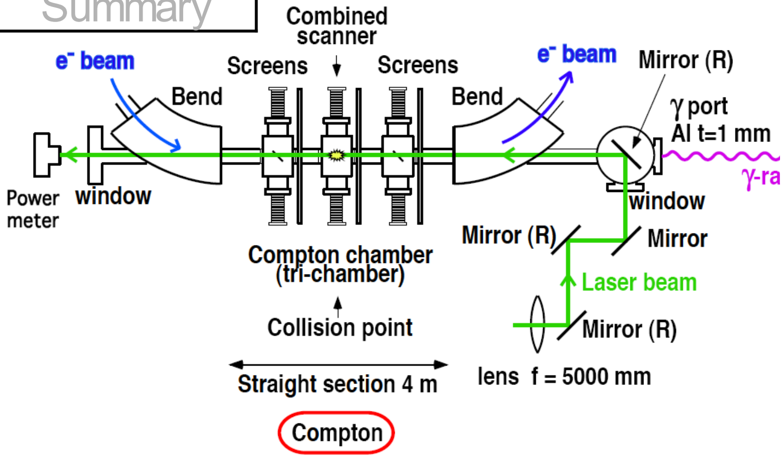


Selection of gammas before target

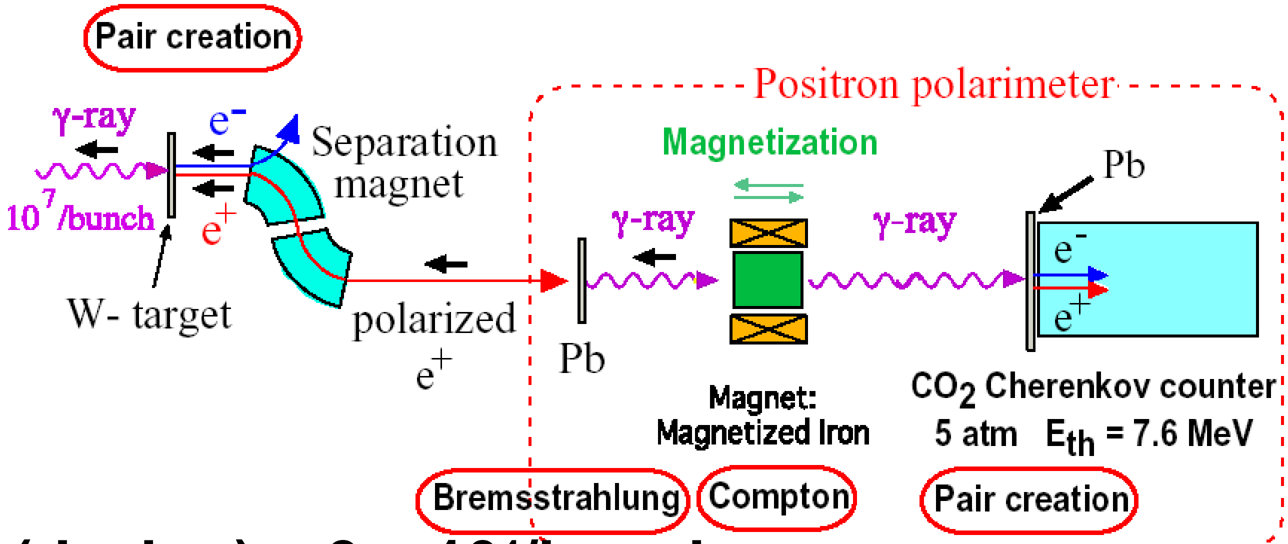
Selection of positrons after target

# Compton Scheme (4)

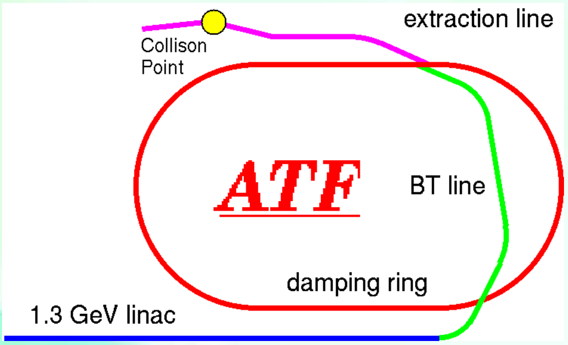
## KEK-ATF experiment



## Positron: production, selection, and polarimetry



- Ne+(design) = 3 x $10^4$/bunch
- Pol(estimation) = 80%
- Pol(experiment) ~ 73±15(stat)± 19(sys)%

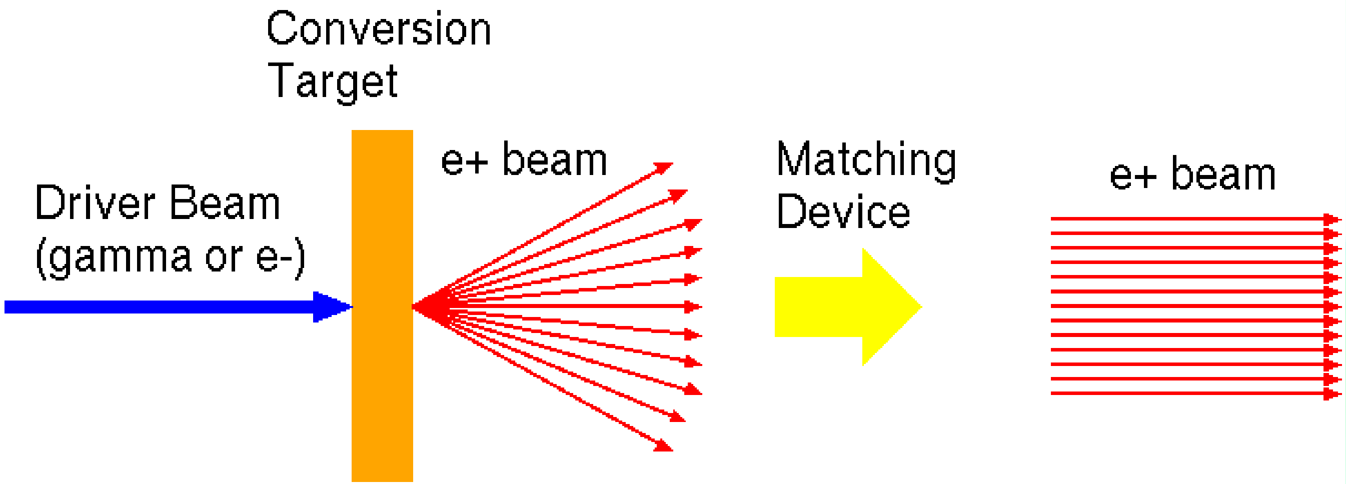


# Positron Capture

# Positron Capture (1)

Positron Generation
Positron Source
**Positron Capture**
LC Positron Source
Summary

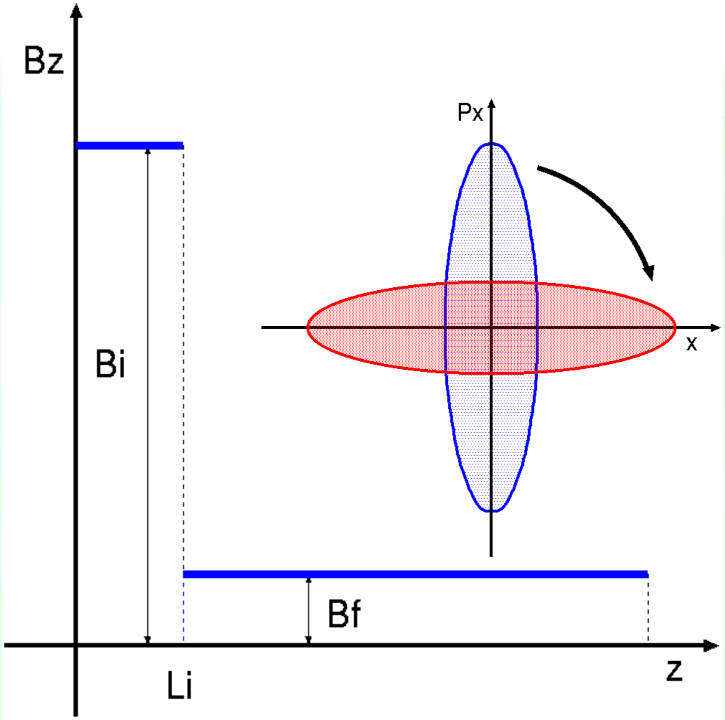
- Positrons are generated as a mixture of positrons, electrons, and gammas.
  - Select only positrons from the flux.
  - Capture the positron in a RF bucket.
- The generated positrons are distributed in a small spot size and in a large momentum space. To convert it to the parallel beam, capture devices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

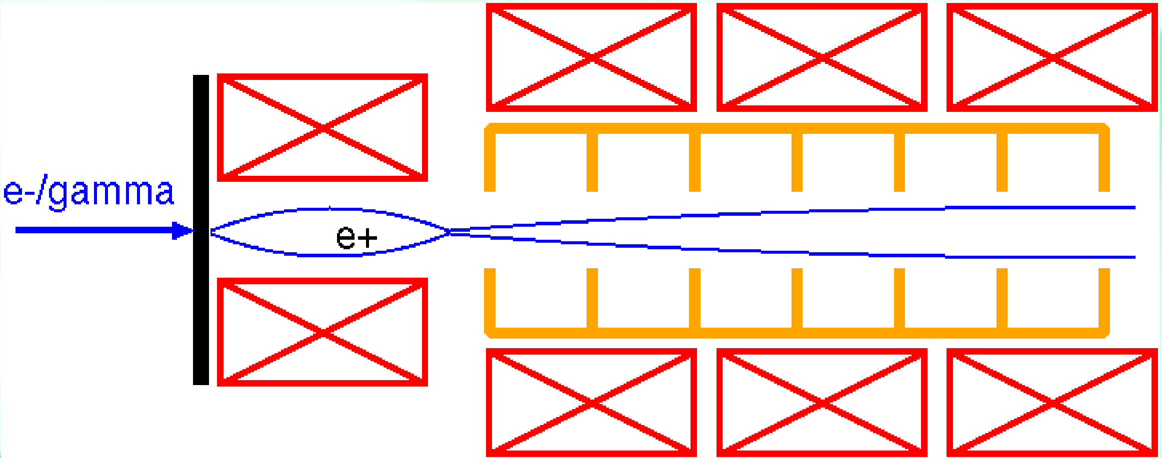


# QWT(1)

- Positron Generation
- Positron Source
- **Positron Capture**
- LC Positron Source
- Summary

- 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)

Positrons start at (x,y,z)=(0,0,0), p=(0,$p_{t0}$, $p_z$). In xy plane, positrons are circulated with radius ρ.

$$\rho = \frac{p_{t0}}{eB_i} \qquad (2-1)$$

Time to travel πρ in xy plane,

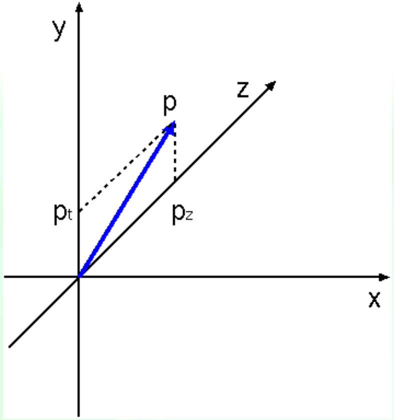
$$t_{xy} = \frac{\gamma m \pi \rho}{p_{t0}} = \frac{\gamma m \pi}{eB_i} \qquad (2-2)$$

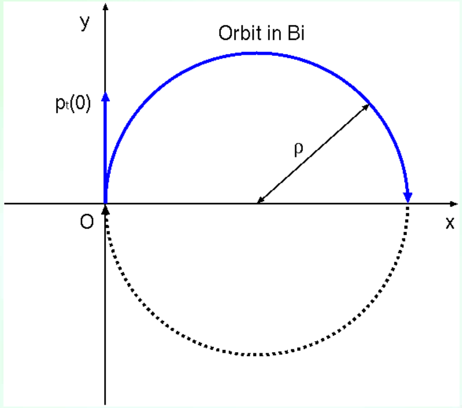
Time to travels $L_i$ in z

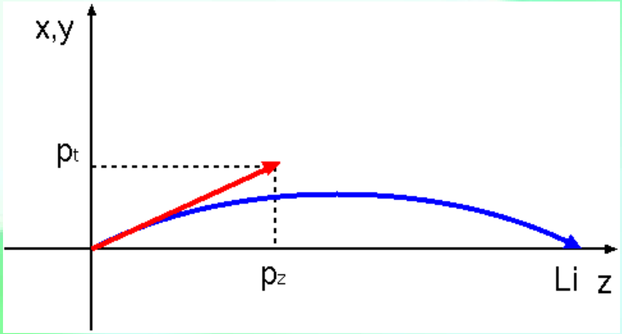
$$t_z = \frac{L_i m \gamma}{p_z} \qquad (2-3)$$

The capture condition is these are same. Only positrons satisfying the condition are captured by QWT.

$$\frac{L_i m \gamma}{p_z} = \frac{\gamma m \pi}{e B_i} \qquad (2-4)$$



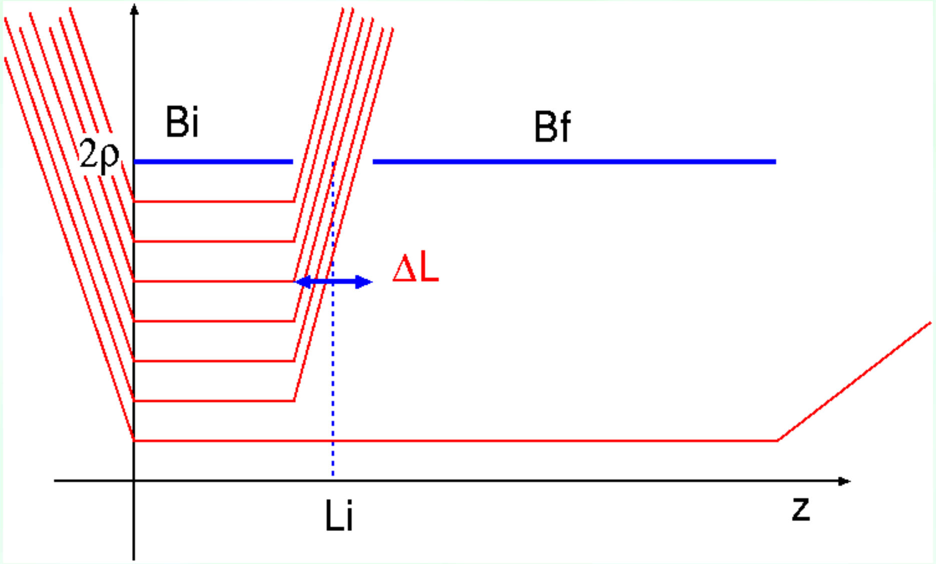




# QWT(3)

At the boundary of $B_i$ and $B_f$, transverse magnetic field $B_t(z)$ is appeared. In radius 2ρ, magnetic flux in $B_i$ region is

$$\Phi_i = \pi (2\rho)^2 B_i \quad (2-5)$$



Magnetic flux in $B_f$ region is

$$\Phi_f = \pi (2\rho)^2 B_f \quad (2-6)$$

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

$$\int 4\pi\rho B_t(z)\,dz = \Phi_i - \Phi_f$$

$$= 4\pi\rho^2 (B_i - B_f) \quad (2-7)$$

$$\int B_t(z)\,dz = \rho (B_i - B_f) \quad (2-8)$$

# QWT(4)

Momentum change at the boundary is

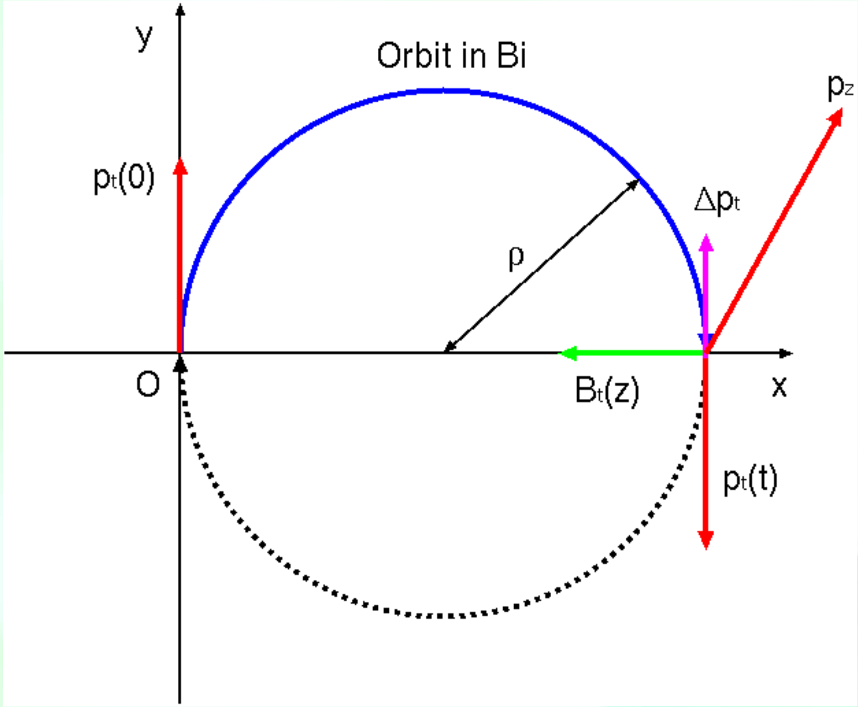
$$\frac{dp_t(t)}{dt} = e\,v_z B_t(z) \quad (2-9)$$

Integrating this equation, total momentum change is

$$\Delta p_t = e\,v_z \int B_t(z)\,dt$$

$$= e\,v_z \int B_t(z)\frac{dz}{v_z}$$

$$= e\rho(B_i - B_f) \quad (2-10)$$



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

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

$$= p_{t0}\frac{B_f}{B_i} \quad (2-11)$$

# QWT(5)

Positron Generation
Positron Source
**Positron Capture**
LC Positron Source
Summary

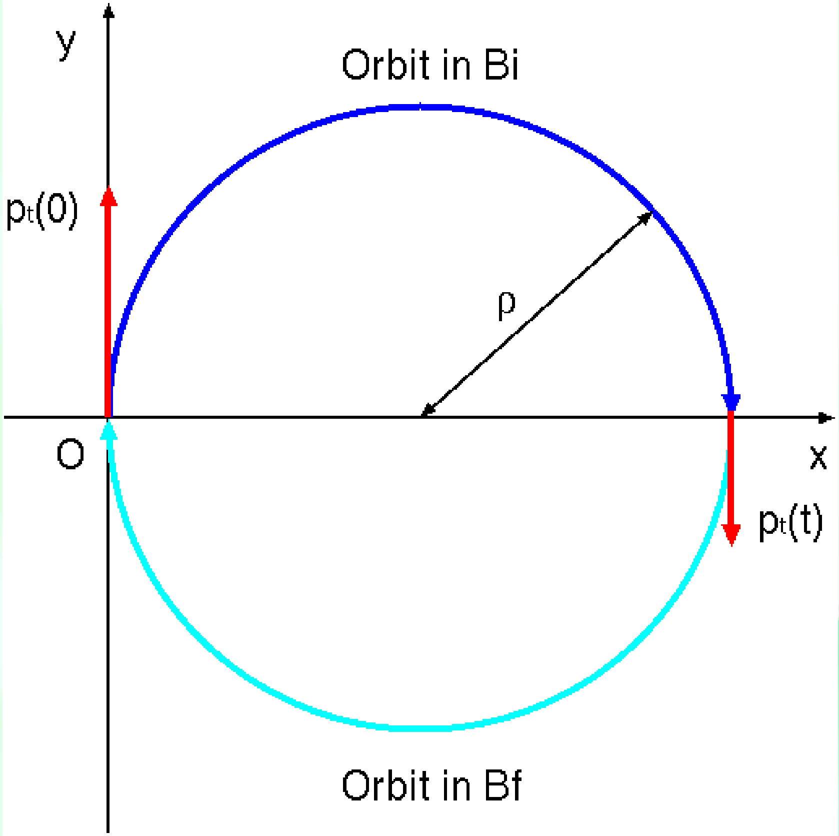
Pt(t) after the kick is

$$p_t(t) = p_{t0}\frac{B_f}{B_i} \quad (2-12)$$

Radius of circulating motion of this particle in $B_f$ is

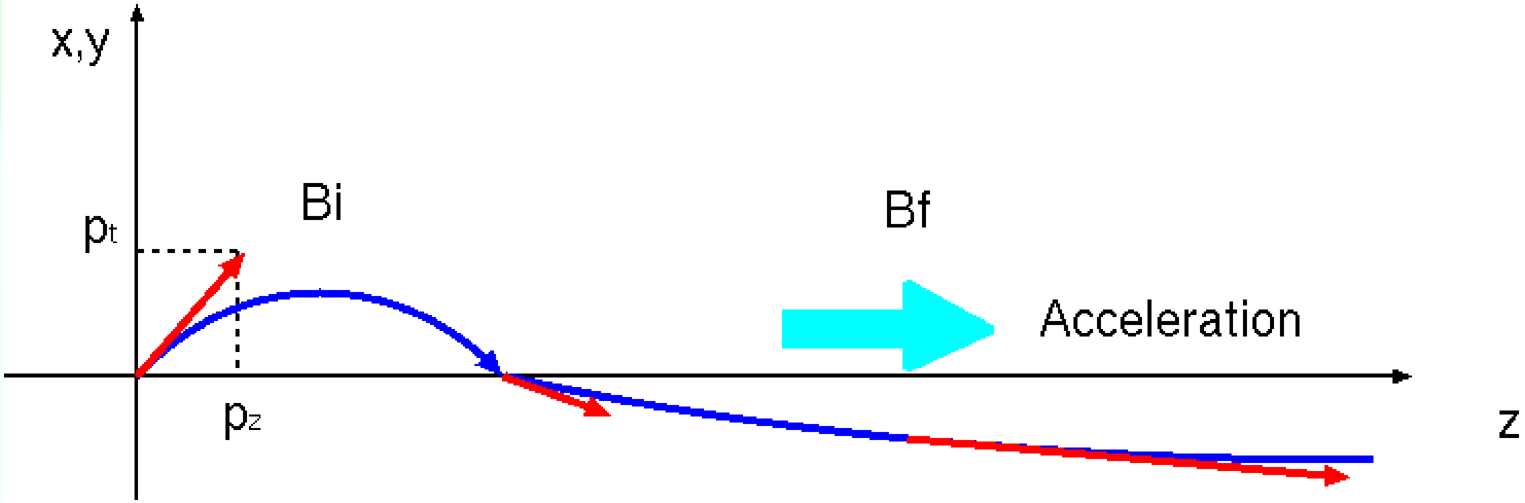
$$\rho_f = \frac{1}{eB_f}\frac{P_{t0}B_f}{B_i} = \frac{p_{t0}}{eB_i} \quad (2-13)$$

The particle continues the circulation with the same radius, but less Pt.



# QWT(6)

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



# QWT(7)

The positrons only with the appropriate condition are captured by QWT.

$$p_z = \frac{L_i e B_i}{\pi} \qquad (2-14)$$

Energy acceptance

$$\frac{\delta E}{E} \sim \frac{B_f}{B_i} \qquad (2-15)$$

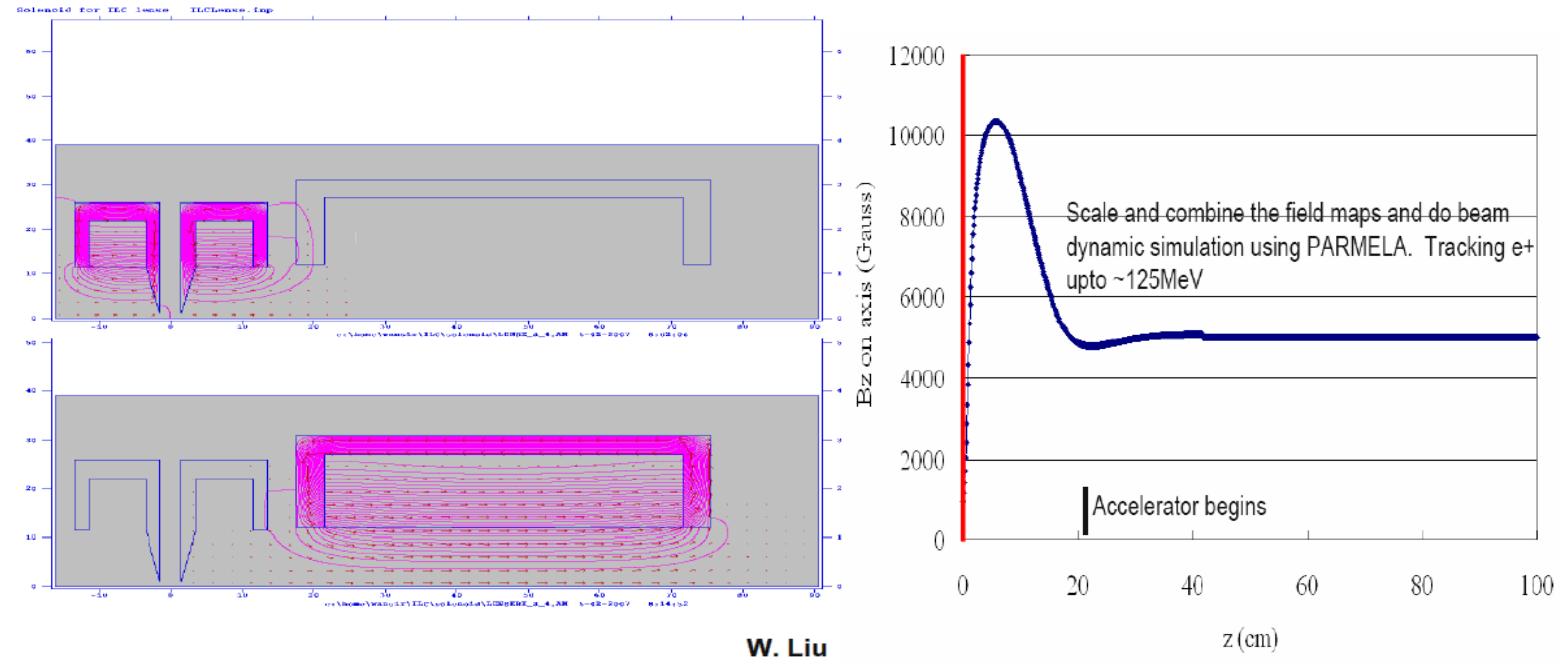
Momentum acceptance

$$2\rho = \frac{2\mathrm{p}_t}{eB_i} < a \qquad (2-16)$$

$$p_t < \frac{eB_i a}{2} \qquad (2-17)$$

# QWT(8)

Positron Generation
Positron Source
Positron Capture
LC Positron Source
Summary



Scale and combine the field maps and do beam dynamic simulation using PARMELA. Tracking e+ upto ~125MeV

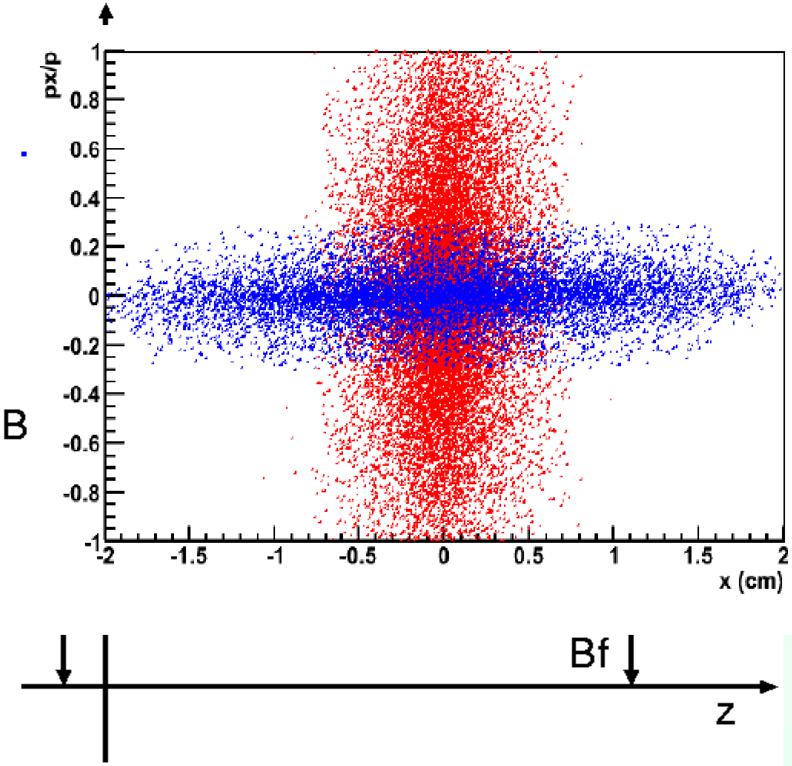
W. Liu

- Initial strong solenoid magnet with bucking to cancel B field on target.
- $B_f$ is 0.5 T.
- NC L-band accelerator is placed in $B_f$ region.

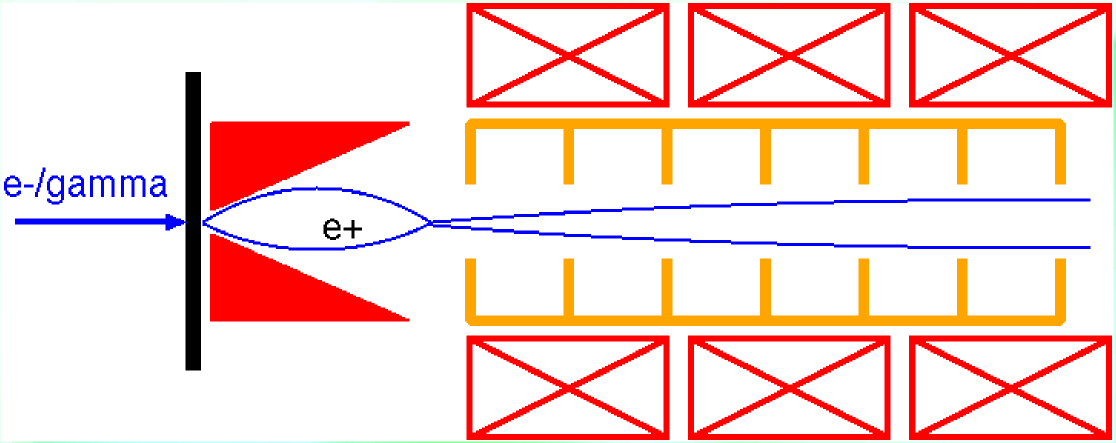
# AMD(1)

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

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



- AMD has relatively large energy acceptance.



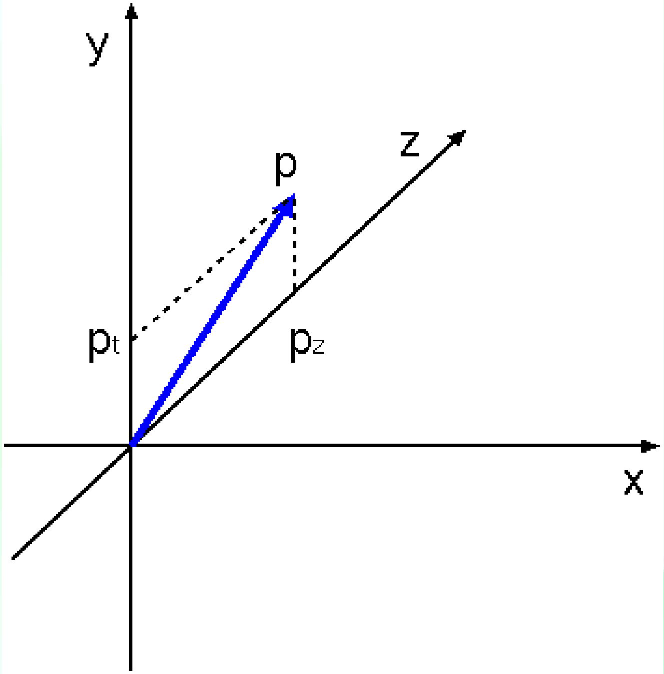
# AMD (2)

Positron Generation
Positron Source
**Positron Capture**
LC Positron Source
Summary

Positrons start at $(x,y,z)=(0,0,0)$, $p=(0,p_{t0},p_z)$.

In xy plane, positrons are circulated with radius $\rho(z)$,

$$\rho(z)=\frac{p_t(z)}{eB(z)} \qquad (2-19)$$



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

$$\frac{1}{2\pi}\int pdq=2\rho\, p_t(z)=2\frac{p_t(z)^2}{eB(z)} \quad (2-20)$$

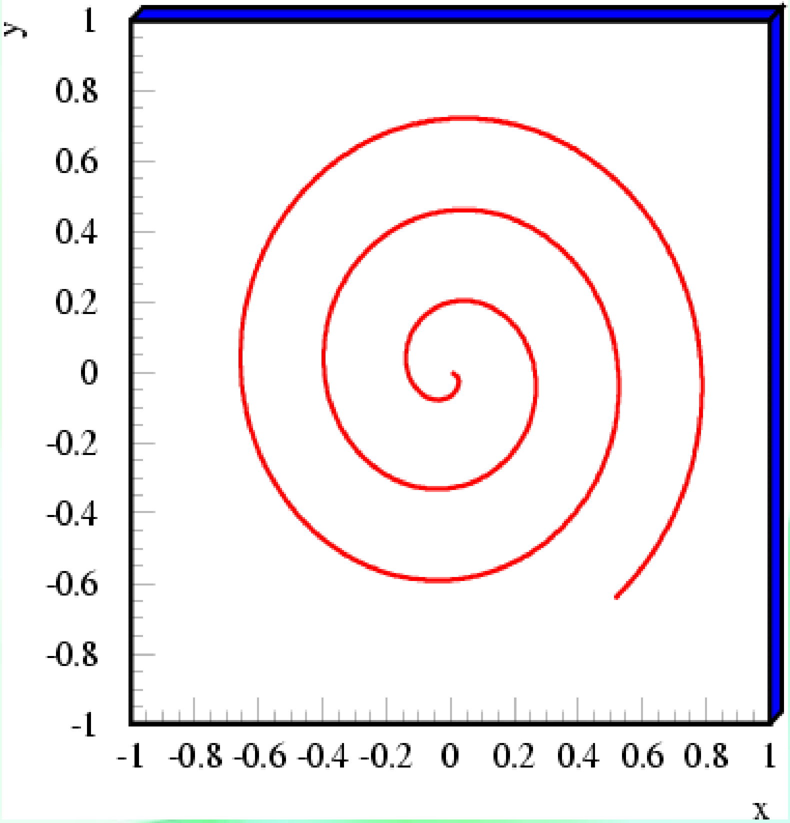
# AMD(3)

- Positron Generation
- Positron Source
- **Positron Capture**
- LC Positron Source
- Summary

Due to the adiabatic condition,

$$\frac{p_t(z)^2}{eB(z)} = \frac{p_{t0}^2}{eB_i} \qquad (2-21)$$

$$p_t(z) = \sqrt{\frac{B(z)}{B_i}}\, p_{t0} \qquad (2-22)$$



The radius is

$$\rho(z) = \frac{p_t(z)}{eB(z)} = \frac{1}{e\sqrt{B(z)B_i}}\, p_{t0} \qquad (2-23)$$

$$\rho_f = \frac{1}{e\sqrt{B_f B_i}}\, p_{t0} \qquad (2-24)$$

# AMD(4)

Adiabatic case

$$\rho_a(z) = \frac{1}{e\sqrt{B(z)B_i}} p_{t0} \qquad (2-26)$$

Non adiabatic case

$$\rho_{na}(z) = \frac{p_{t0}}{eB(z)} \qquad (2-25)$$

The ratio (compensation by AMD)

$$\sqrt{\frac{B(z)}{B_i}}$$

# AMD(5)

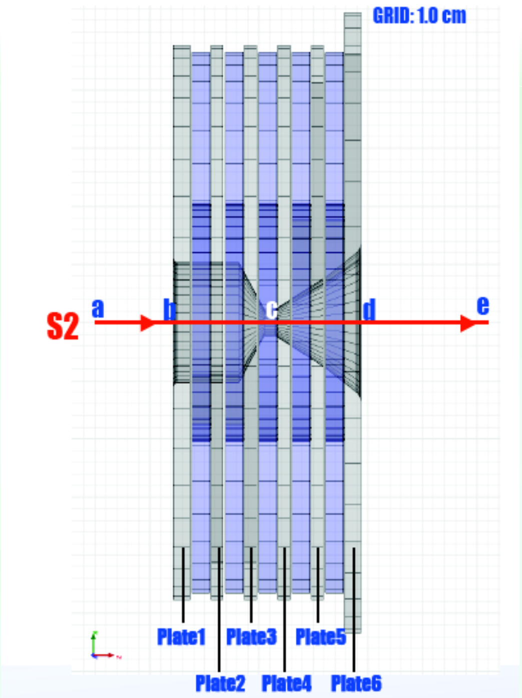
Acceptance on transverse momentum

$$p_t < \frac{a}{2} e \sqrt{B_f B_i} \qquad (2-27)$$

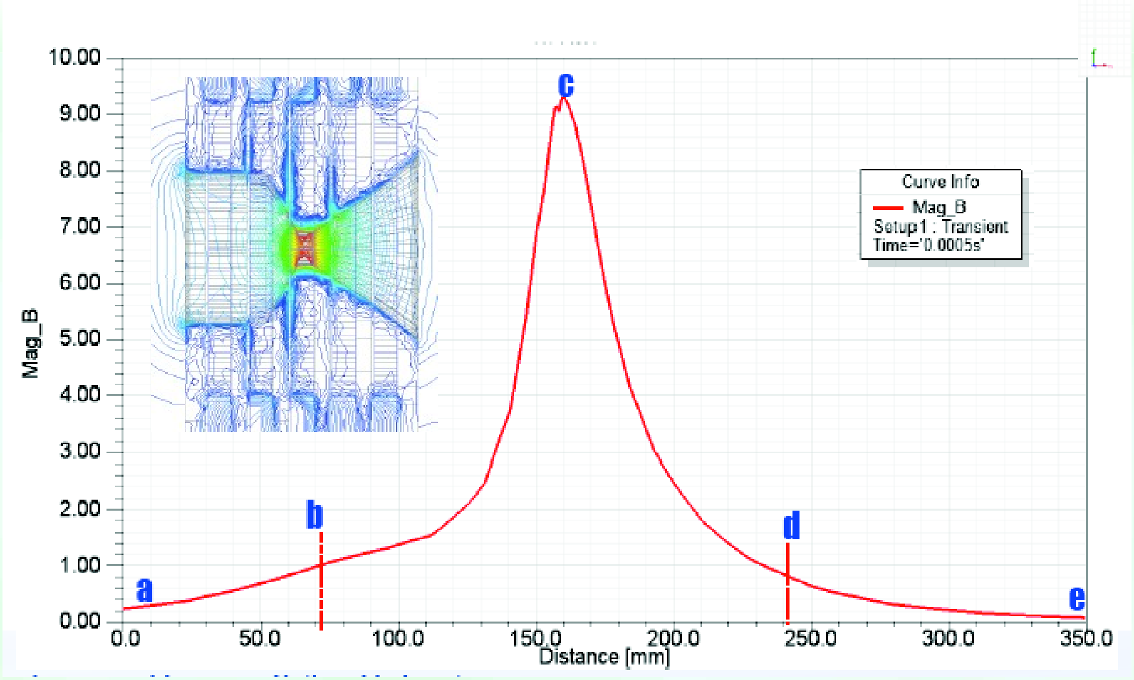
Acceptance on longitudinal momentum (adiabatic condition)

$$p_z < 0.5 \frac{eB_i}{\mu} \qquad (2-28)$$

# AMD(6)



|B| along S2 for the case of with Shaping Plates at t = 0.5 ms



- 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

# Parameters

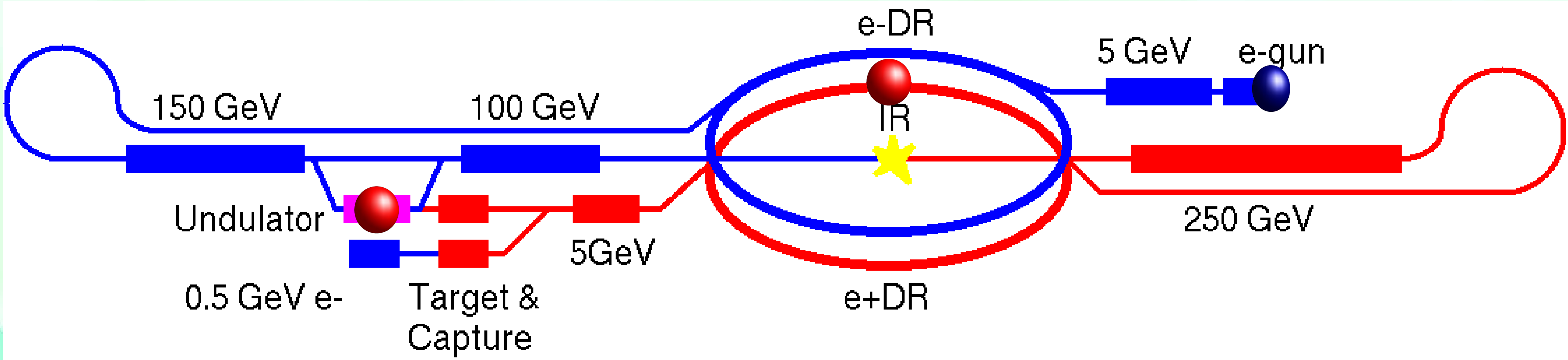
Positron Generation
Positron Source
Positron Capture
**LC Positron Source**
Summary

| Parameter | ILC | CLIC | Unit |
|---|---|---|---|
| Bunch charge | 3.20 | 0.60 | nC |
| Norm. emittance (εx+εy) | 0.09 | ? | m.rad |
| Bunch separation | 369 (670) | 0.5 | ns |
| Bunch number in macro pulse | 2625(1312) | 312 | number |
| Macro pulse length | 970(880) | 0.16 | μs |

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

# ILC Positron Source

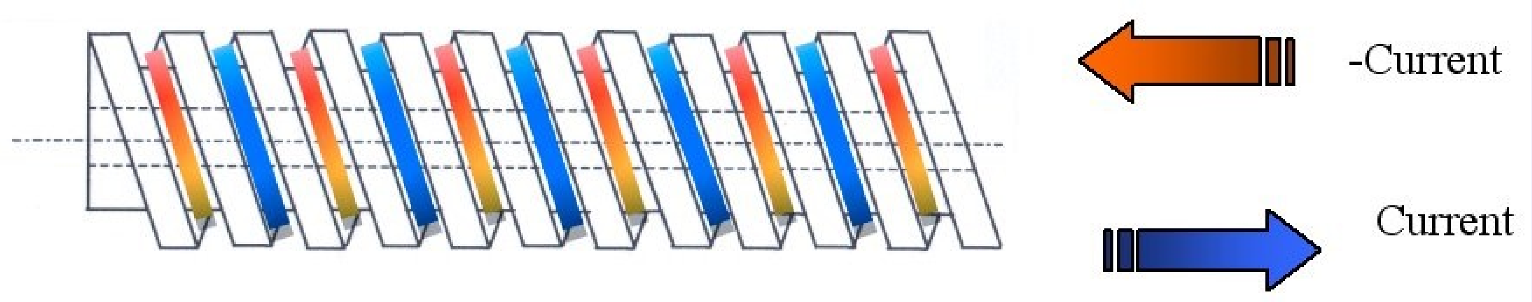
- 150GeV (250GeV for SB2009) electrons generate gammas.
- Gamma rays are converted to positron.
- A positron source driven by 0.5 GeV electron is a back up for high availability.
- A common 5 GeV positron booster.

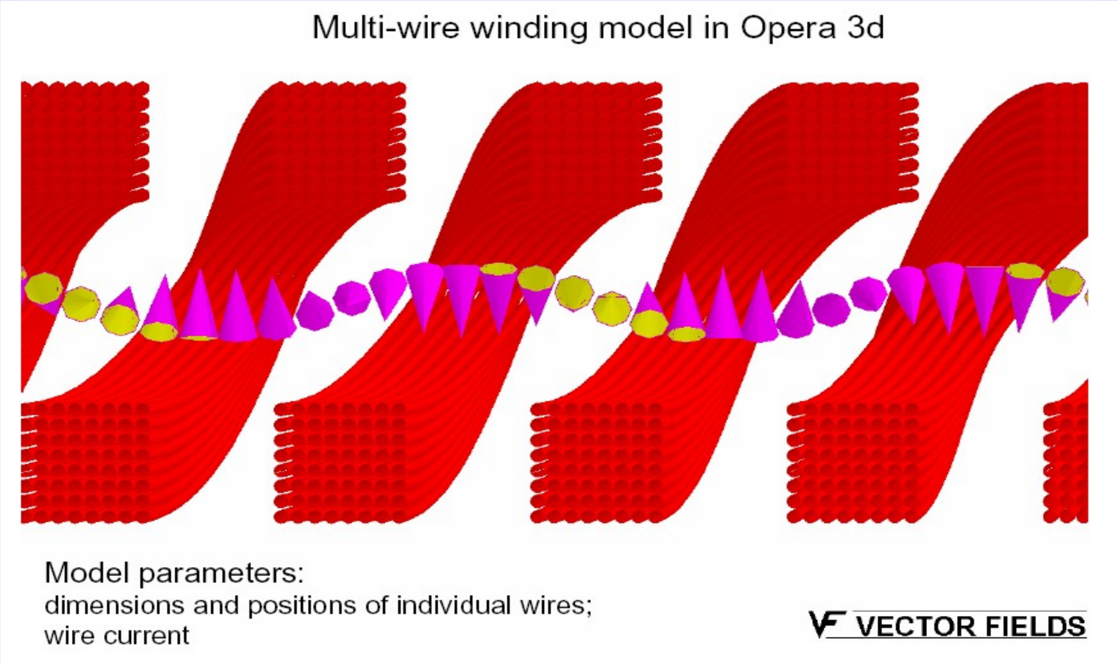


# System Specifications

| 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 (250) | GeV |
| Drive beam energy loss | 4.8 | GeV |
| Undulator length | 147 (231) | m |
| Polarization (upgrade with 300m und.) | 60 | % |

# Helical Undulator



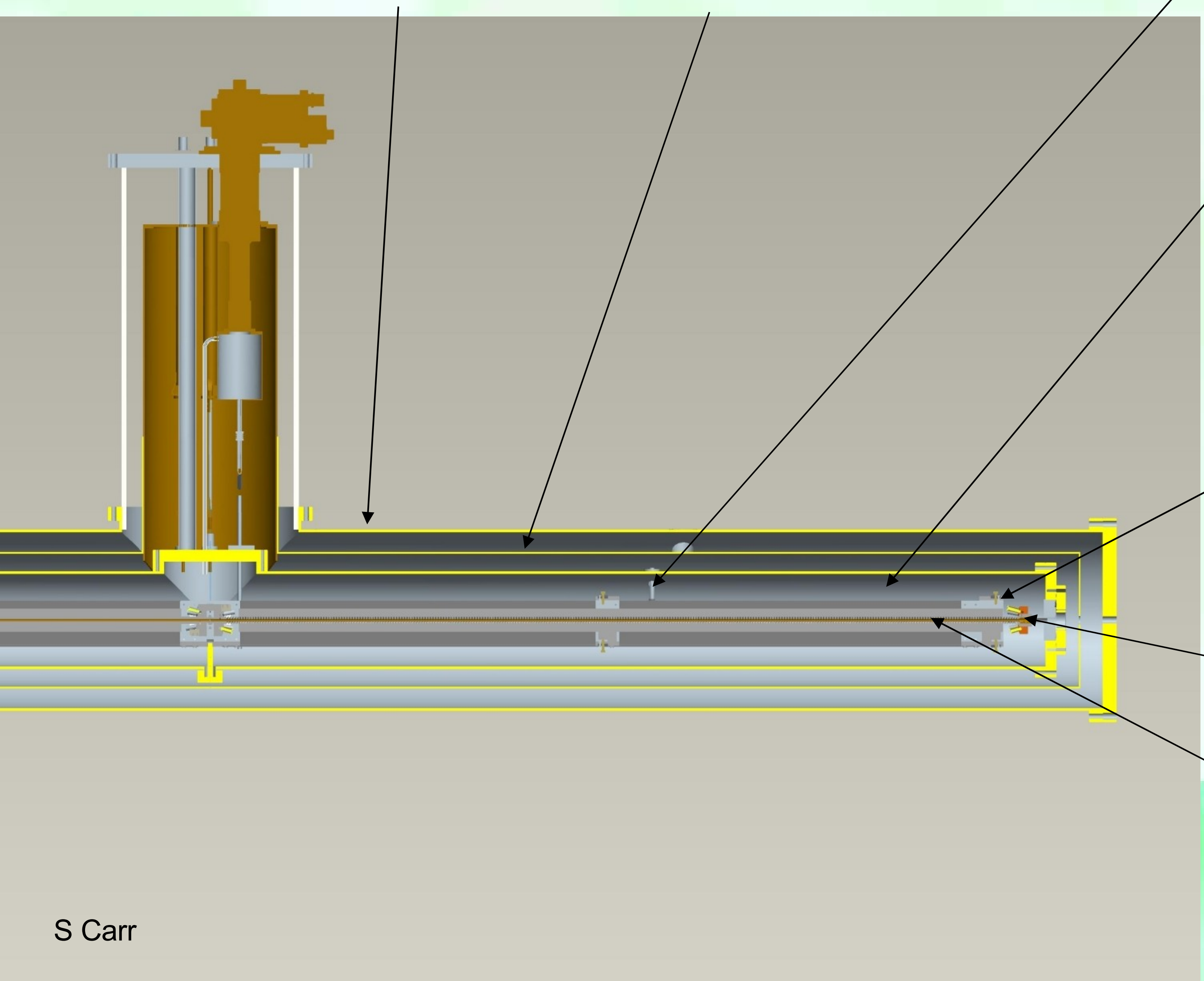


By Yury Ivanyushenkov

# 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 (231) | m |
| Beam Aperture | 5.85 | mm |
| Photon Energy (1st hrm) | 10.07 | MeV |
| Max. photon power | 131 | kW |

# Undulator Cryo-module



Stainless steel vacuum vessel with Central turret

50K Al Alloy Thermal shield. Supported from He bath

U beam Support rod

Stainless Steel He bath contains100L liq He. Supported by 4 rods attached to the vacuum vessel

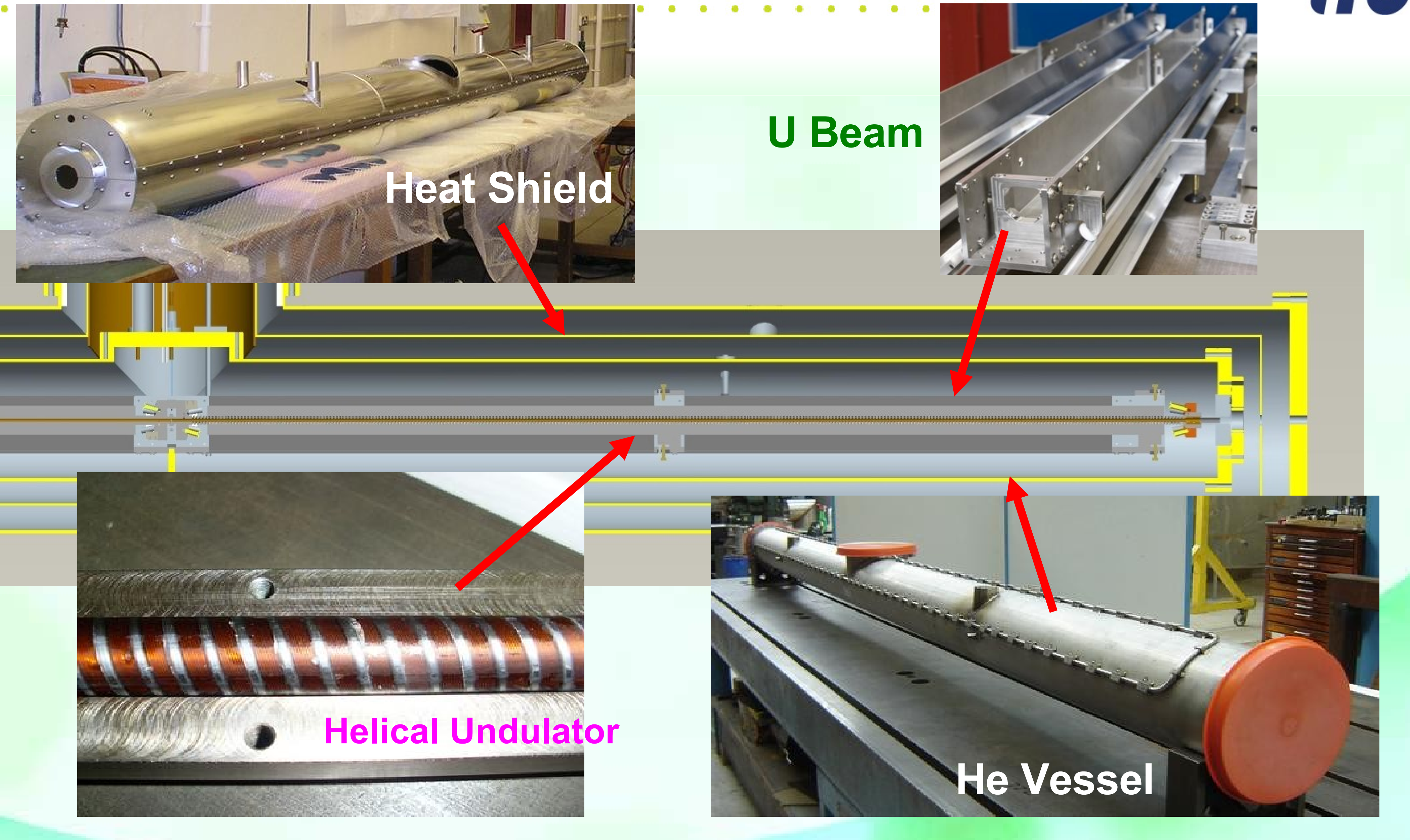
U Beam used to support/align the magnet.

Beam Tube

Magnet cooled to 4.2K by liq He in bath.

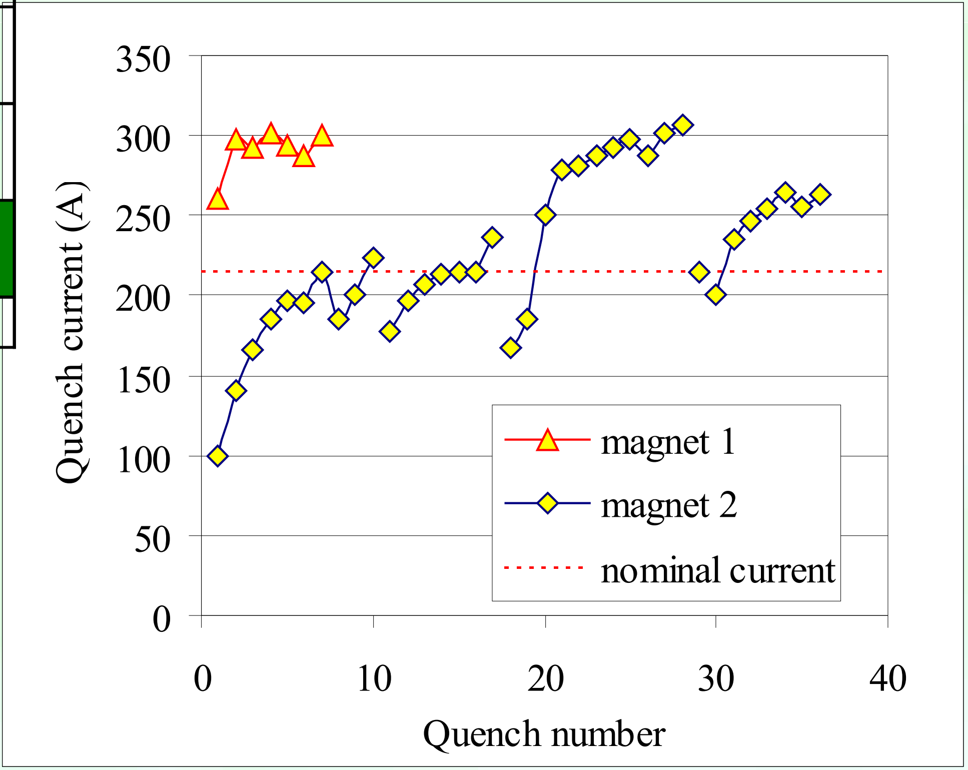
S Carr

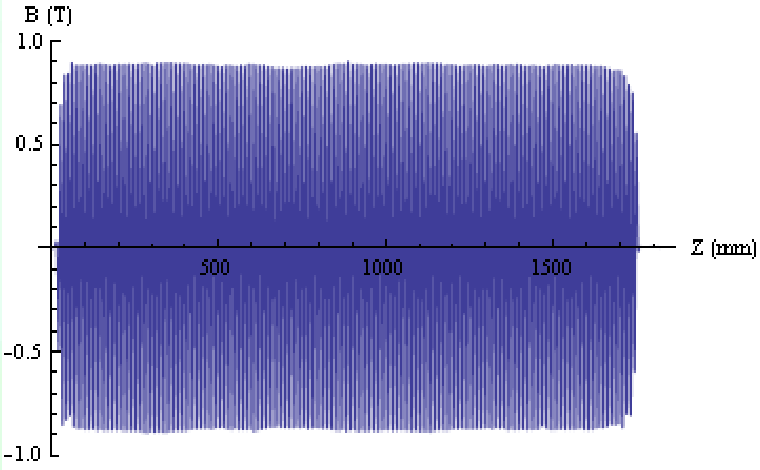
# Undulator Cryomodule (2)



# Undulator Test

Positron Generation
Positron Source
Positron Capture
**LC Positron Source**
Summary

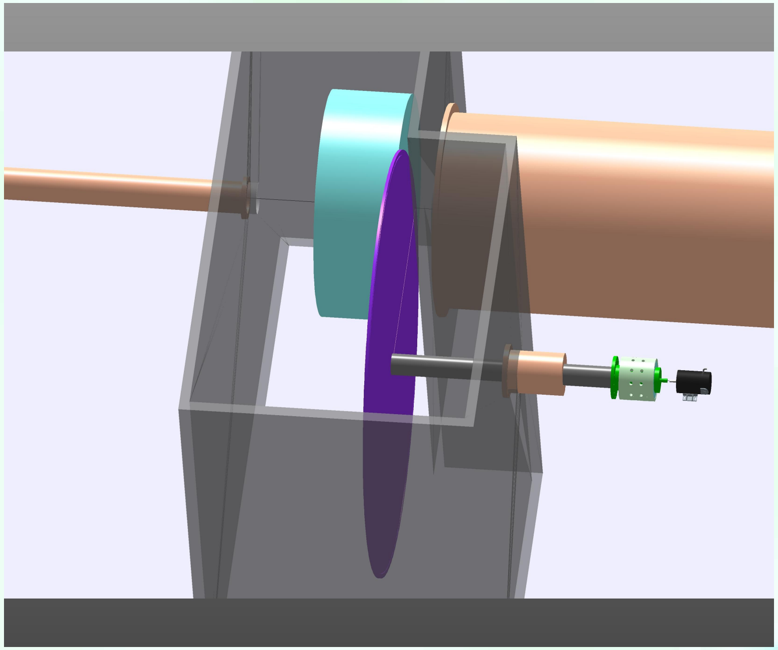


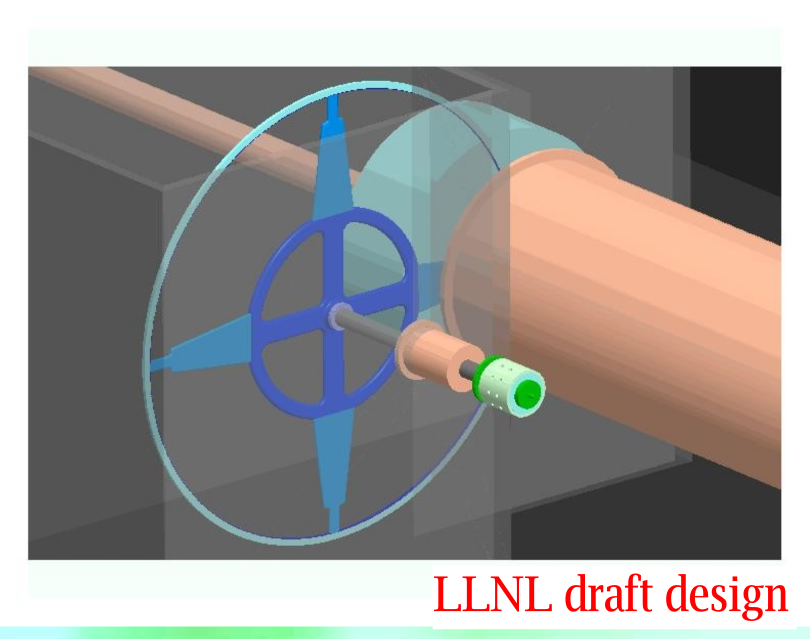


- All two magnets finally satisfied the specification.
- Field profile is measured by hall probe, showing a good quality.

# Target

- Target : Ti-6% Al-4% V with 0.4 $X_0$, rotating with tangential speed 100 m/s .
- Beam spot : 15 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?
- Vacuum seal is a technical issue.



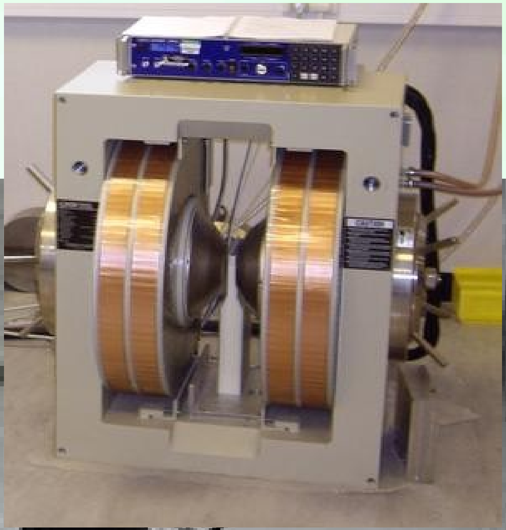


LLNL draft design

# Target Prototype

Positron Generation
Positron Source
Positron Capture
LC Positron Source
Summary

Experiment in Cock-croft Inst. UK

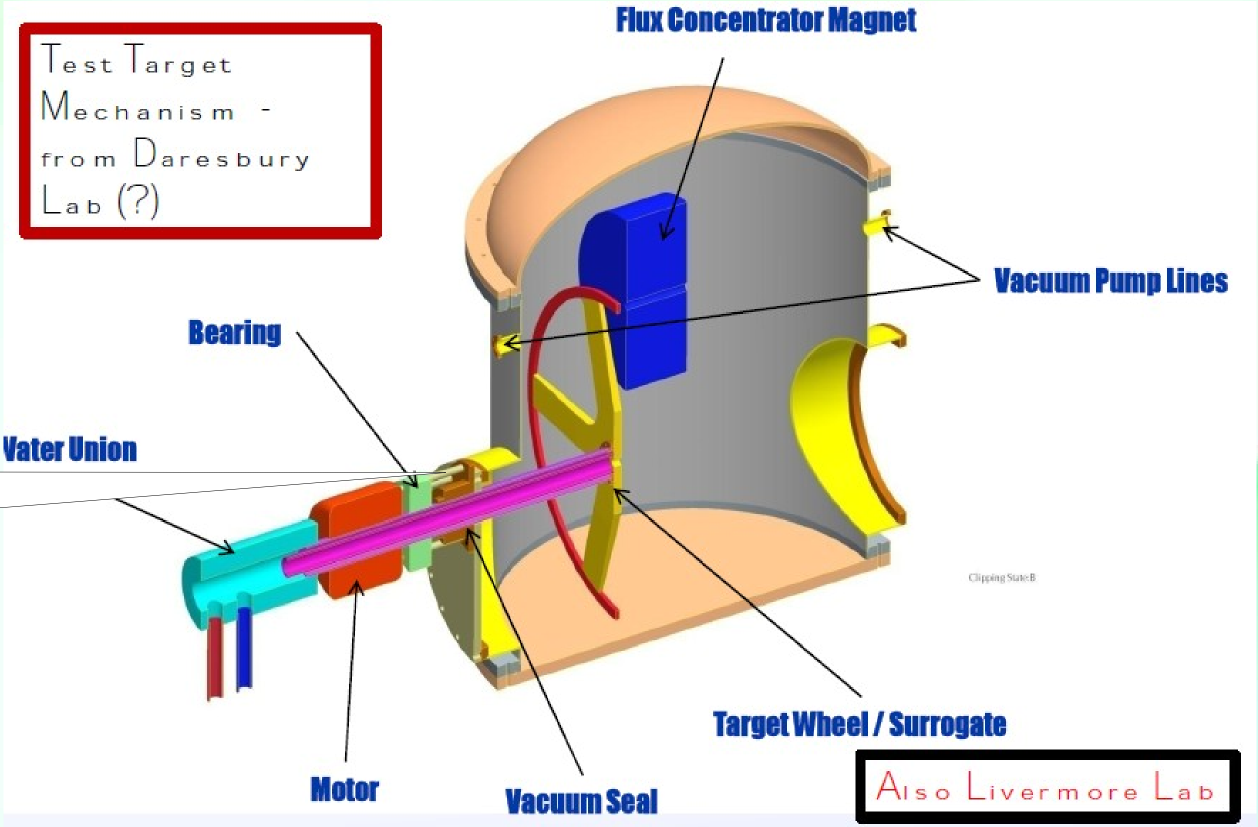


- Test with <1800rpm was done.
- Extrapolating to 2000rpm shows that wheel will be able to operate in immersed fields ~1T.

I. Bailey

# Vacuum Seal

- The rotating target is in ultra-high vacuum.
- Rotating rod must be sealed vacuum-tightly.
- Rotating target in vacuum for the test.



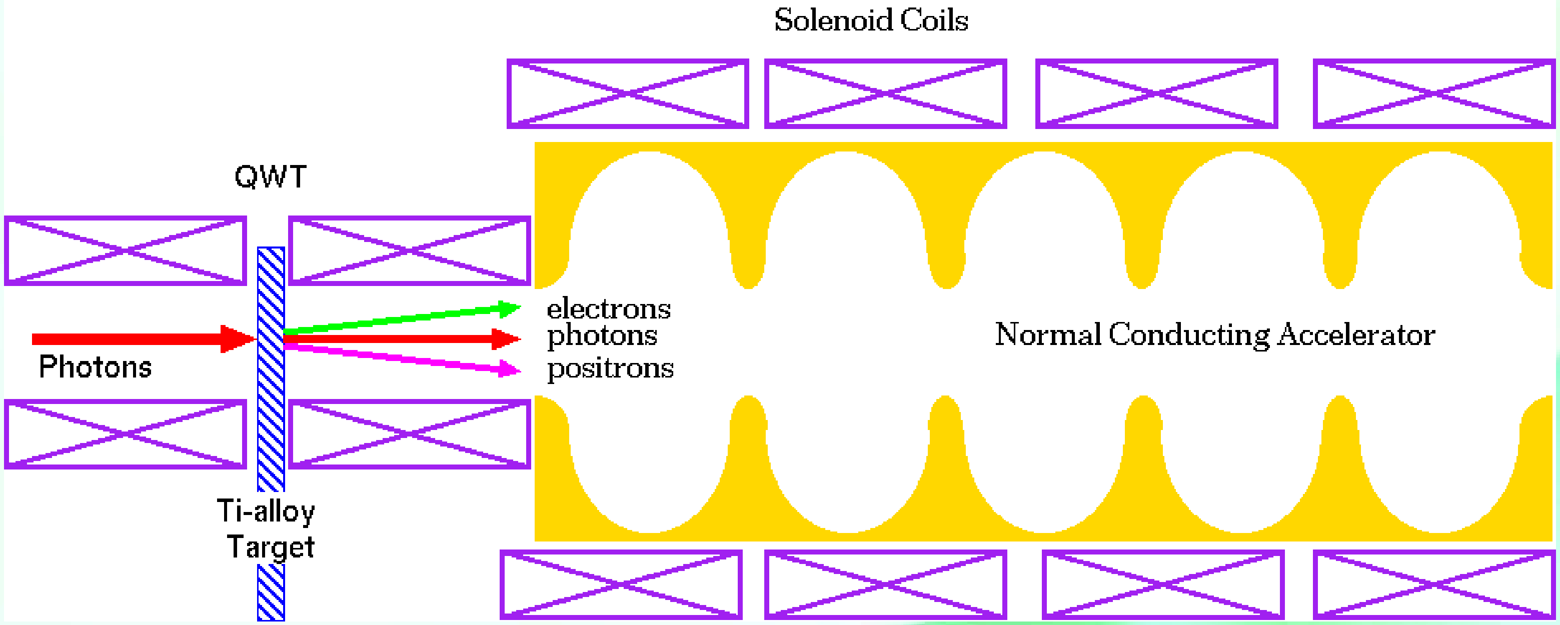
Test Target Mechanism - from Daresbury Lab (?)

Ferro-fluidic seal

Also Livermore Lab

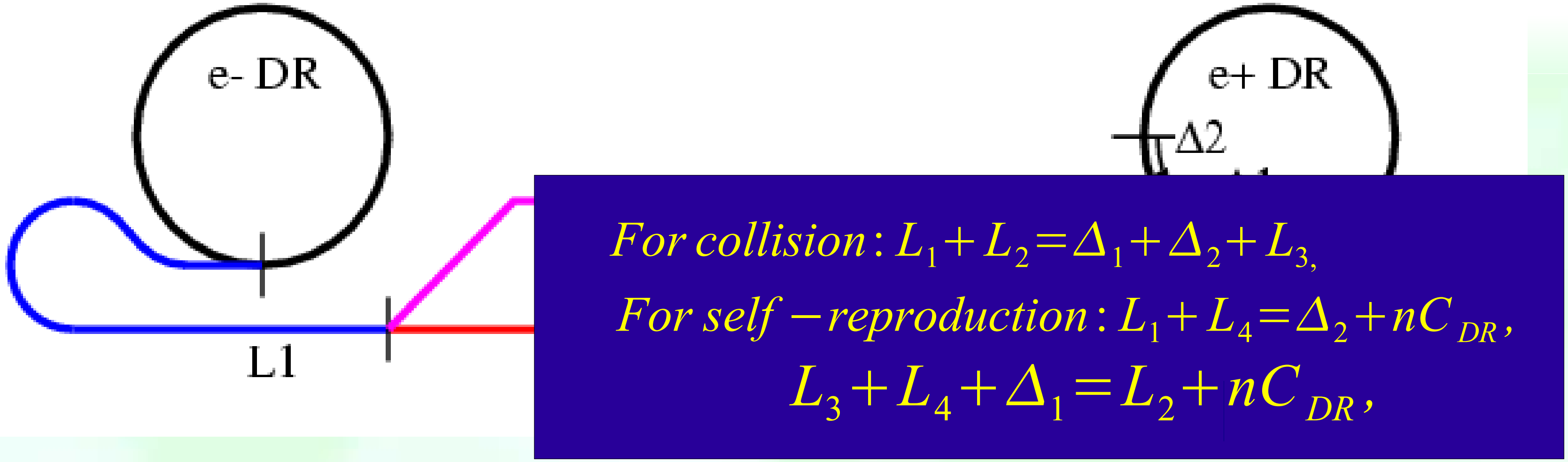
# Positron Capture

- QWT ($B_i$~1T, $B_f$~0.5T in 20cm): pulsed coil with bucking coil to shield magnetic field on target.
- It is replaced when AMD flux concentrator is technically matured.
- L-Band NC accelerator tube with 12 ~ 15 MV/m.



# Path length Condition

Positron Generation
Positron Source
Positron Capture
**LC Positron Source**
Summary



$$\mathit{For\ collision}: L_1 + L_2 = \Delta_1 + \Delta_2 + L_{3,}$$

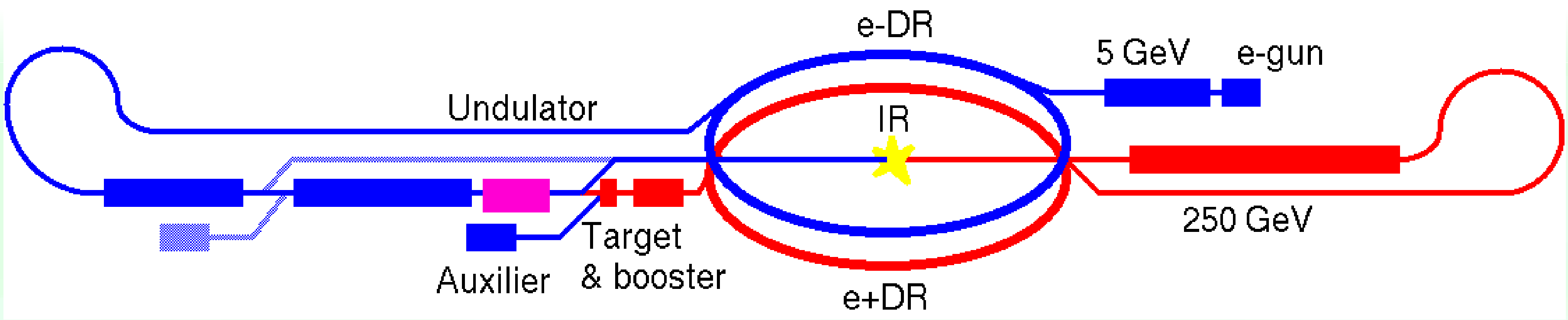
$$\mathit{For\ self-reproduction}: L_1 + L_4 = \Delta_2 + nC_{DR},$$

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

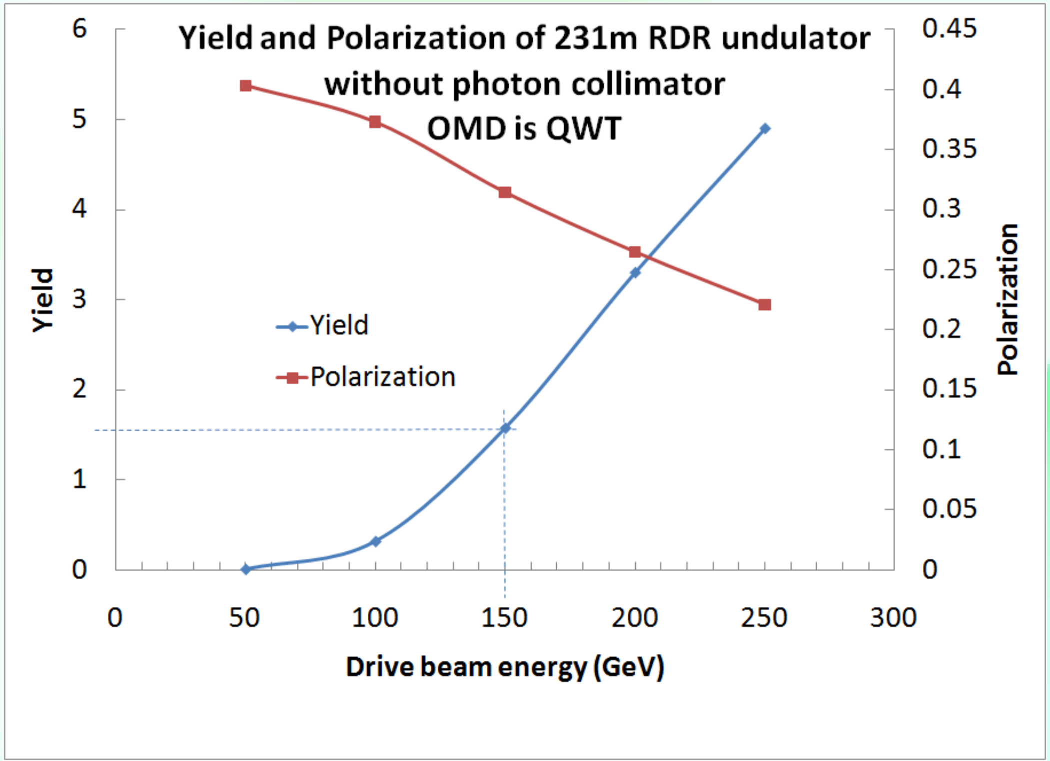
- Positron beam is generated by electron bunch.
- The generated positron must be wait 200ms in DR until the next collision.
- Generation and collision are performed simultaneously. The DR bucket must be vacant for the generated positron.
- To fulfill the condition with a flexibility, the path-length must satisfy the self-reproduction condition.
  - Positron is stored in the same DR bucket as the collision partner (positron) of the electron, which generates the new positron.

# Positron Yield in SB2009

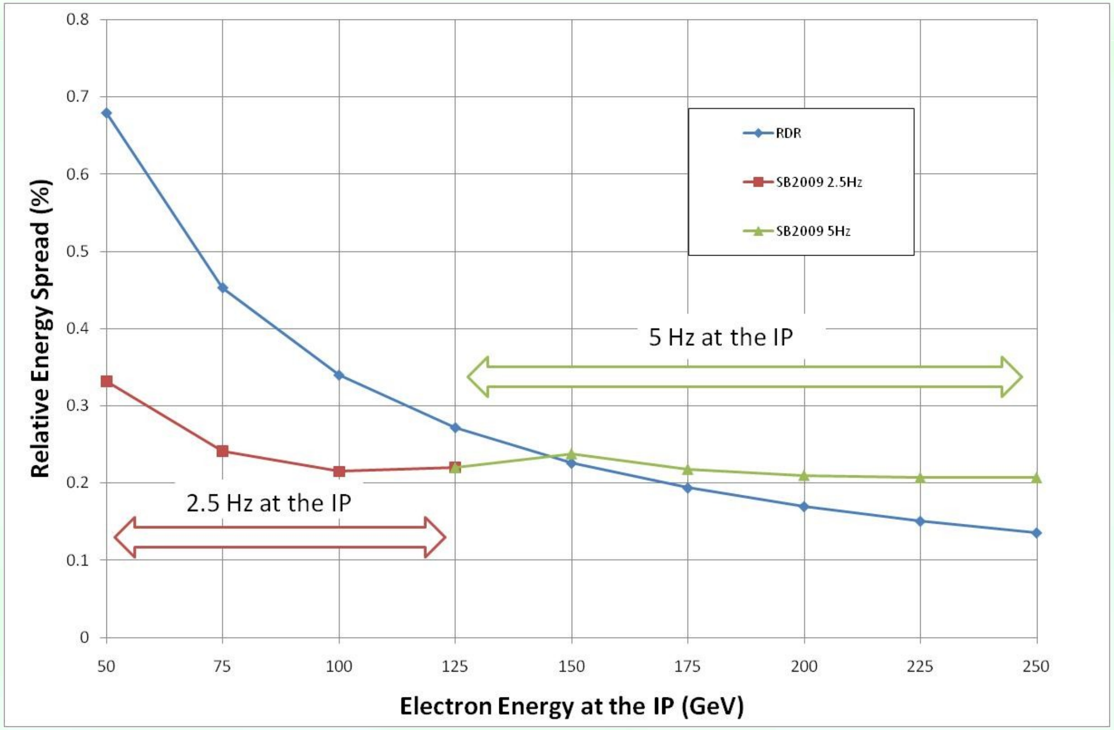
Positron Generation
Positron Source
Positron Capture
LC Positron Source
Summary



- In the laest configuration (SB2009), the undulator is moved to the end of the linac.
- Drive energy for undulator is same as the collision energy.
- Low positron yield at the low energy running.
    - Alternate operation
    - Dual linac operation



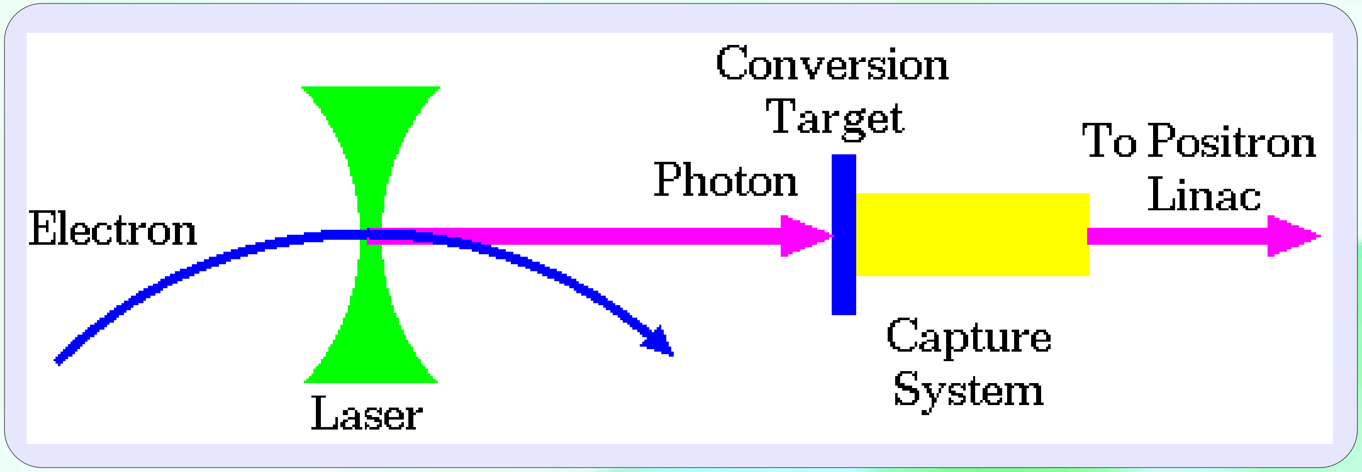
# Electron energy spread



- The energy spread is increased by the undulator radiation.
- In RDR, it is 0.15% at 250GeV. It enhances by deceleration at lower energy.
- In SB2009, the enhancement is not occurered.

# Laser Compton Scheme

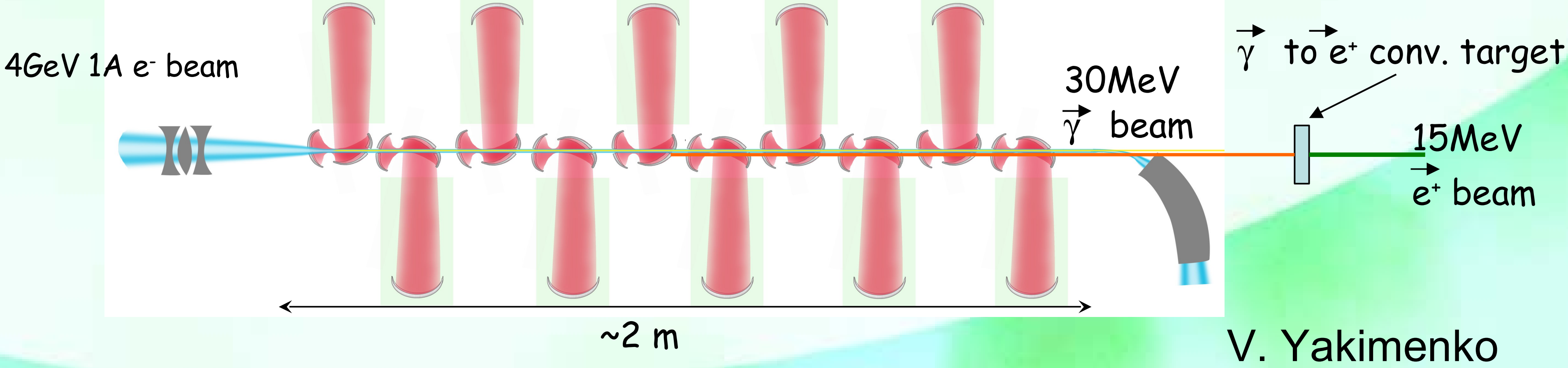
- Several proposals with different electron drivers and photon (laser) sources.
  - Storage ring, ERL(Energy Recovery Linac), Linac
  - Nd:YAG, CO2 + Optical cavity,
- The required electron energy is a few GeV and a dedicated electron driver is reasonable,
- But it is a technical challenge to obtain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



# Linac Laser Compton

Positron Generation
Positron Source
Positron Capture
LC Positron Source
Summary

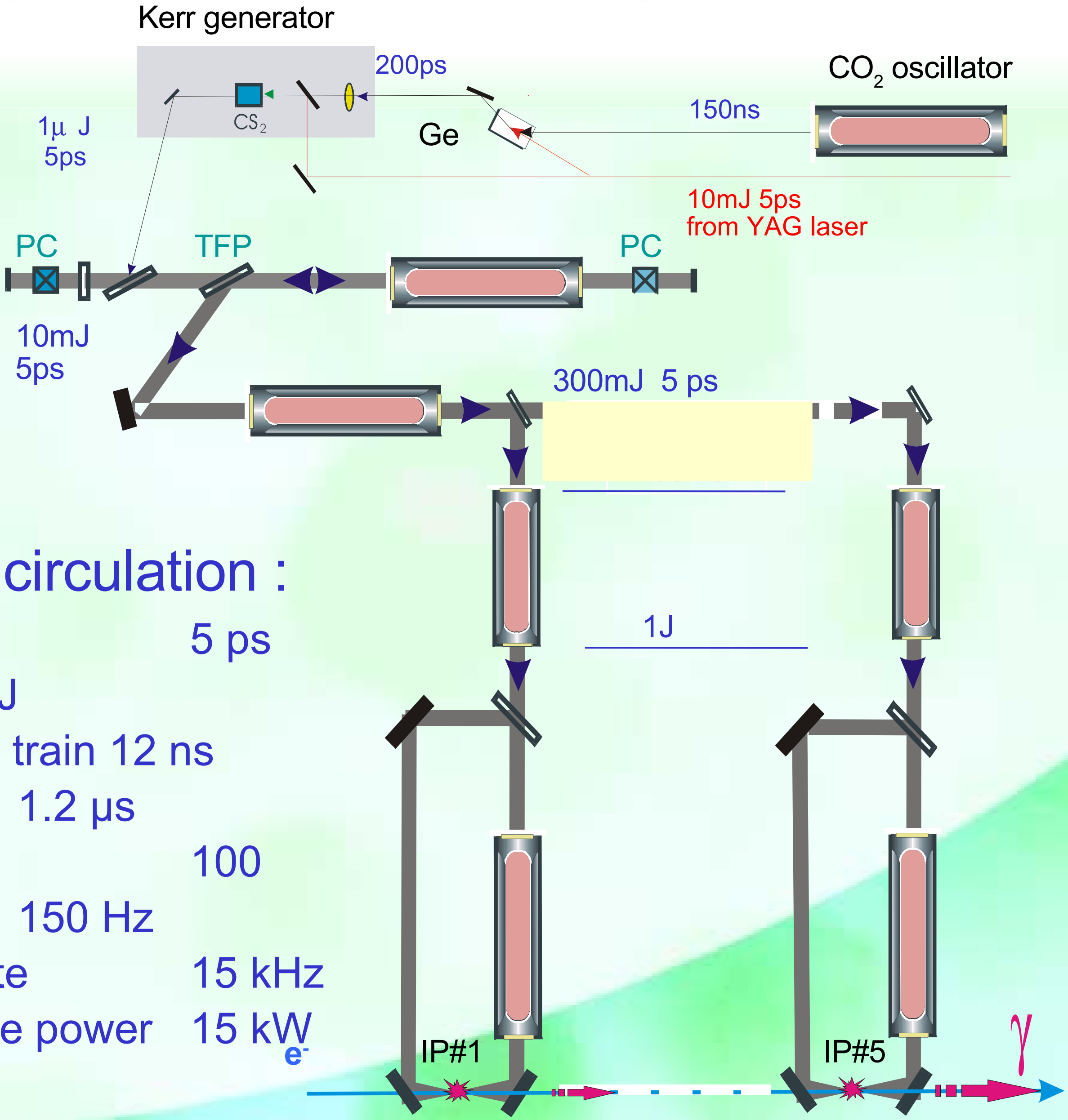
- Polarized gamma-ray beam is generated in the Compton back scattering inside optical cavity of $CO_2$ laser beam and 4 GeV e-beam produced by linac.
- Laser system relies on the commercially available lasers but need R&D for high repetition operation.
- Ring cavity with laser amplifier realizes the $C0_2$ laser pulse train.



V. Yakimenko

# Linac Laser Compton (2)

Linac Laser Compton scheme is designed with $CO_2$ laser system.



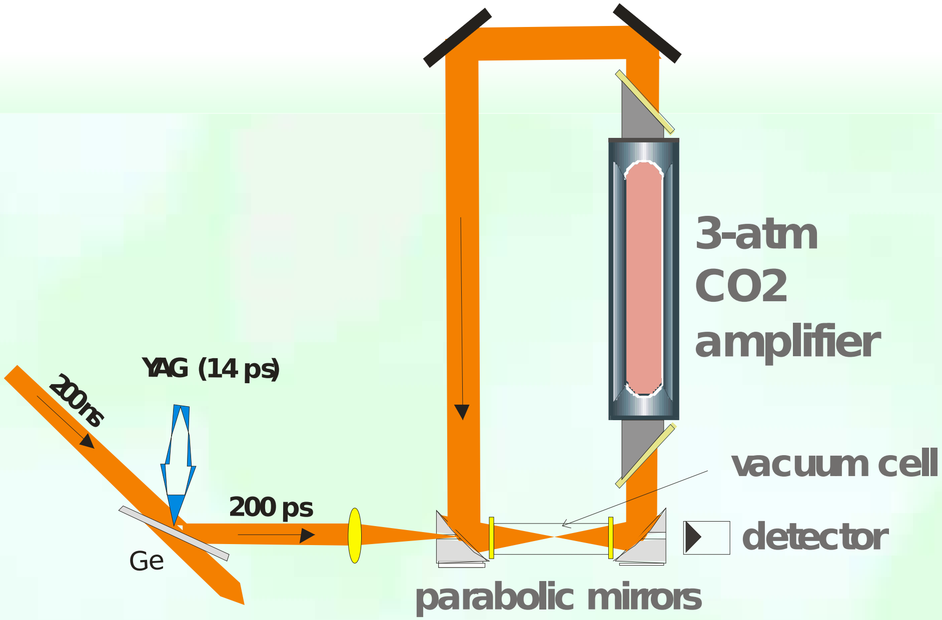
intra-cavity pulse circulation :

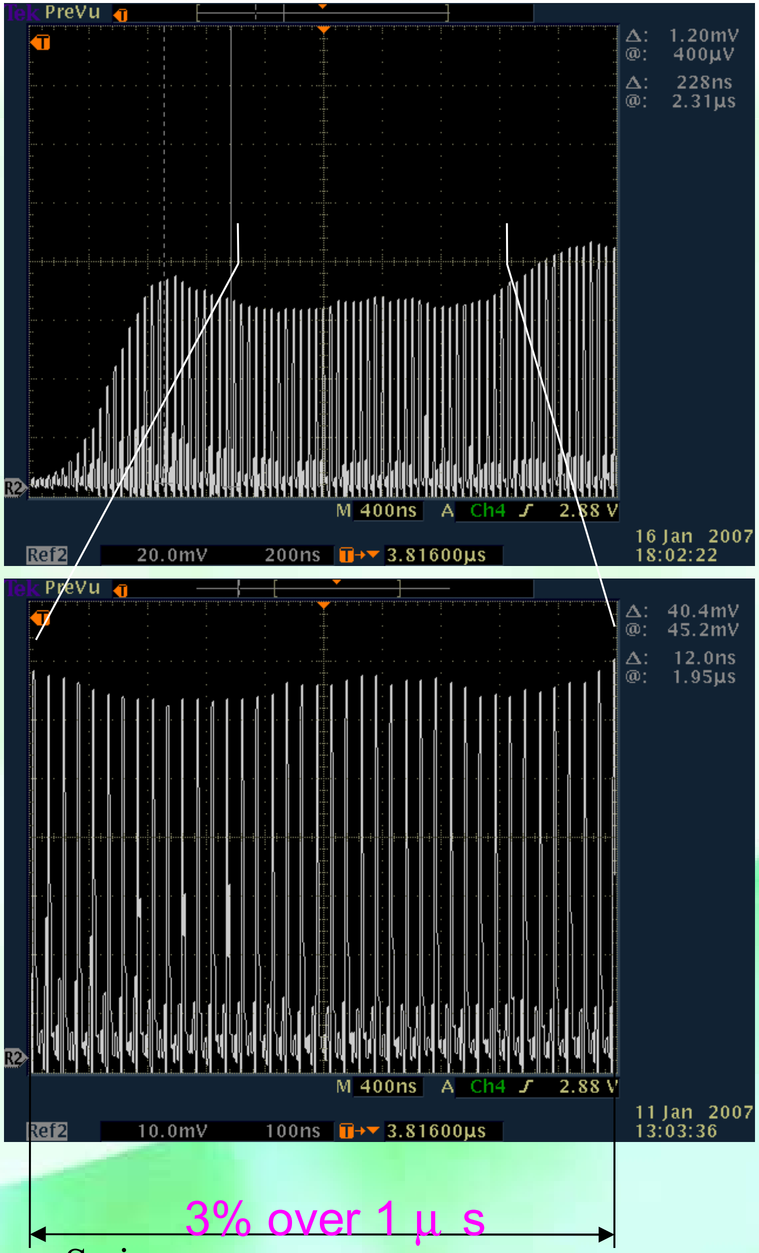
| | |
|---|---|
| – pulse length | 5 ps |
| – energy per pulse | 1 J |
| – period inside pulse train | 12 ns |
| – total train duration | 1.2 μs |
| – pulses/train | 100 |
| – train repetition rate | 150 Hz |
| – Cumulative rep. rate | 15 kHz |
| – Cumulative average power | 15 kW |

BROOKHAVEN NATIONAL LABORATORY

V. Yakimenko, I. Pogorelsky

# CO2 Laser Test





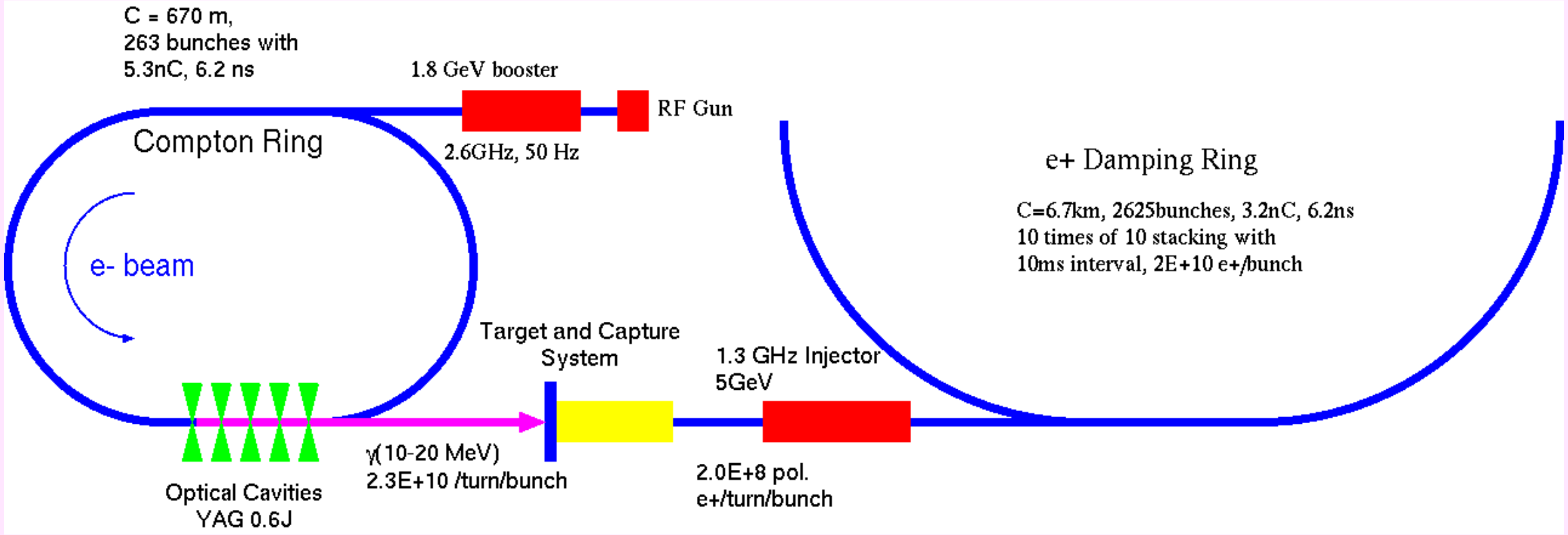
## Observations:

- Optical gain over 4 µs.
- Single seed pulse amplification continues to the end.
- 3% flatness over 1µs.

V. Yakimenko, I. Pogorelsky

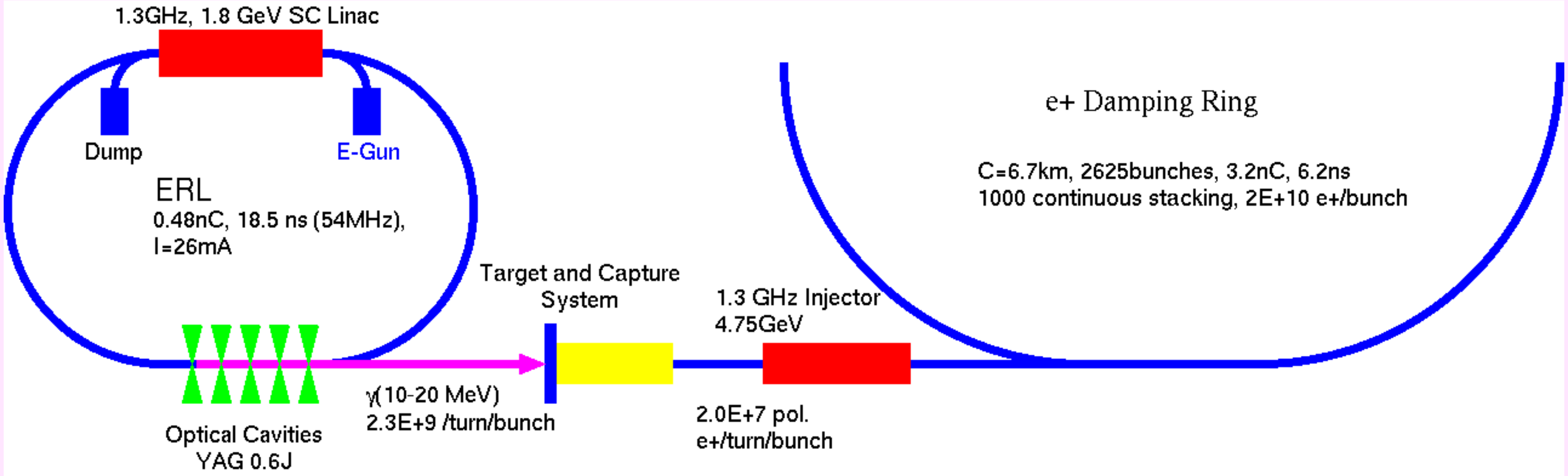
# Compton Ring

- 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.

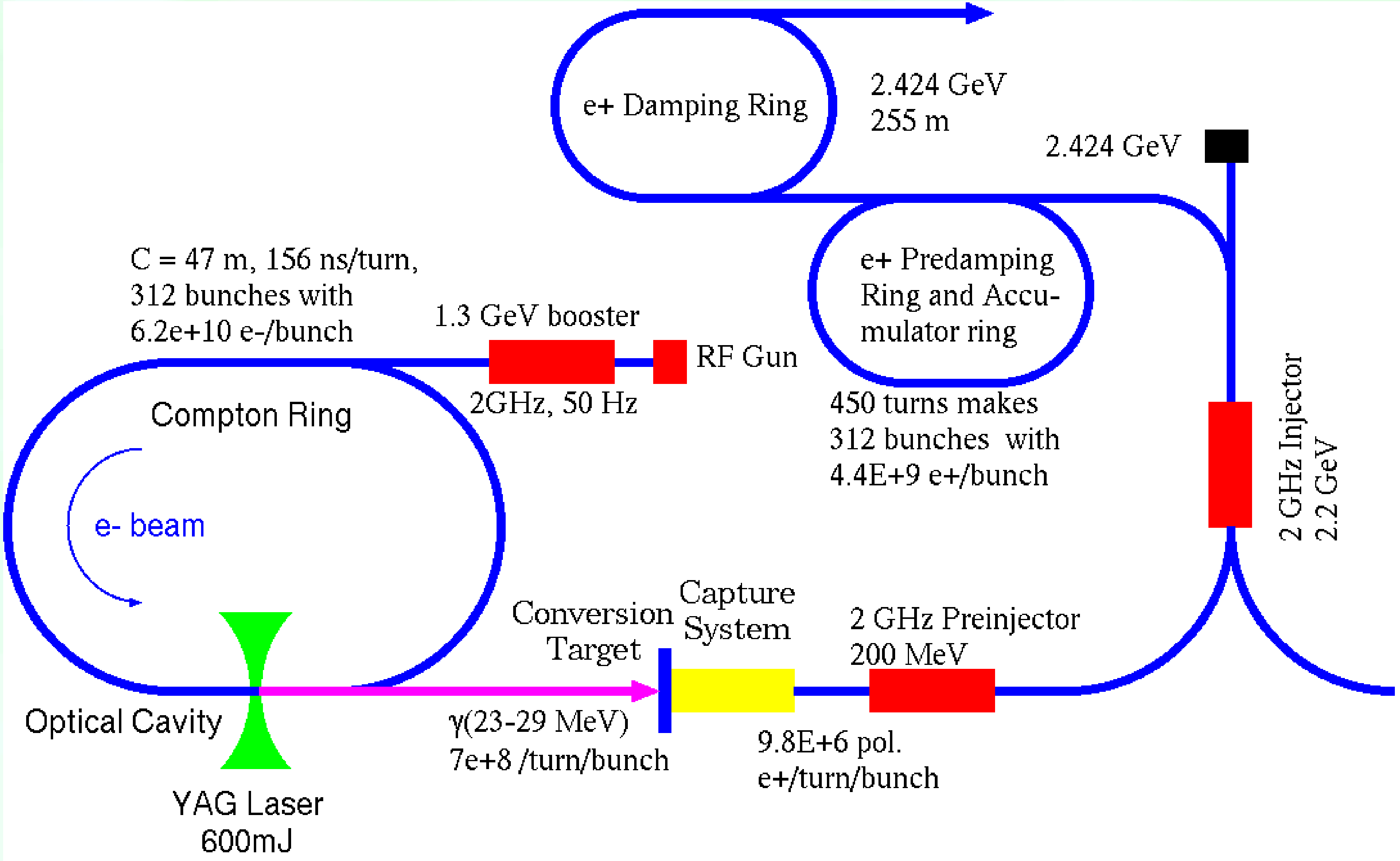


# ERL

- ERL(Energy Recovery Linac) is employed as the dedicated electron driver.
  - 0.48nC, 18.5ns (54MHz) ~ 26mA, E=1.8GeV
  - $N_\gamma$=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



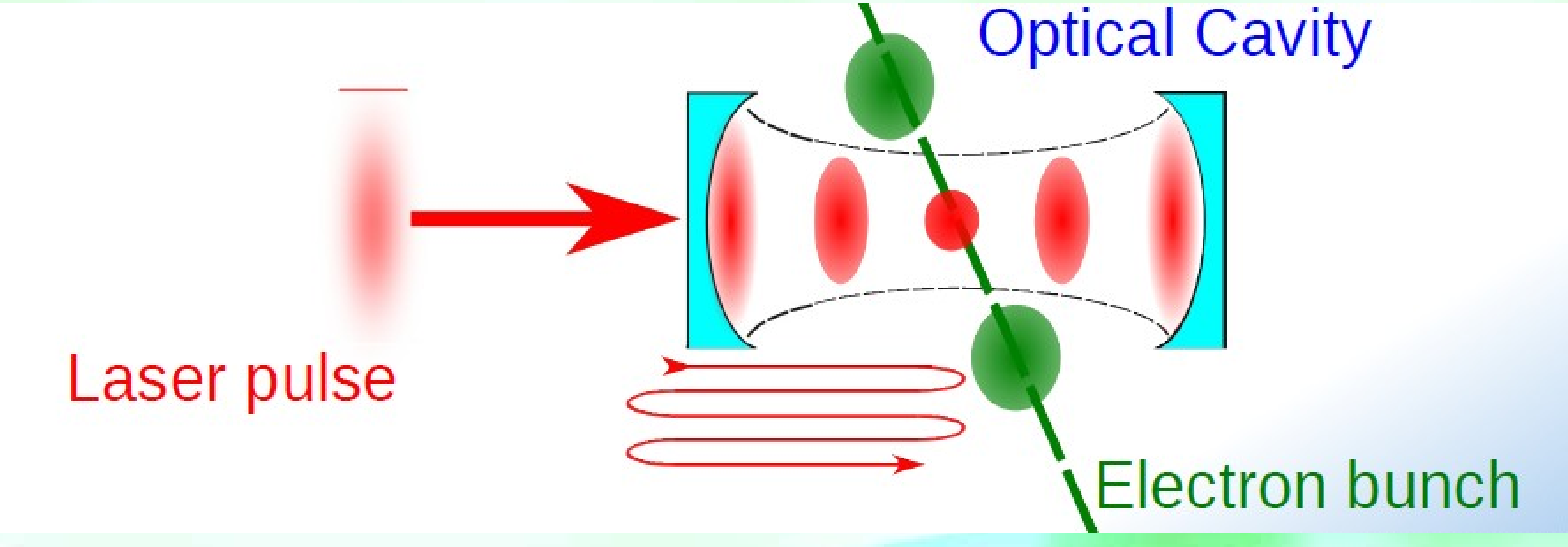
# Pulse Stacking Cavity

Positron Generation
Positron Source
Positron Capture
LC Positron Source
Summary

- ► Many laser pulses are stored and the power is enhanced by the pulse stacking. The enhancement is essential.
- ► Pulsed laser is stacked when appropriate conditions of the external cavity  are satisfied.

$$L_{cav} = nL_{rep}$$

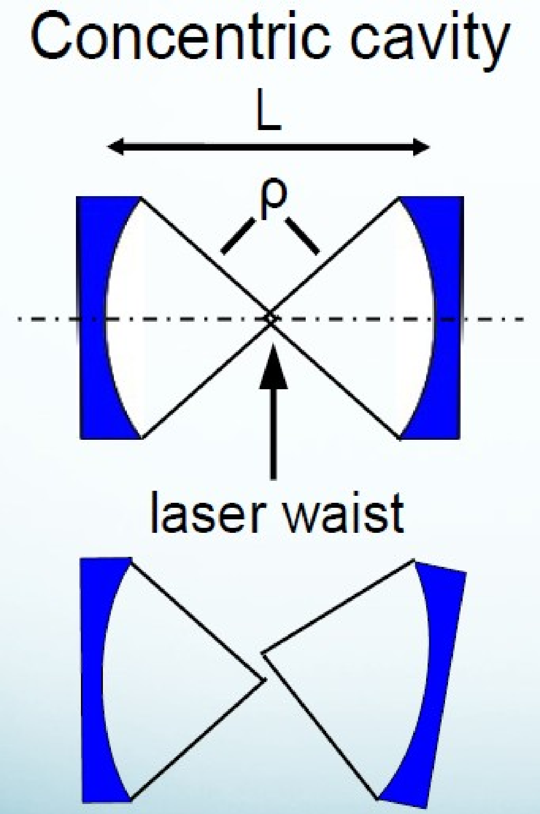
$$L_{cav} = m\frac{\lambda}{2}$$

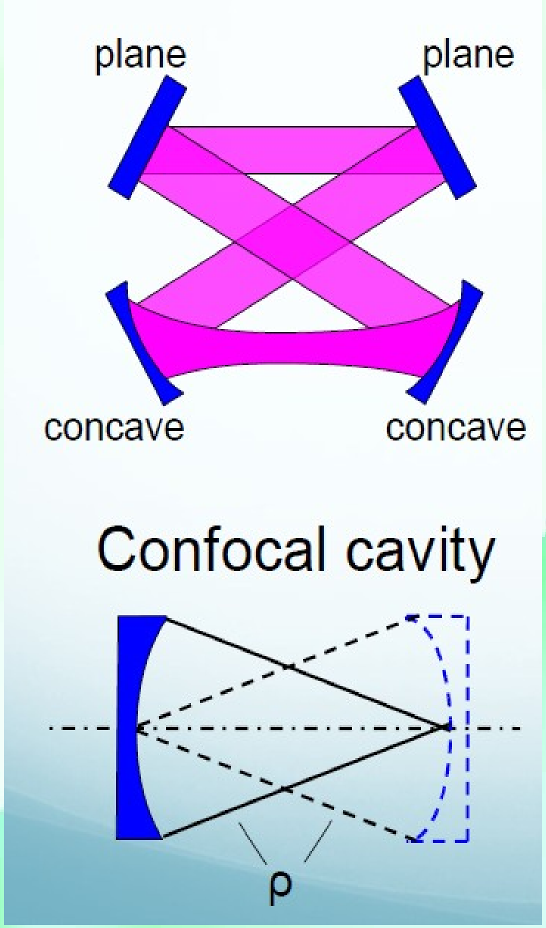


# How many mirrors? (1)

Positron Generation
Positron Source
Positron Capture
LC Positron Source
Summary

- 2 mirrors:
  - Simple,
  - unstable due to concentric geometry,
  - hard to obtain high finesse.
- 4 mirrors:
  - Complicated,
  - stable due to confocal geometry,
  - easy to obtain high finesse.





# How many mirrors ?(2)

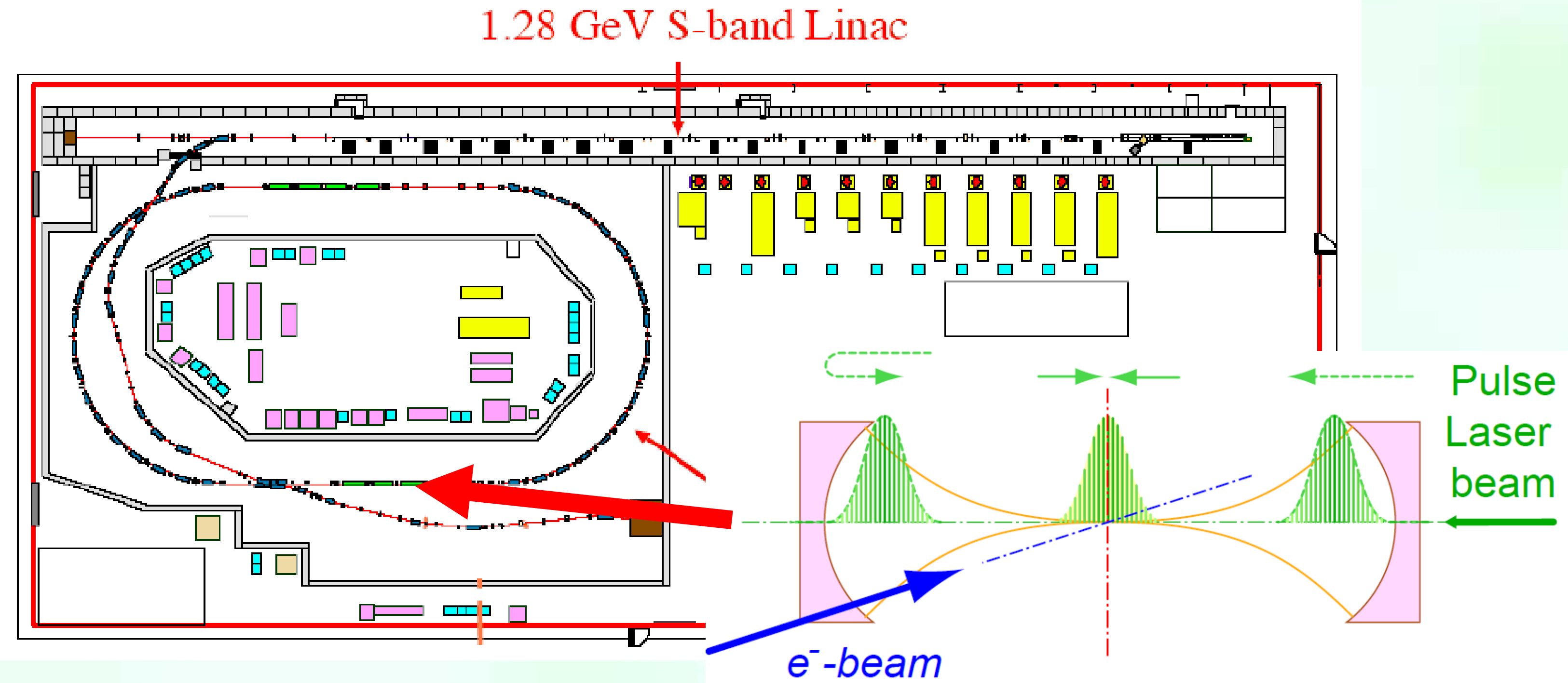
- KEK-ATF and LAL advance experiments with external cavity to stack laser beam.
- Goal is to achieve high enhancement & small beam spot size.
  - LAL cavity has theoretically high enhancement, but needs more complicated control.
  - KEK cavity has less enhancement, but its control is simpler.

| Lab. | LAL | KEK |
|---|---|---|
| Cavity | 4-mirror confocal | 2-mirror concentric |
| Finesse | 10000 | 1000 |
| Waist size (2σ) | <20um | 60um |

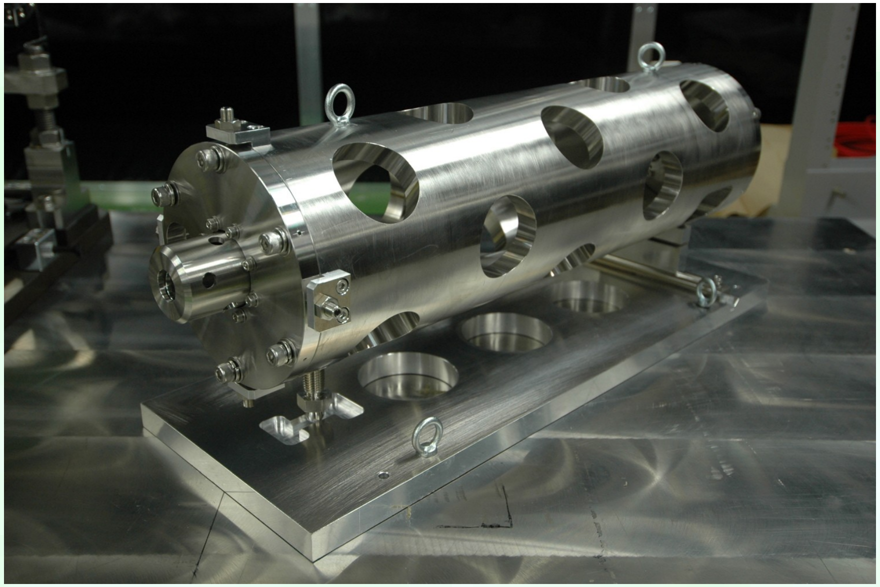
# KEK-ATF experiment (1)

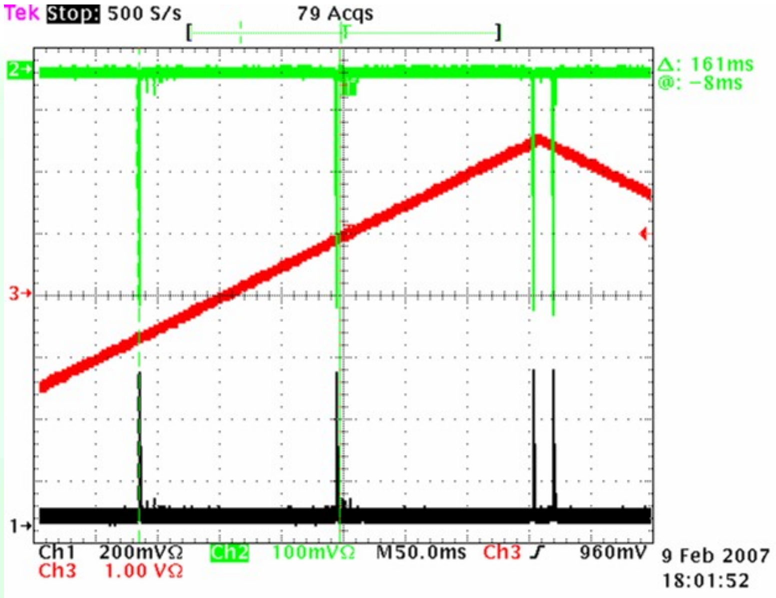
Positron Generation
Positron Source
Positron Capture
LC Positron Source
Summary

- ► Pulse train from 10 W YAG:VAN 357 Mhz mode-lock laser is stored in an optical cavity.
- ► $L_{cav}$=420 mm, crossing angle 12 deg.
- ► R=99.7%, 1000 finesse.
- ► 2σ=60μm.
- ► Laser-Compton collision with stored electron beam.



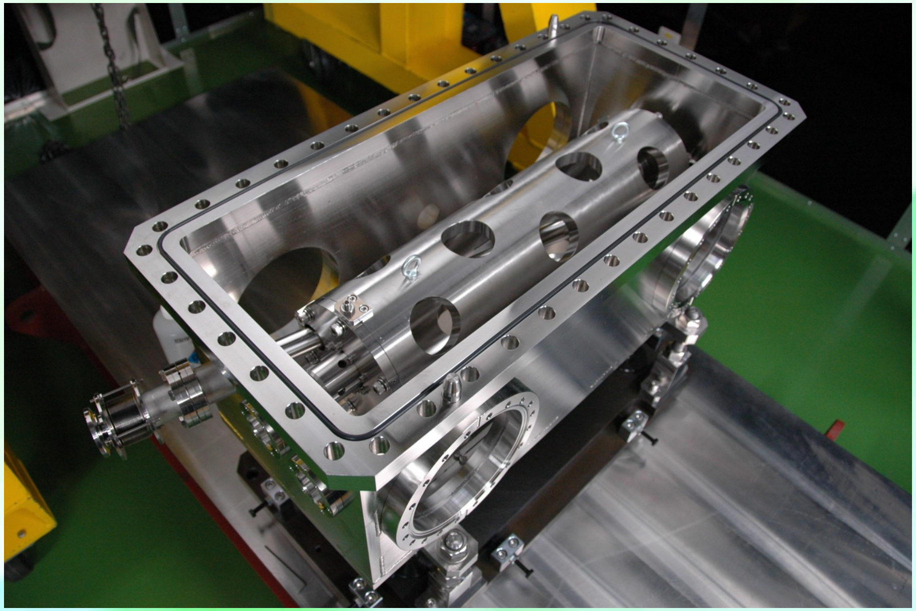
# KEK-ATF experiment (2)





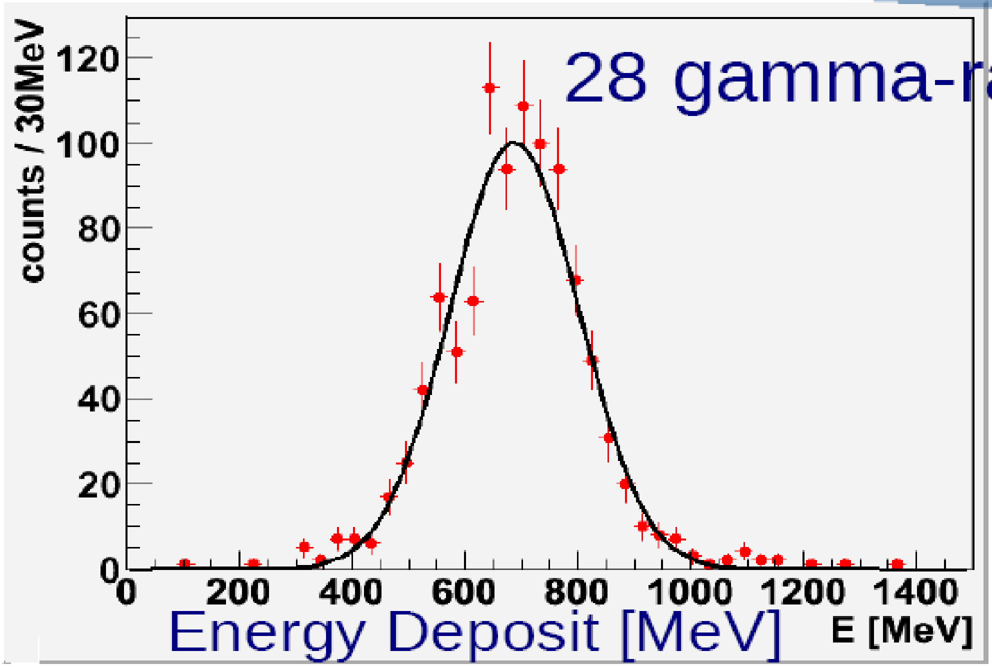
Laser Power

- ► Beam waist achieved inside the cavity is stably about 60μm.
- ► Cavity is “locked” for synchronization with the laser pulse.
- ► Enhancement ~ 760.
- ► 1.48kW stored power.



# KEK-ATF experiment (3)

## Observed Gamma-ray Spectrum



e- ring opr. mode
20 bunches / train

We observed 28.1±0.1 gamma-rays / train.
All solid angle → 60 gamma-rays / train

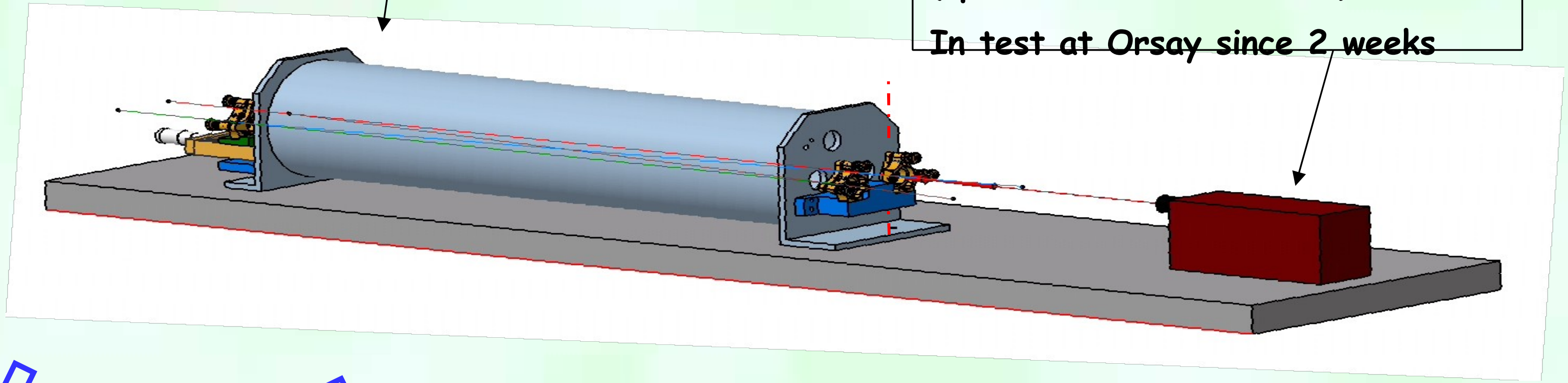
→ $60 \times 2.16$MHz ~ $1.2 \times 10^8$ [gamma / second]
Revolution

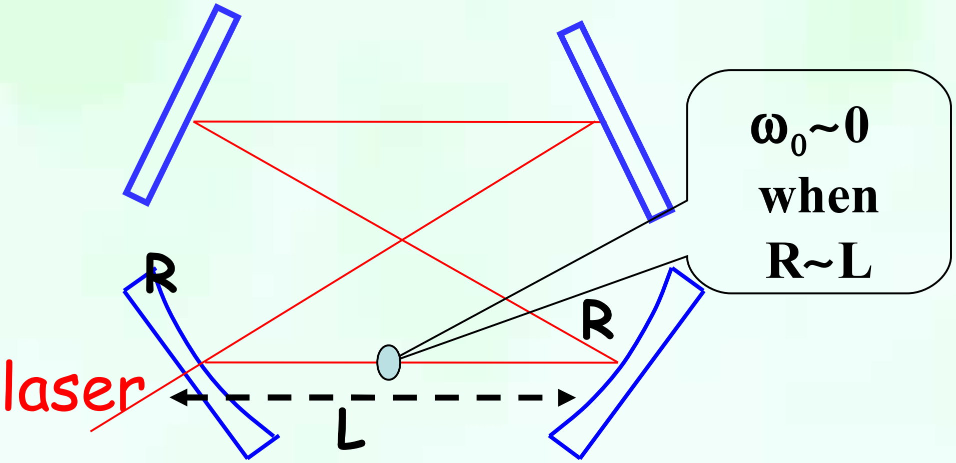
S. Miyoshi. Posipol09

# LAL 4 mirrors cavity (1)

Cavity vessel under construction in the LAL workshop

Cw laser diode in extended cavity config (optical feedback forseen)
In test at Orsay since 2 weeks



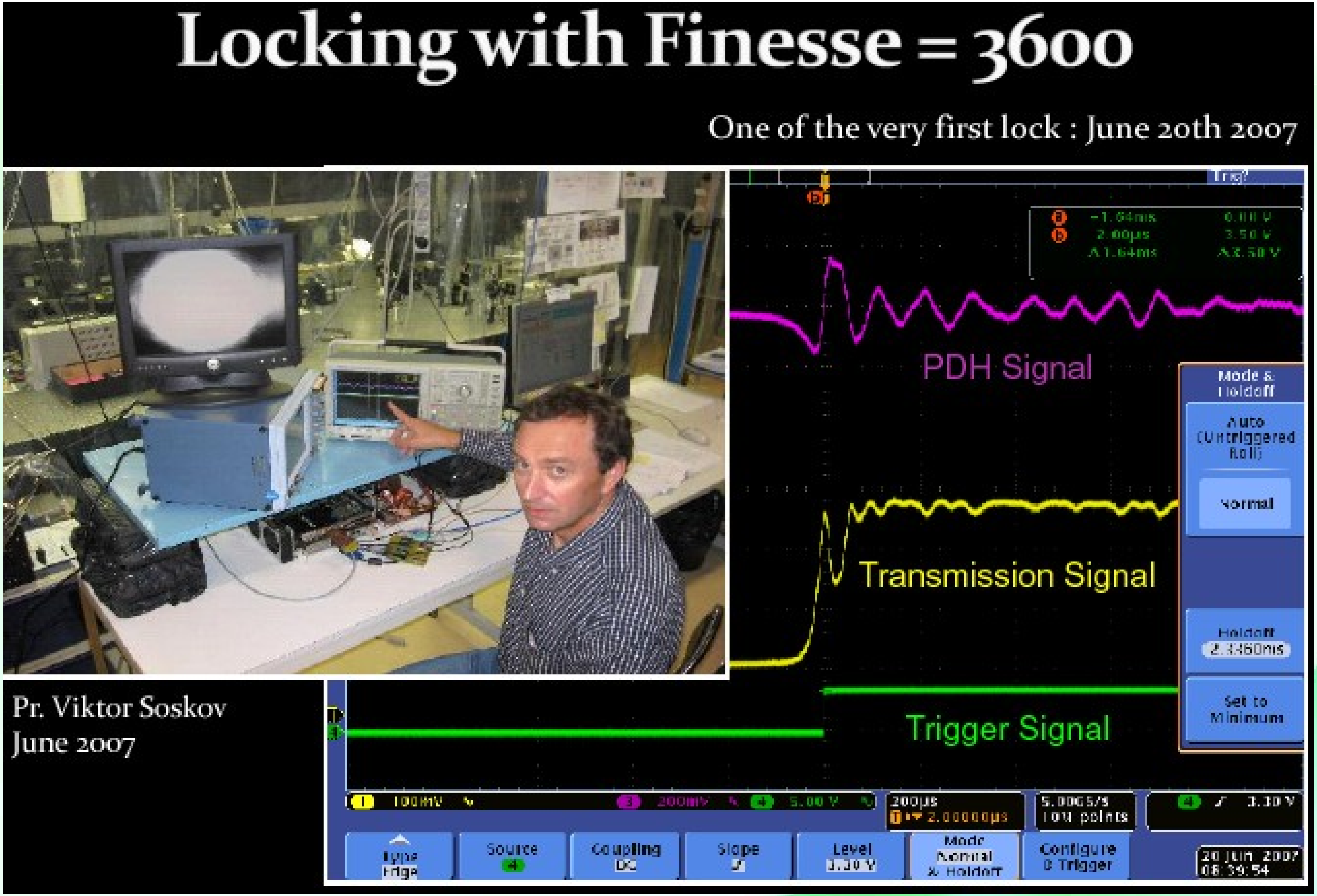


## 4 mirror non planar cavity

- Reduction of astigmatism
- Circular polarisation much less sensitive to mirror misalignment
- Spot size on focal point is adjusted independently from synchronization.

**by F. Zomer (LAL)**

# LAL 4 mirrors cavity (2)



## Locking with Finesse = 3600

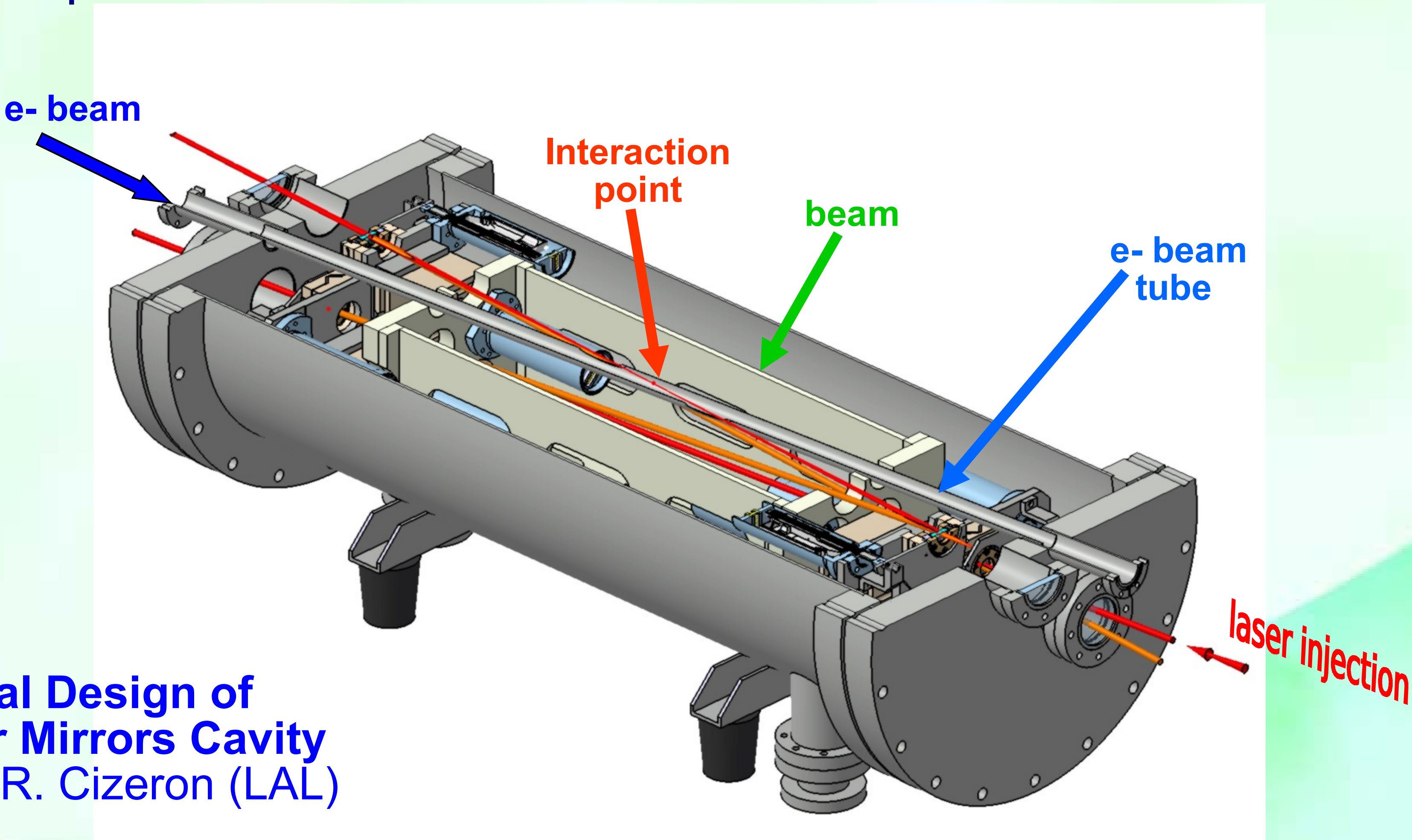
One of the very first lock : June 20th 2007

Pr. Viktor Soskov
June 2007

R. Chiche

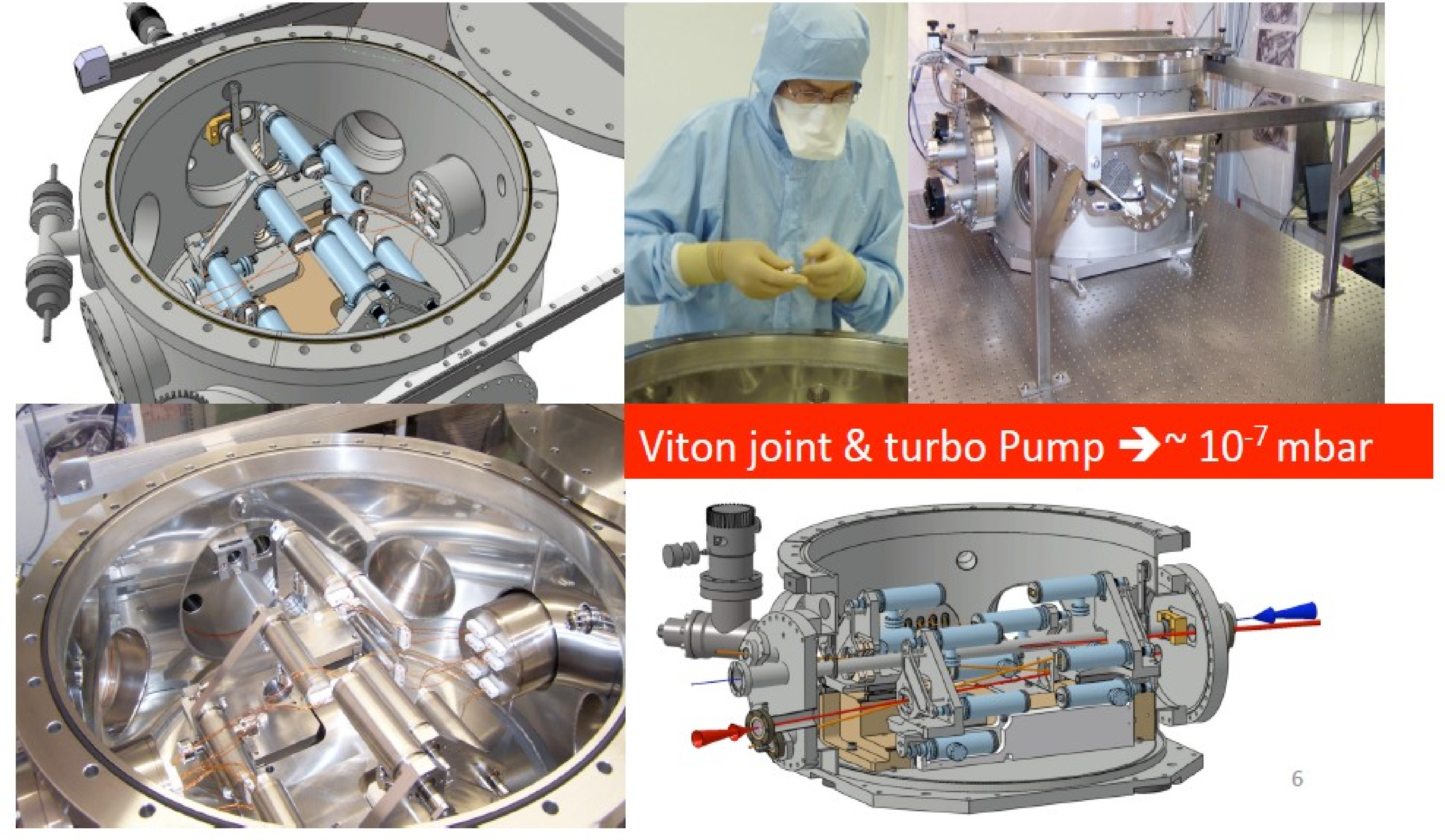
# LAL 4 mirrors cavity (3)

- ►After the off-line development of LAL cavity, a beam test is carried out at KEK-ATF eventually.
- ►This high enhancement cavity will be a prototype of ILC positron source.



**Mechanical Design of Final Four Mirrors Cavity**
R. Cizeron (LAL)

# LAL 4 mirror cavity (4)



Viton joint & turbo Pump → ~ $10^{-7}$ mbar

F. Zomer

# Fibre Laser (1)

Positron Generation
Positron Source
Positron Capture
LC Positron Source
Summary

- Double clad-core optical fiber.
- InGaAs LD (940nm) is for pumping.
- Typical core size is 6 – 40 $\mu$m.
- It is an ideal laser for high power operation.

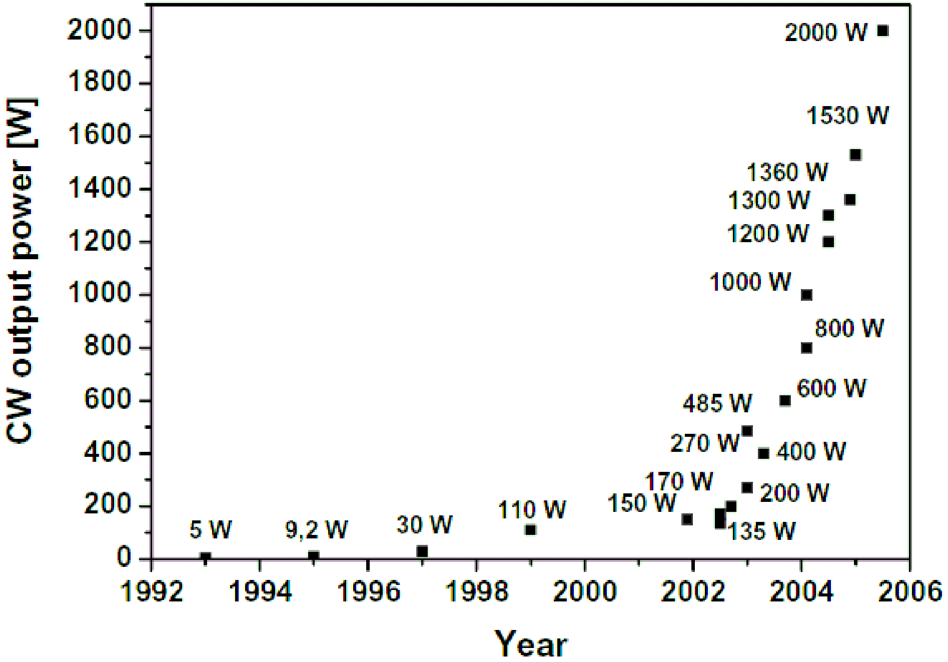
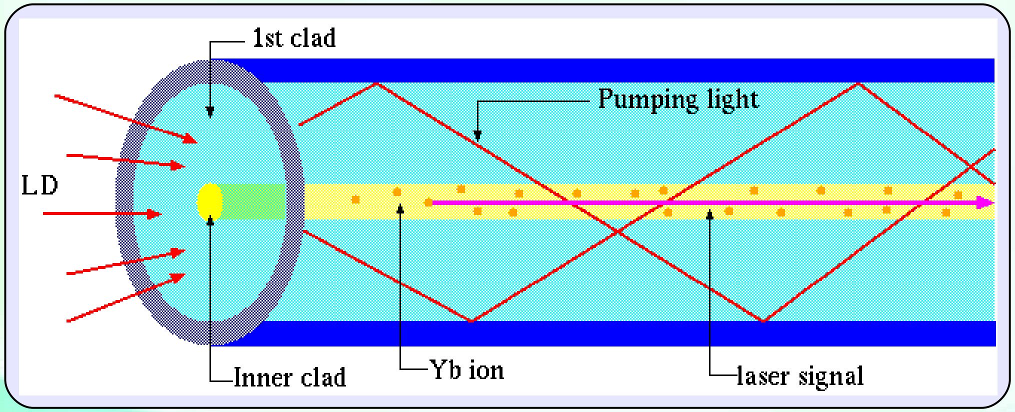


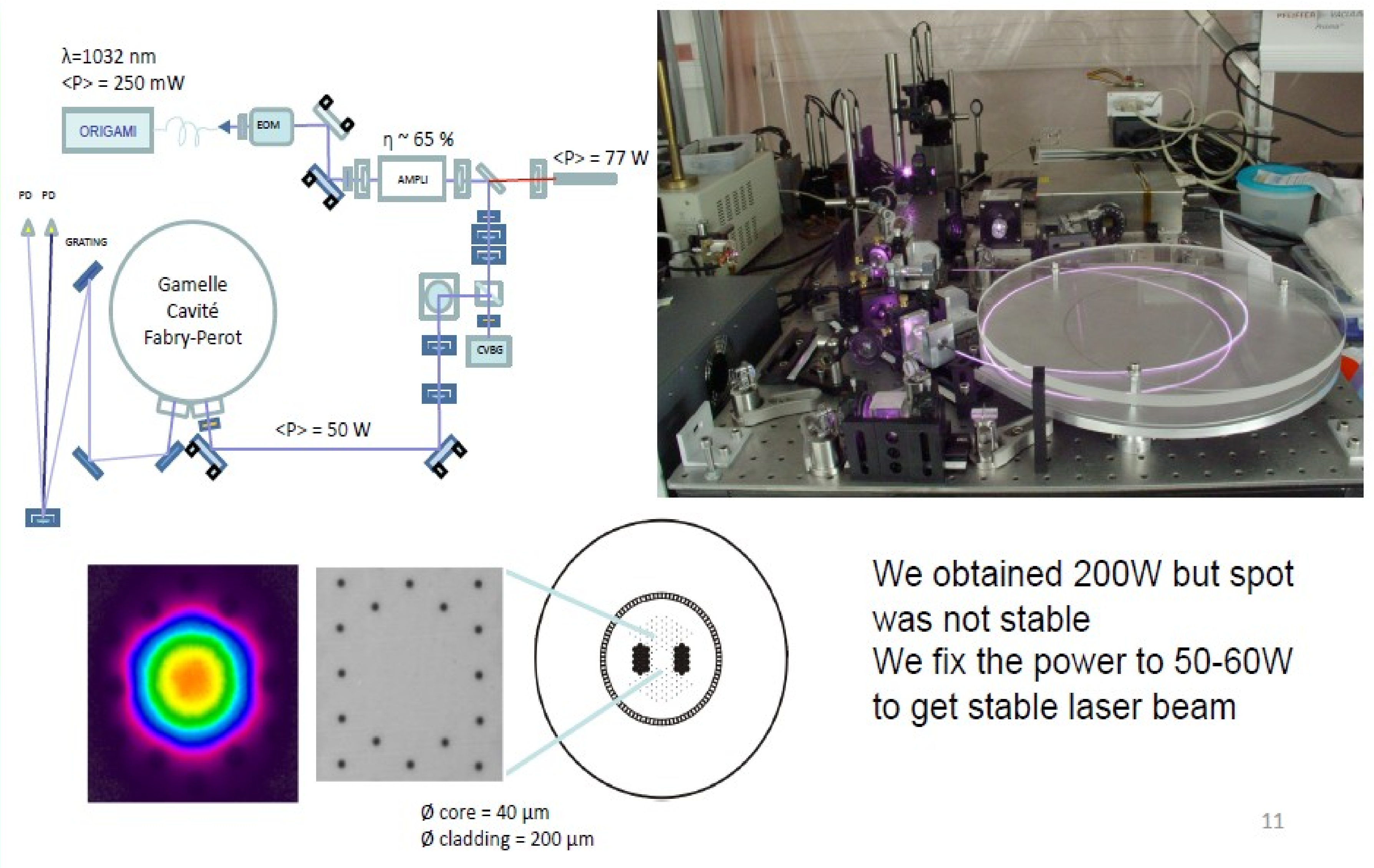
Fig. 4: Power evolution of cw double-clad fiber lasers with diffraction-limited beam quality over the last decade

J. Limpert



By M. Hanna

# Fibre Laser (2)



We obtained 200W but spot was not stable
We fix the power to 50-60W to get stable laser beam

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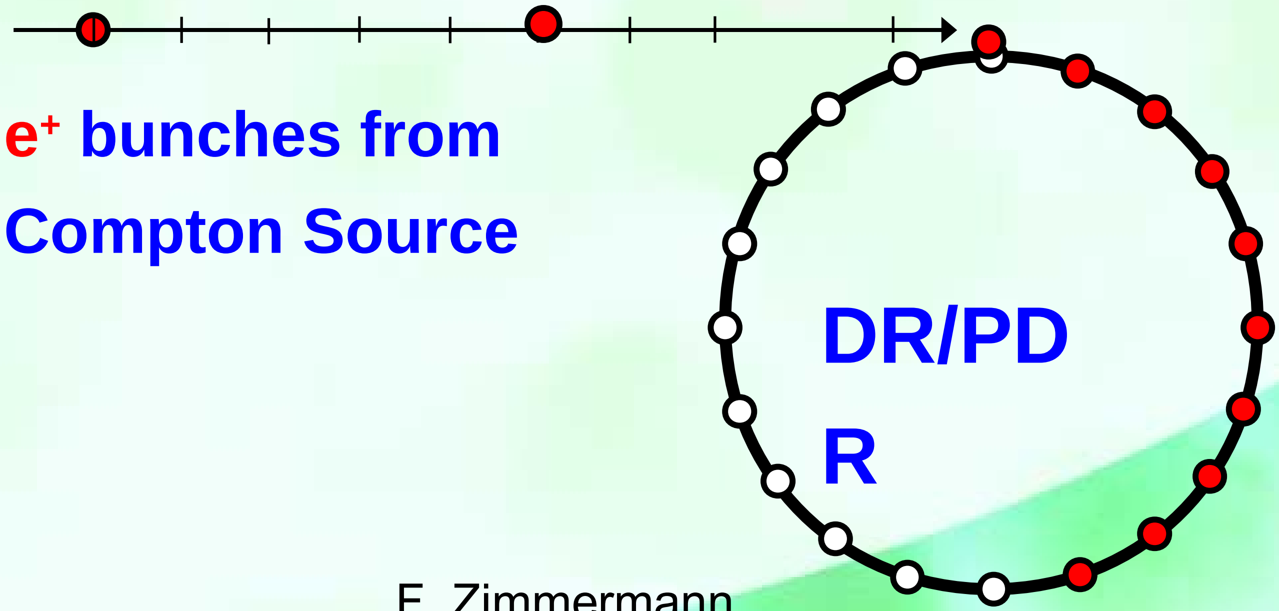
# Positron Stacking (1)

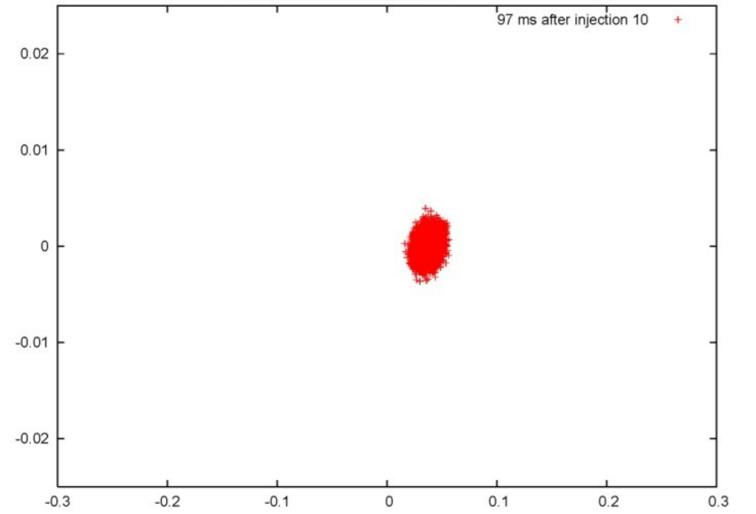
- Except linac scheme, # of positron by a single collision is not sufficient.
- We need accumulate positrons from many collisions to achieve the required bunch intensity for ILC and CLIC.
- Positron stacking: many positron bunches are injected to a same bucket in DR/PDR.



F. Zimmermann

# Positron Stacking (2)

- Simulation for the positron stacking in ILC DR is performed.
- The positron is injected in off-synchronous phase.
- The capture efficiency is 94.7 %. The 5.3% loss is similar to the loss for single injection.



cycle 1, before 1st injection
cycle 2, before 1st injection
cycle 3, before 1st injection

cycle 1, after 5th injection
cycle 2, after 1st injection
cycle 10, after 30th injection
cycle 1, after 10th injection

10 ms after cycle 10
cycle 2, after 5th injection

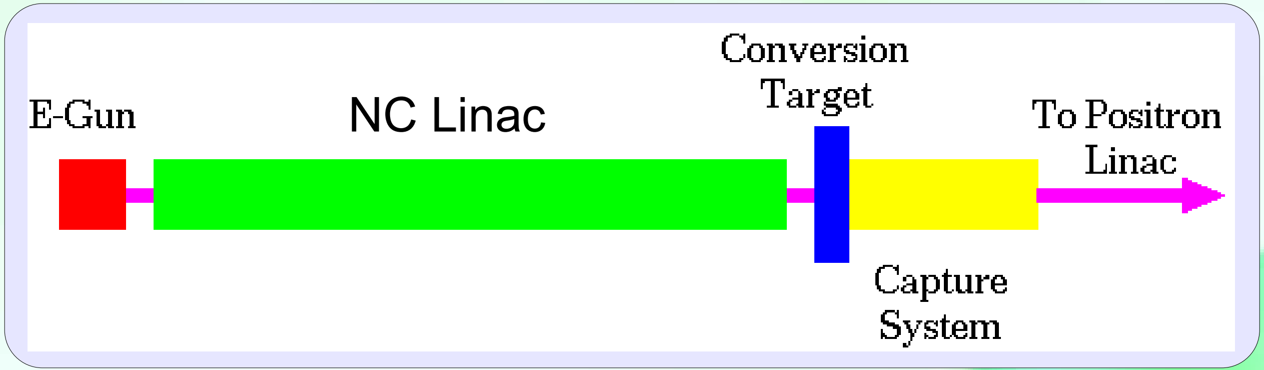
97 ms after cycle 10
cycle 1, after 30th injection
cycle 2, after 30th injection

$z_{off}$=0.045 m, $\delta_{min}$=5.7x$10^{-3}$, $\delta_{step}$=0.175x$10^{-3}$/turn

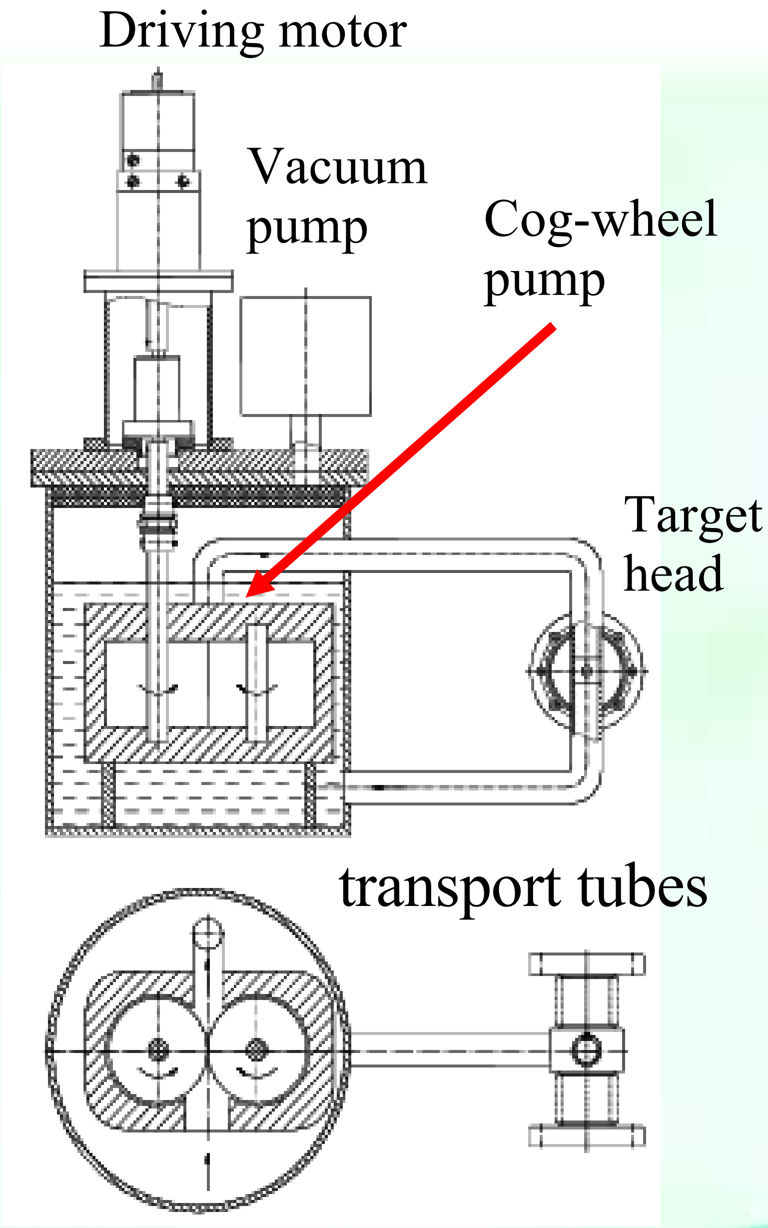
F. Zimmermann

# Electron Driven Scheme (1)

- Electron driven is the only scheme, which is ever been operated, 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

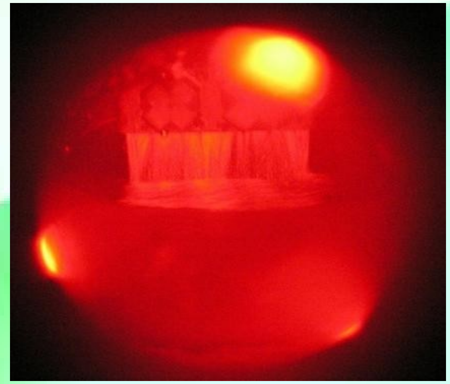


# Liquid Pb target (1)



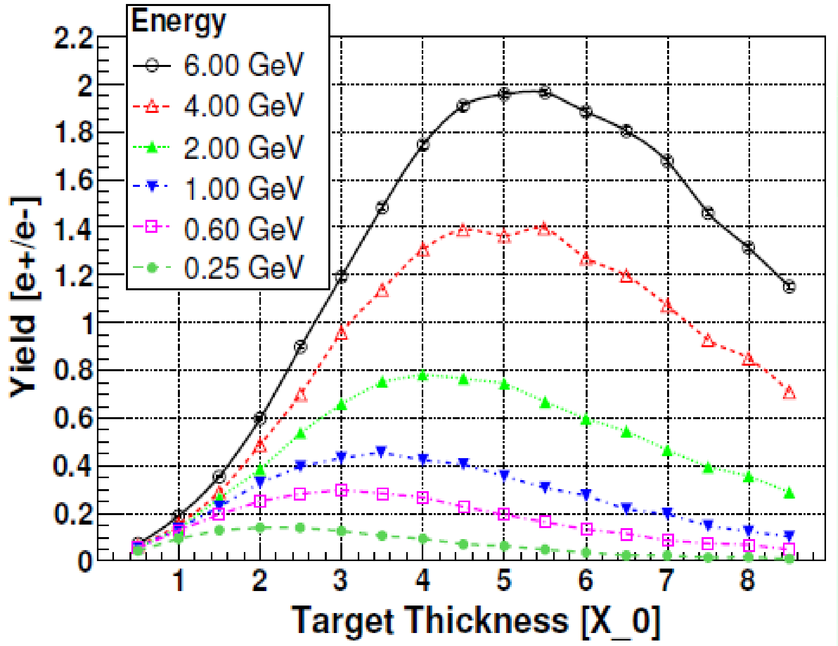
- Liq. Pb target system avoid fear for target damage.
- A prototype in BINP has been operated 20000h without any troubles.
- Damage for isolation window , which is light material, is an issue.
- Another issue is Pb boiling at 2200K.

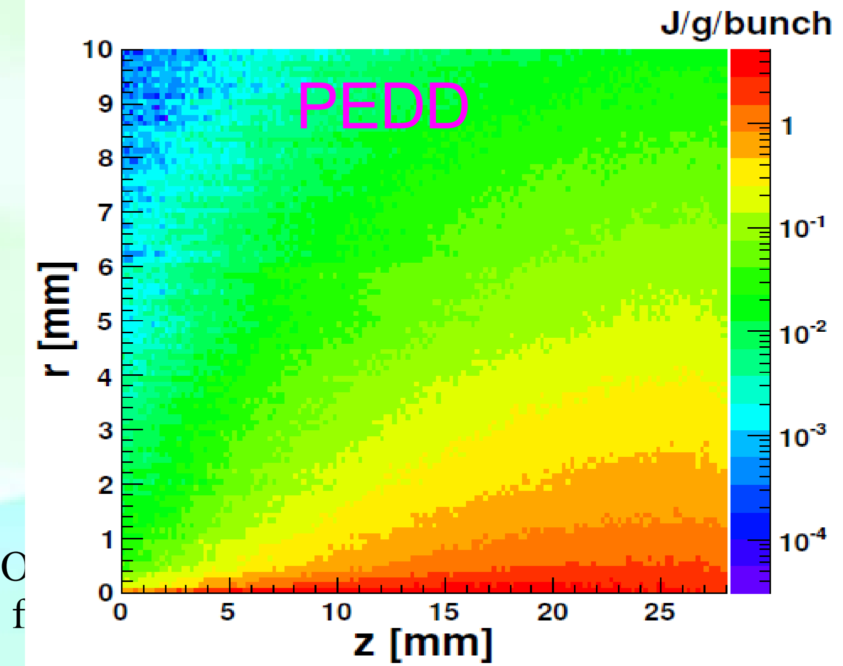
Pb 90% Sn 10%, 300˚C, in vacuum



# Liq. Pb target (2)

- Simulation by A. Ushakov
  - Pb target, 3 mm BN window for isolation.
  - Pencil-like e- beam
  - AMD field: 6 T to 0.5 T
  - E-field: 14.5 MeV/m
  - 10 mm long. bunch size
- 0.4 J/g/bunch for 2.0GeV.
- Reliability of BN window is an issue.



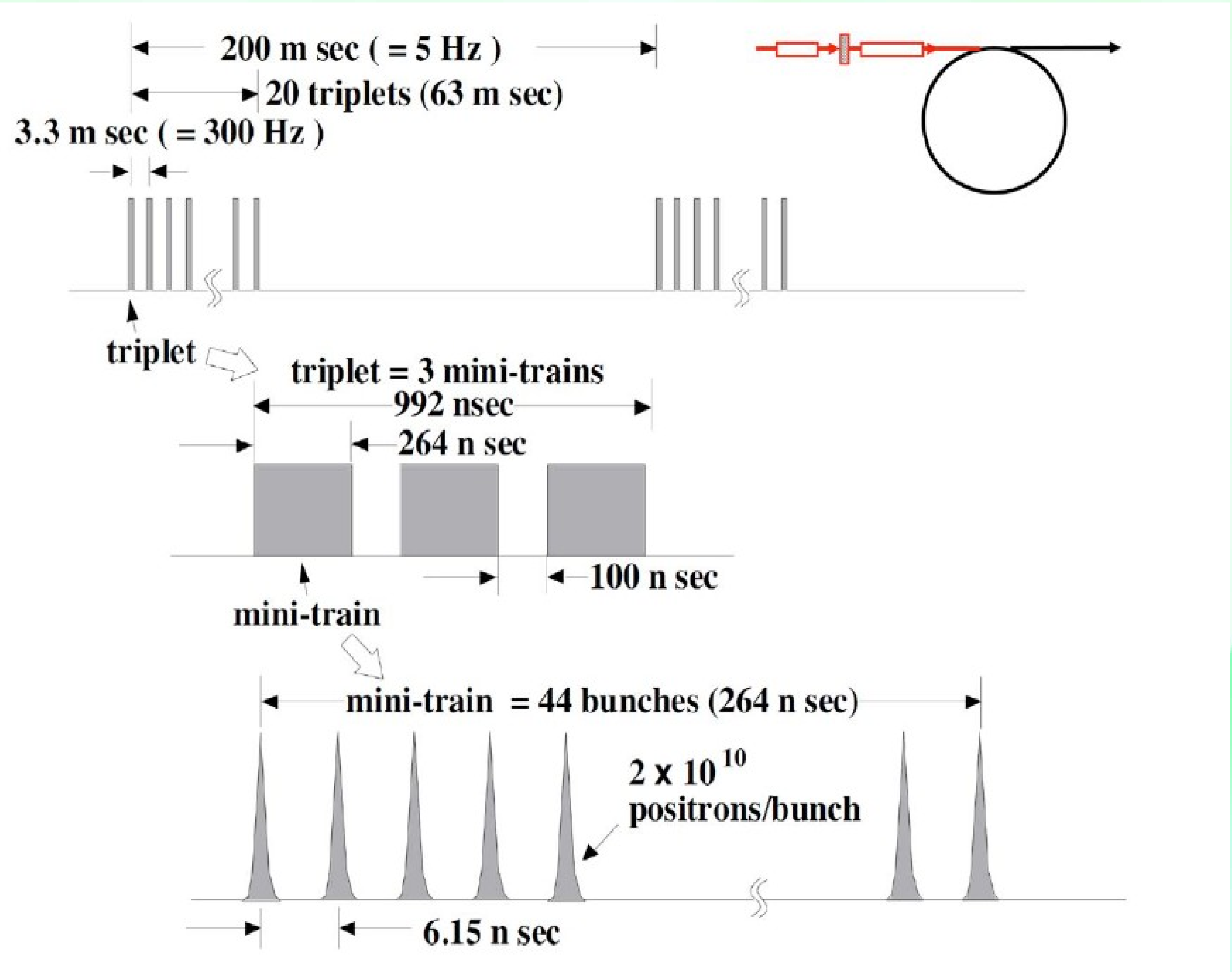


A. Ushkov, Posipol2010

# 300Hz Generation (1)

Positron Generation
Positron Source
Positron Capture
LC Positron Source
Summary

- To mitigate damage on the target, 63ms instead of 1ms .
- 3 mini-train compose one triplet, repeated by 300Hz.
- Thermal load on the target is relaxed during the interval.

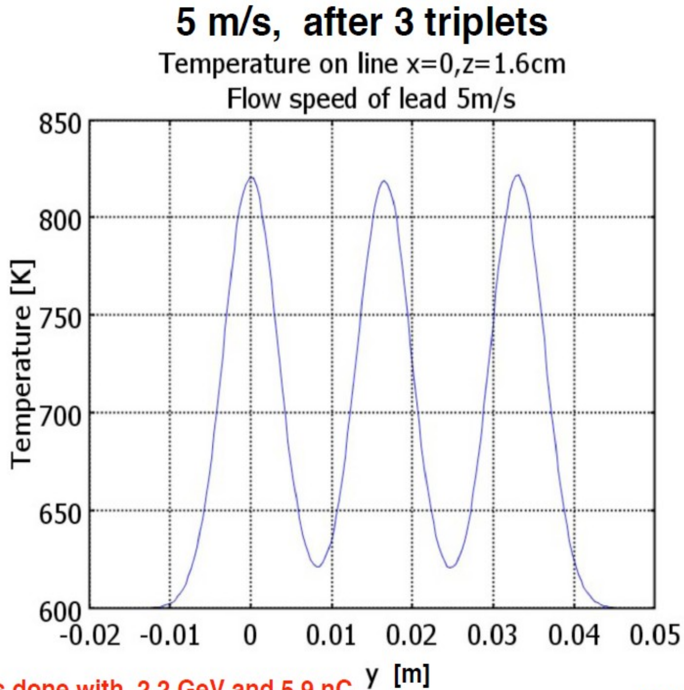


T. Omori

# 300Hz Generation (2)

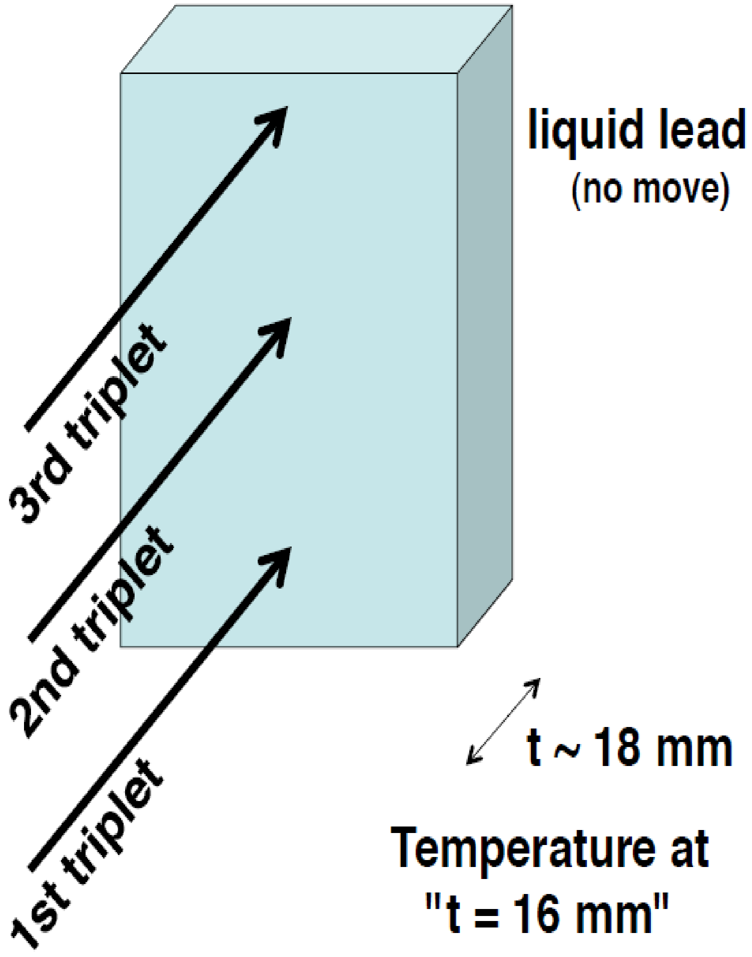
## Simulation of heating by beam (Wanming-san)

10m/s flow of Liq. Pb is enough to mitigate the thermal load.
(Pb boiling point is 2200K)



sim. was done with 2.2 GeV and 5.9 nC.
If 2.2 GeV --> 3.5 GeV, delta_T change 220 K --> 350 K

Wanming (ANL)

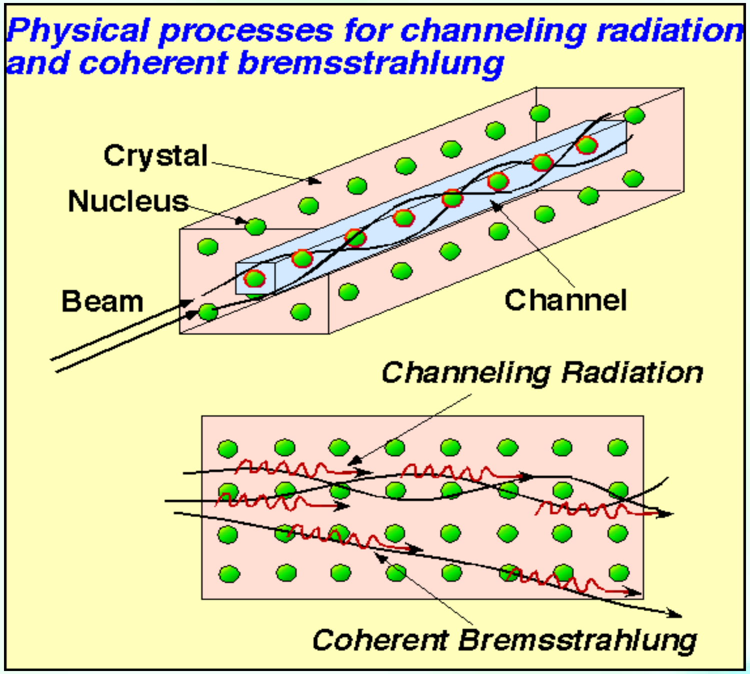


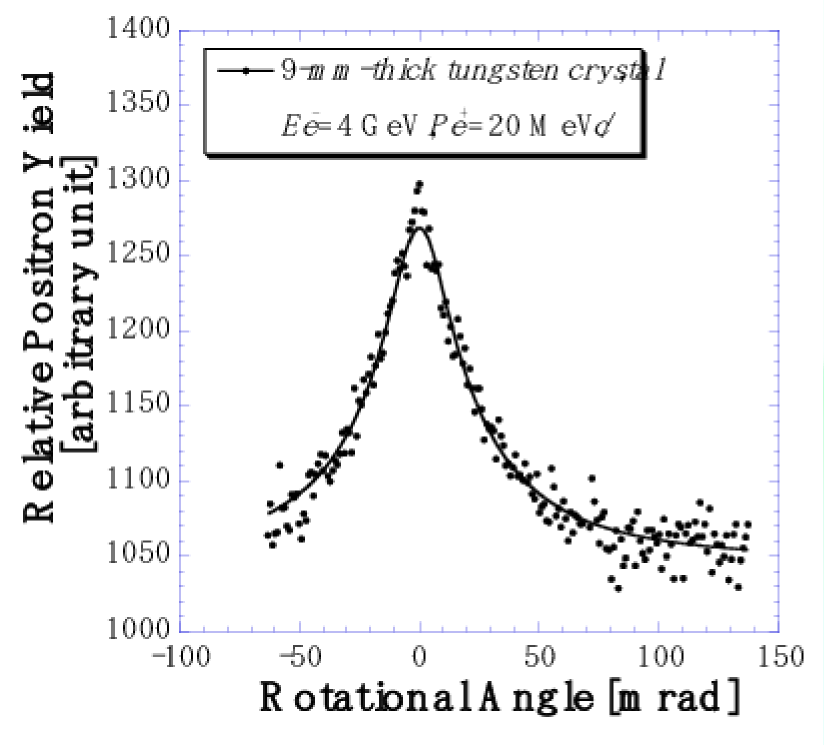
Temperature at
"t = 16 mm"
is monitored

T. Omori

# Crystalline Target (1)

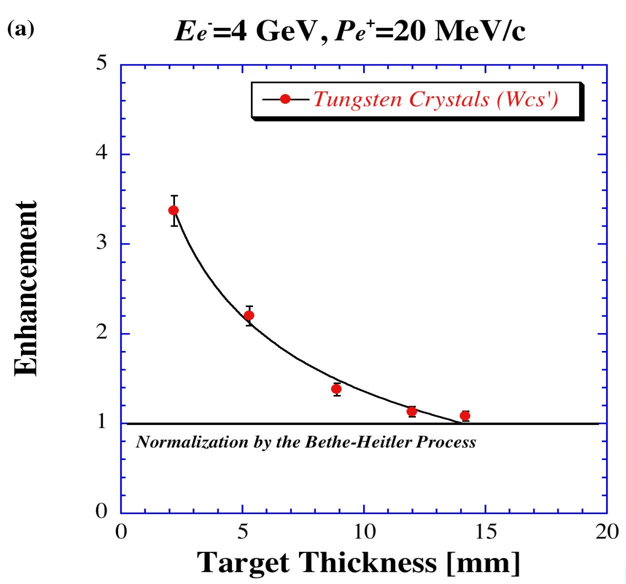
- Gamma radiation by e- beam in a crystalline W target along the crystal axis is enhanced by channeling and coherent bremsstrahlung.
- Less beam power for an equivalent e+ yield.
- A clear enhancement on the positron generation with the crystalline W target is experimentally confirmed at KEKB injector.

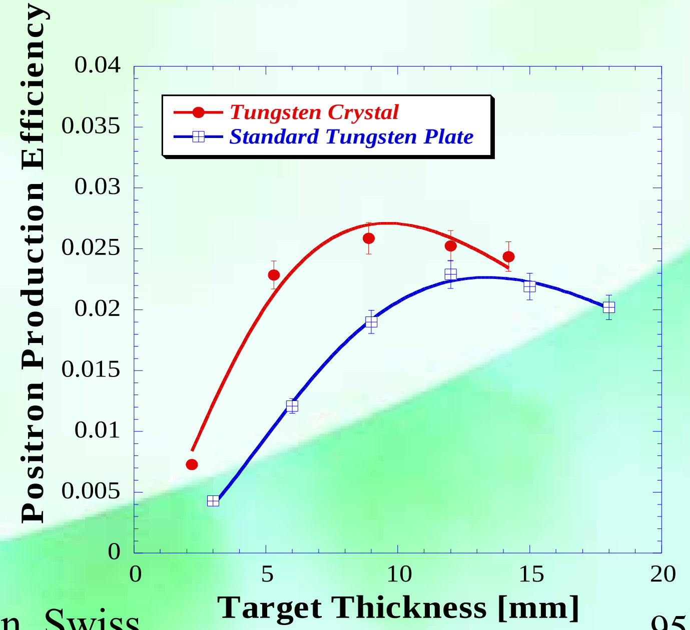

*Physical processes for channeling radiation and coherent bremsstrahlung*



# Crystalline Target (2)

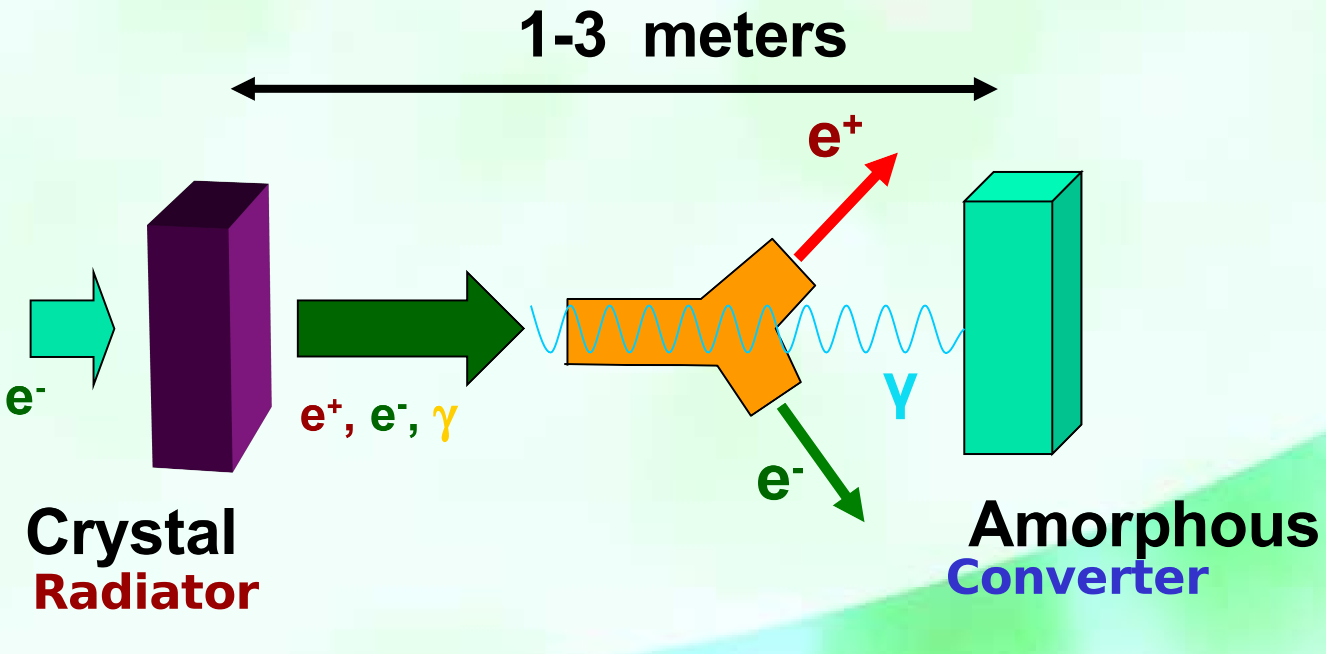
- Positron yield by the crystalline target is enhanced by ~30% with thinner (~9mm) target thickness.
- The heat load becomes almost half compare to the amorphous target.
- The heat load normalized to the generated positron flux is 40% of that by amorphous target. It relaxes the technical limitation very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





# Crystalline Target(3)

- Hybrid scheme of crystalline and amorphous targets.
  - Crystal for radiator and Amorphous for converter.
- By sweeping out charged particles, only the photons are impinging on the converter. The energy deposition in the amorphous target is compensated.
- It is the baseline scheme for CLIC.

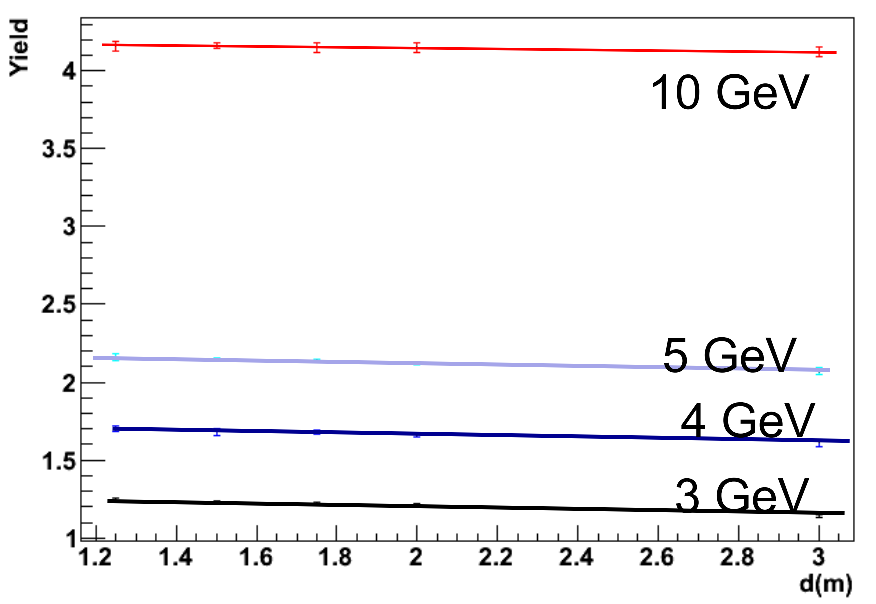


R. Chehab

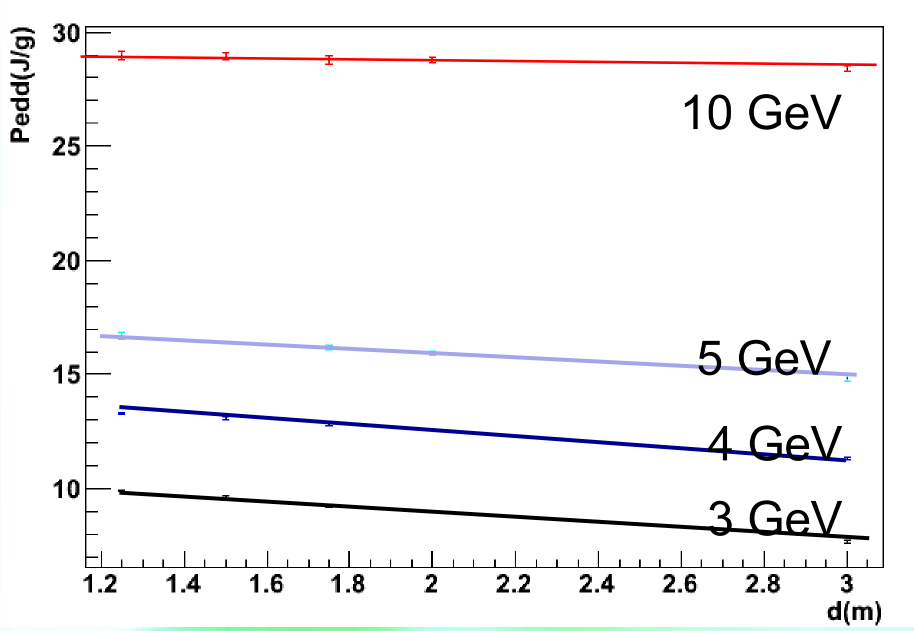
# Crystalline Target(4)

- Positron yield after the AMD r < 2.0 cm (e=10mm of amorphous)
- PEDD for 10mm of amorphous (elementary volume few mm$^3$)
- PEDD is suppressed below the limit, 35 J/g with enough yield, e+/e- > 1.0.

Yield



PEDD



# Summary

- Fundamentals of positron generation and its capture system are explained .
- ILC Positron Source
  - Undulator Scheme is the baseline.
  - Laser Compton and electron driven are alternative.
- CLIC Positron source
  - Hybrid scheme is the baseline.
  - Laser Compton and undulator are alternative.
- Need a lot of interesting works to implement the positron source.
- A common effort for ILC-CLIC on positron source R&D is ongoing.

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