Positron Source for Linear Colliders

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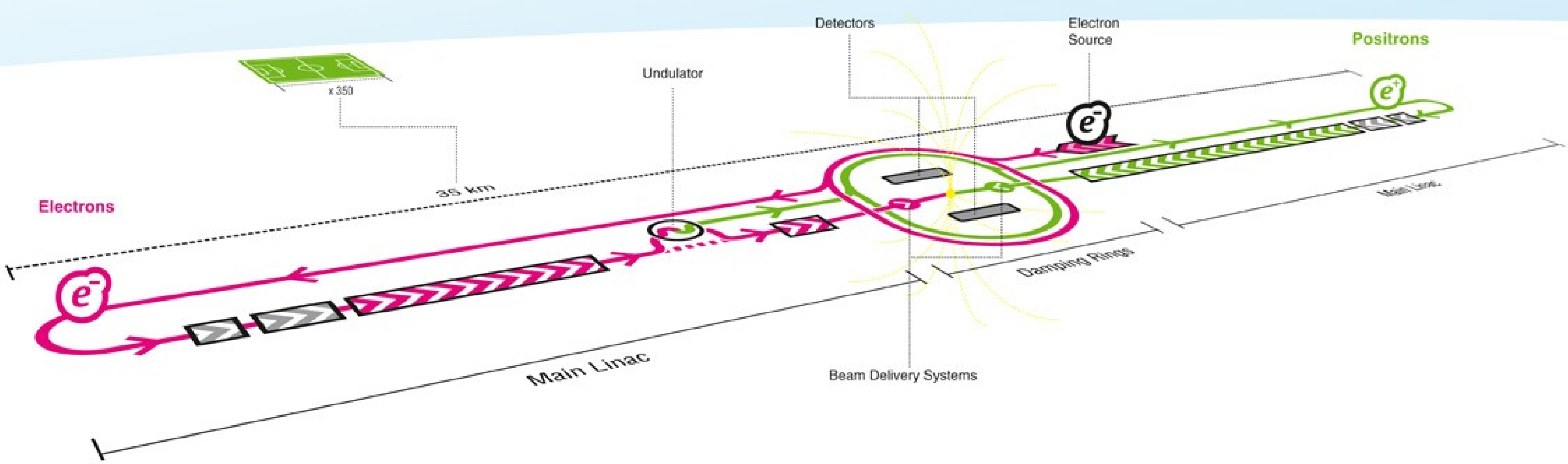

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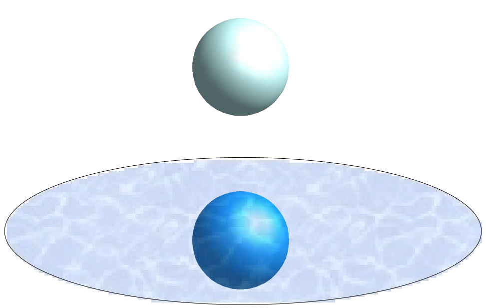
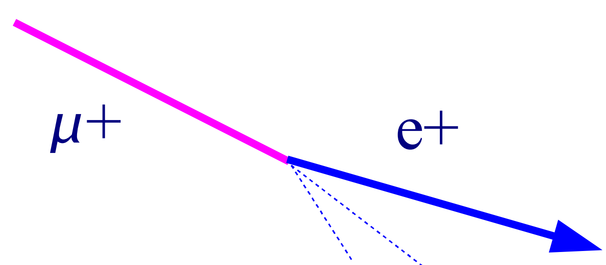
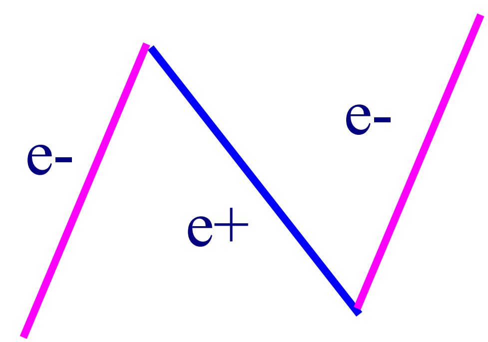
Summary

- 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.

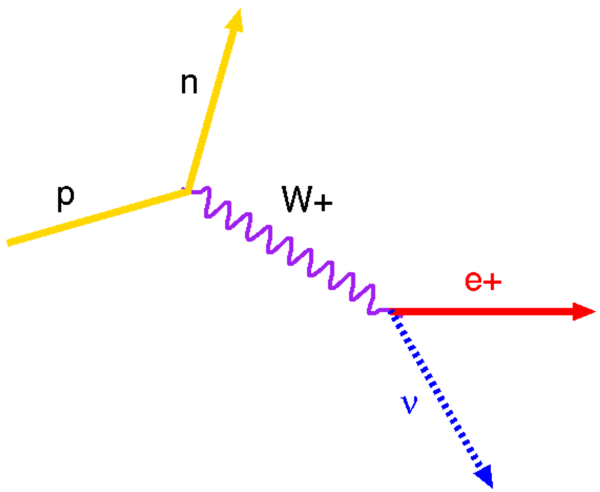


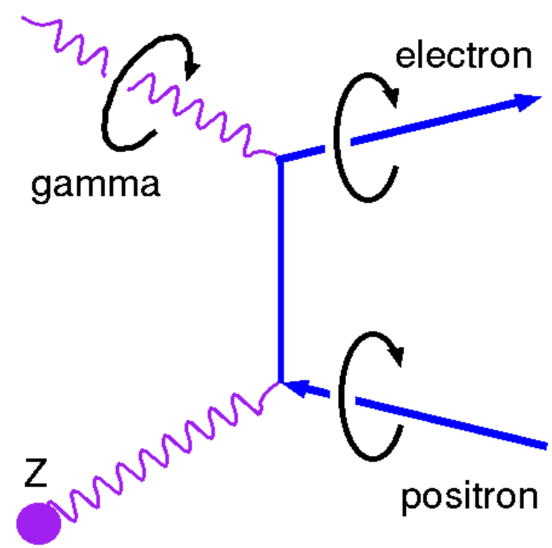




Positron Production (1)

- 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.

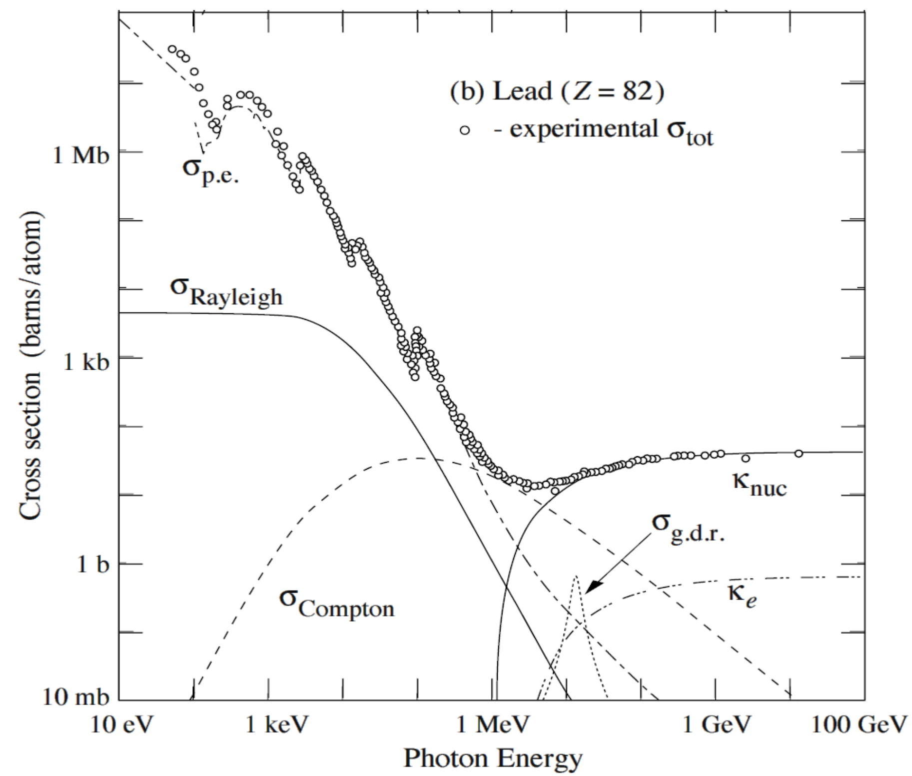




Positron Production (2)

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

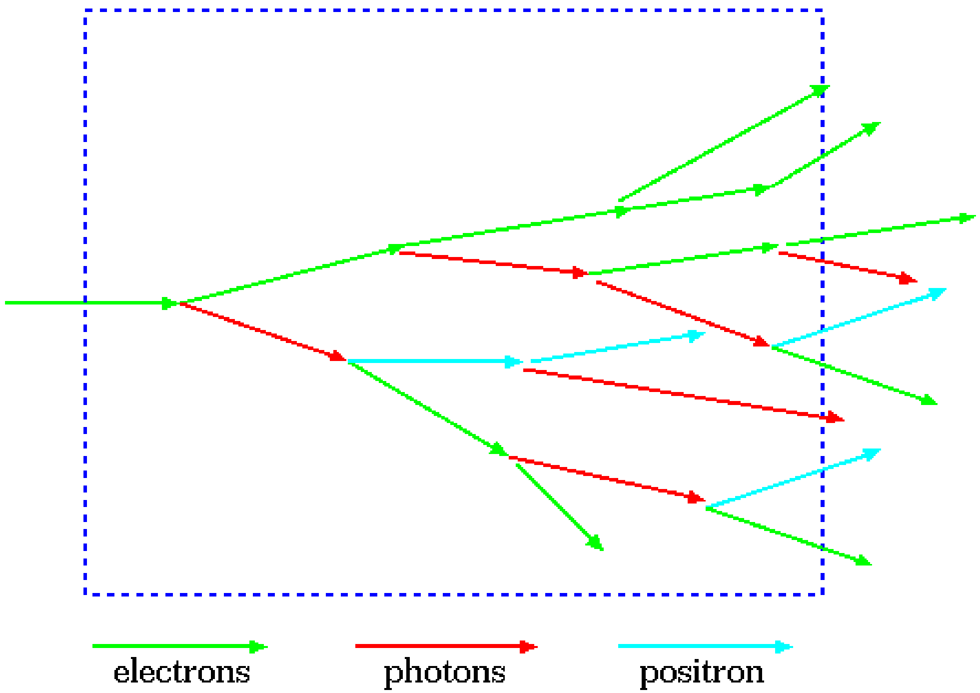
- ▶ Photon interaction in material:
  - – Photo-electron effect(<1MeV)
  - – Compton scattering (1-10MeV)
  - – Pair-creation (>10MeV)
- ▶ Gamma ray, energy >10MeV is required for effective pair creation.



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

EM Shower

- 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**

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

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

EM Shower (3)

- **Positron Generation**
- Positron Capture
- Positron Source
- Positron Source for LC
- 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.

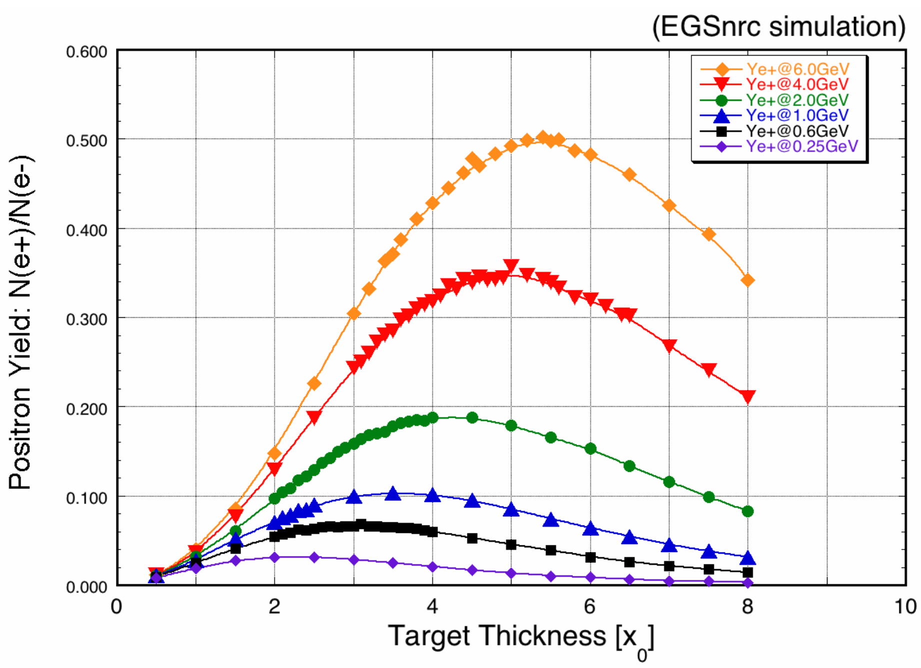
► Approximated expression for the shower max length in X_0;

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

– **E_0: Injected electron**

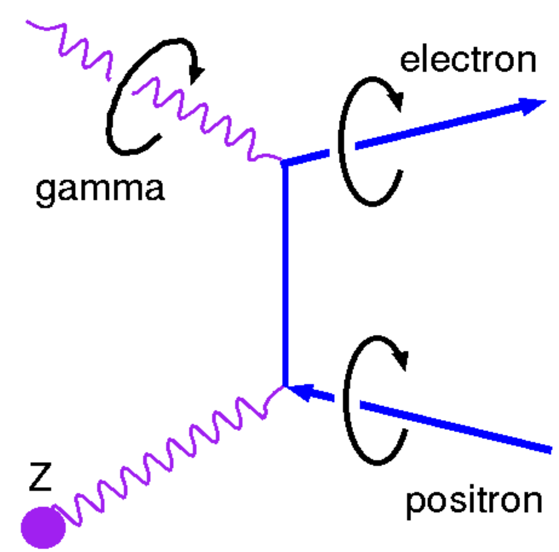
– **e_0: critical energy**

Courtesy of T.Kamitani



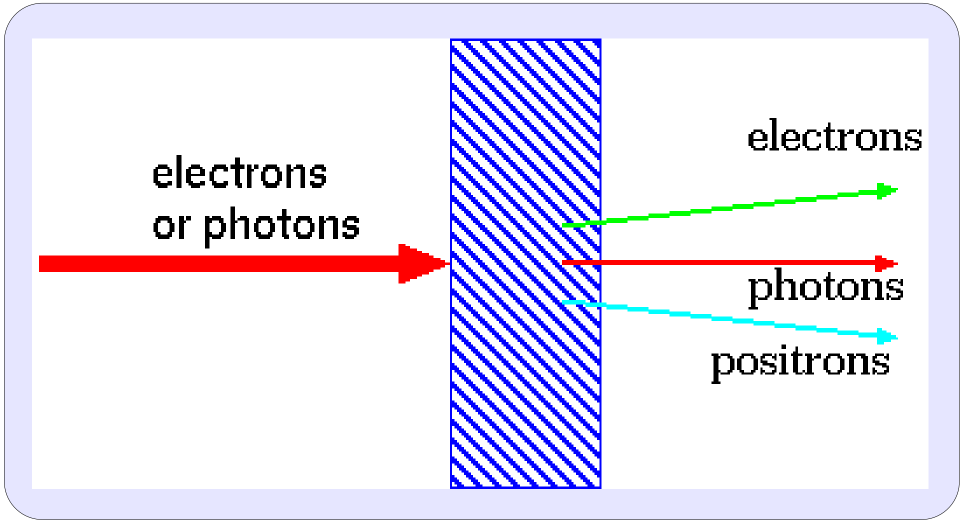
Non Shower Regime

- 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

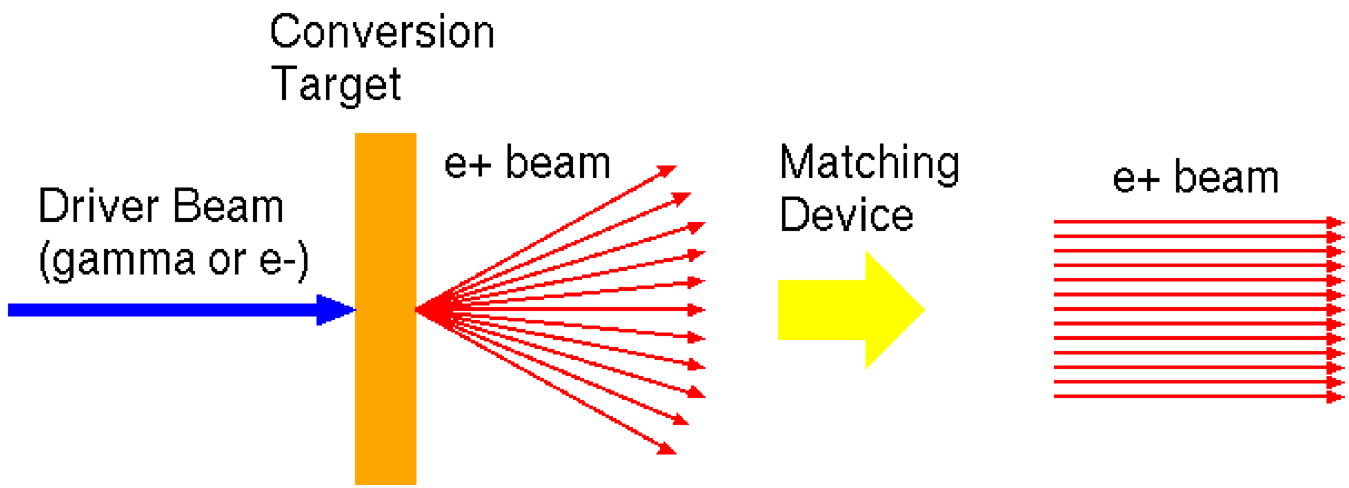
- Positron is generated through pair-creation process.
- Driver beam (electron >100s MeV or photon > 10 MeV) is injected onto the converter and positron is obtained as a mixed flux of e+, e-, and photon.
- Regime is different : EM shower for electron and non-shower for photon.



Positron Capture

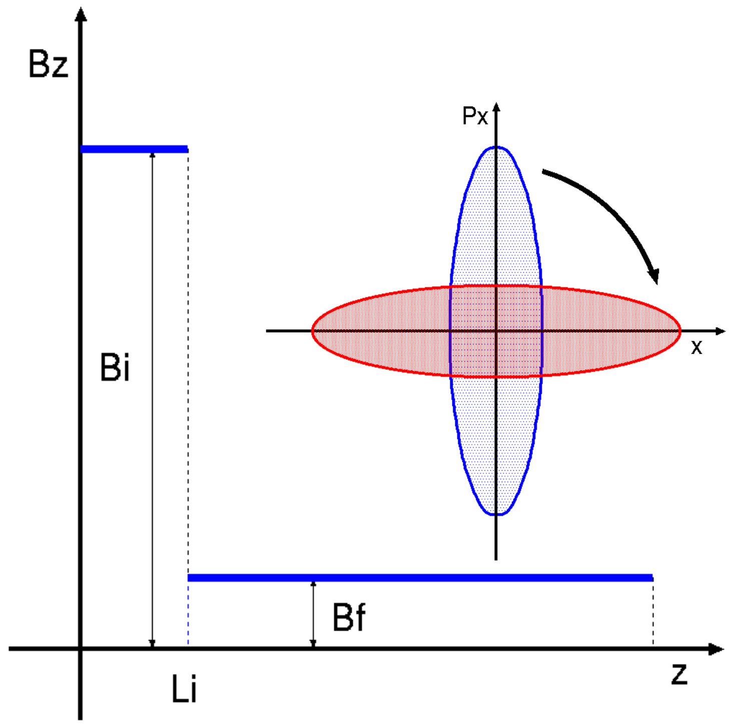
Positron Capture (1)

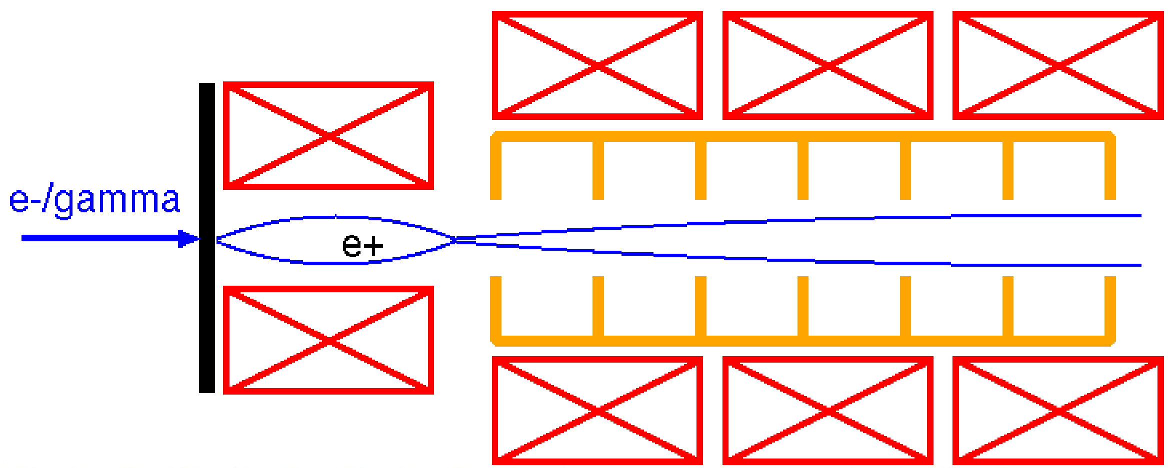
- Positrons are generated as a mixture of positrons, electrons, and gammas.
  - **Select only positrons from the flux.**
  - **Capture the positron in a RF bucket.**
- The generated positrons are distributed in a small spot size and in a large momentum space. To convert it to the parallel beam, capture devices are used
  - **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^o 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 magnetic field B_i and circulated with radius ρ.

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

Time to travel πρ in xy plane,

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

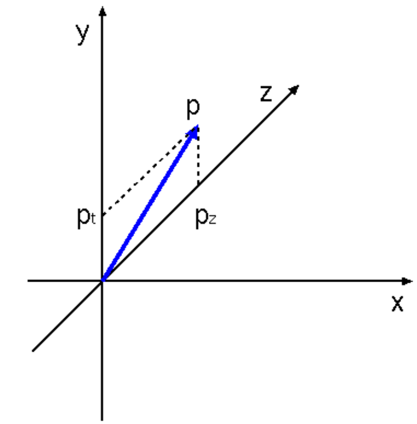
which is independent from p_{t0}. To travels L_i in z

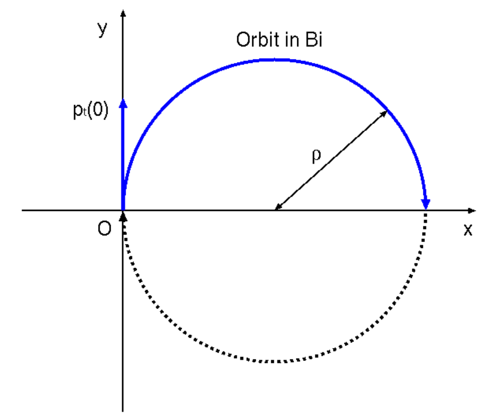
$$t_z=\frac{L_i m\gamma}{p_z} \qquad (2-3)$$

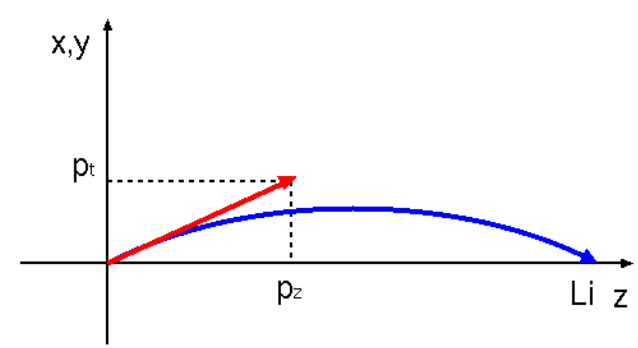
When both times are equal, e+ is captured. The condition for the capture is

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

Only positrons satisfying the condition are captured by QWT.







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

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

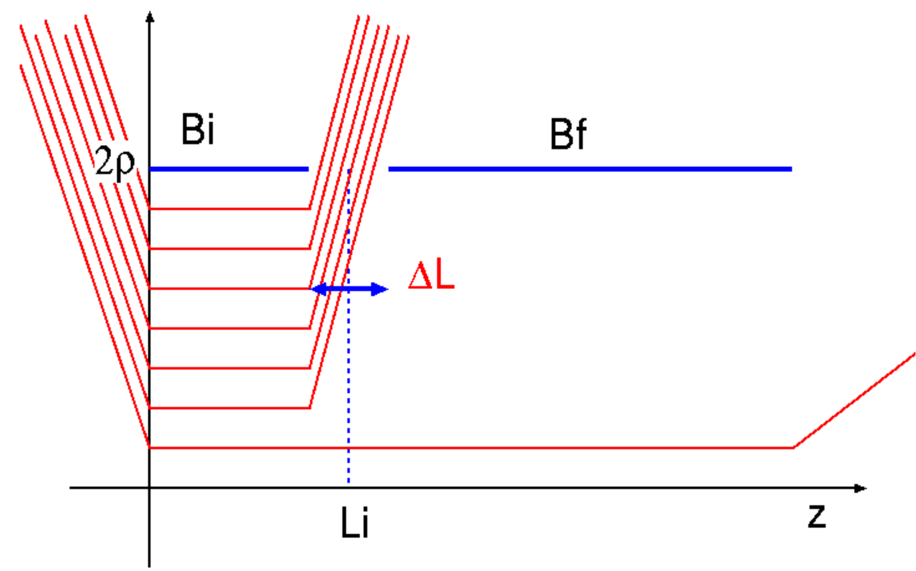
Magnetic flux in B_f region is

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

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 by the kick at the boundary is

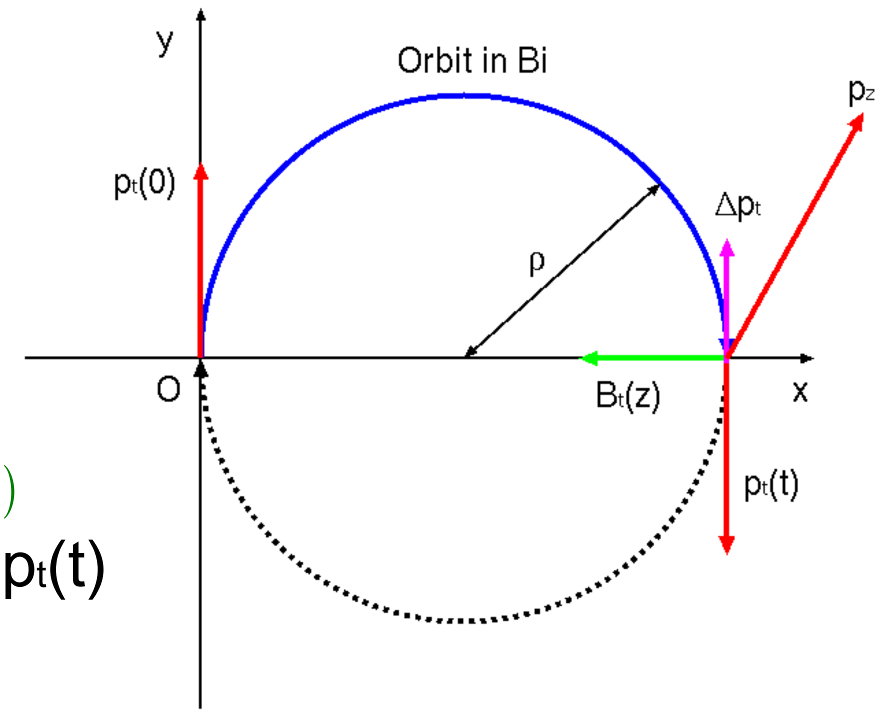
$$\frac{dp_t(t)}{dt} = e\,v_z\,B_t(z) \quad (2-9)$$

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)

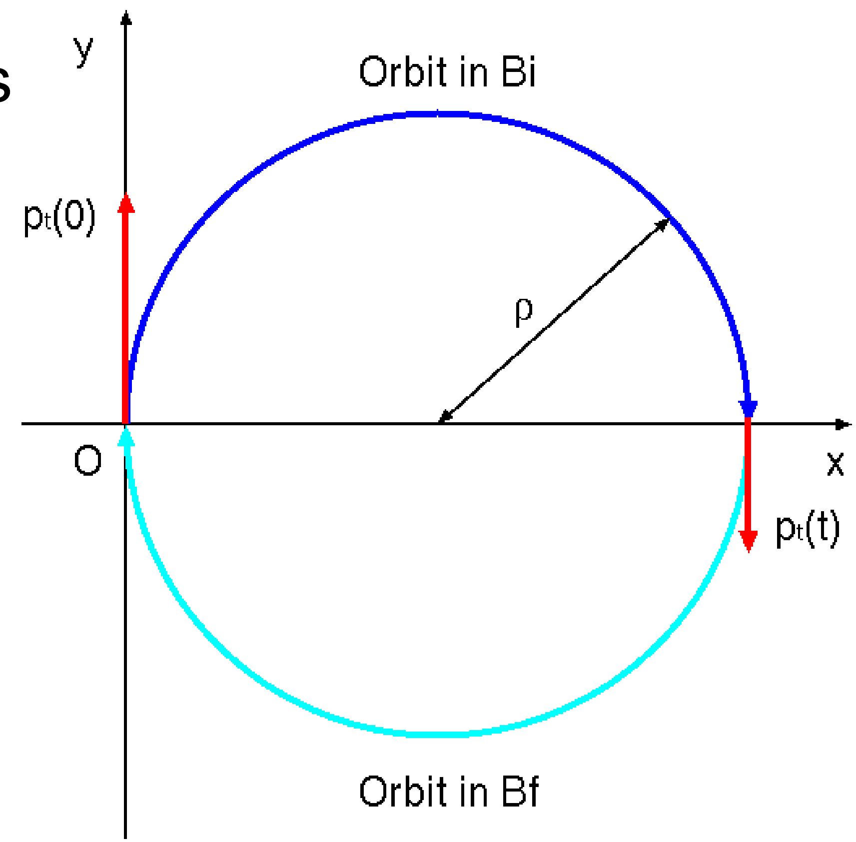
Pt(t) after the kick is

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

Radius of circulating motion of this particle in B_f is

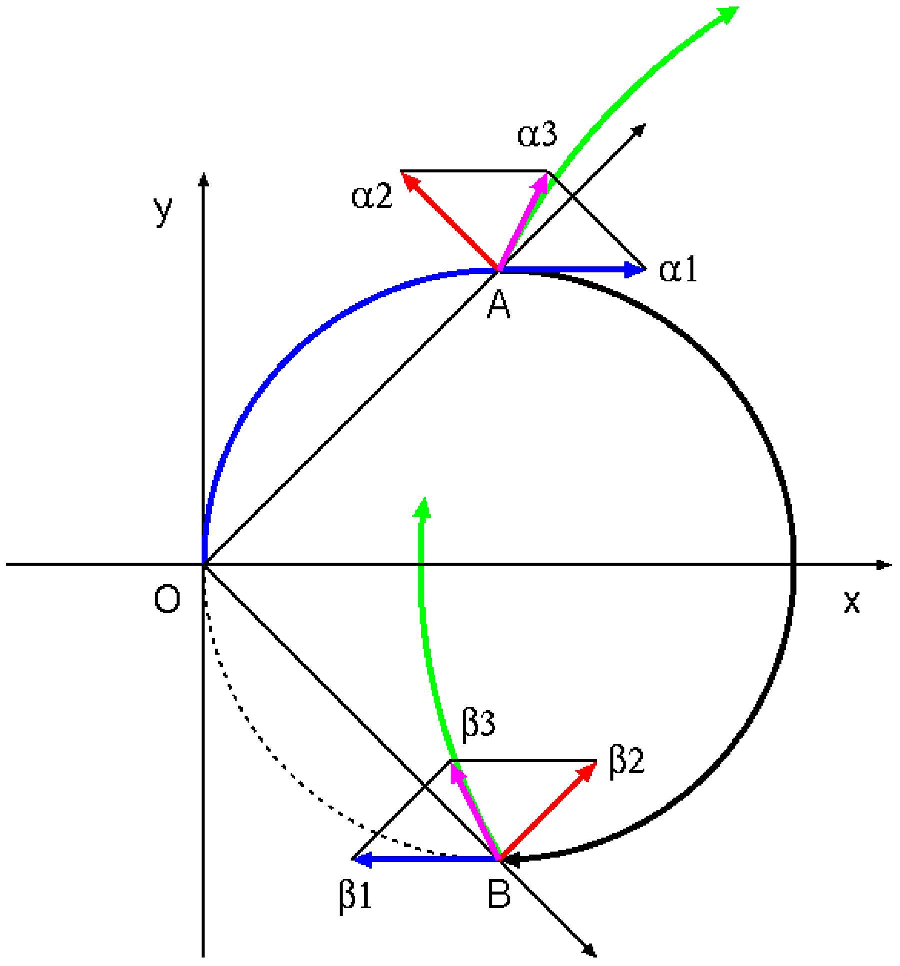
$$\rho_f = \frac{1}{eB_f}\frac{P_{t0}B_f}{B_i} = \frac{p_{t0}}{eB_i} \quad (2-13)$$

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



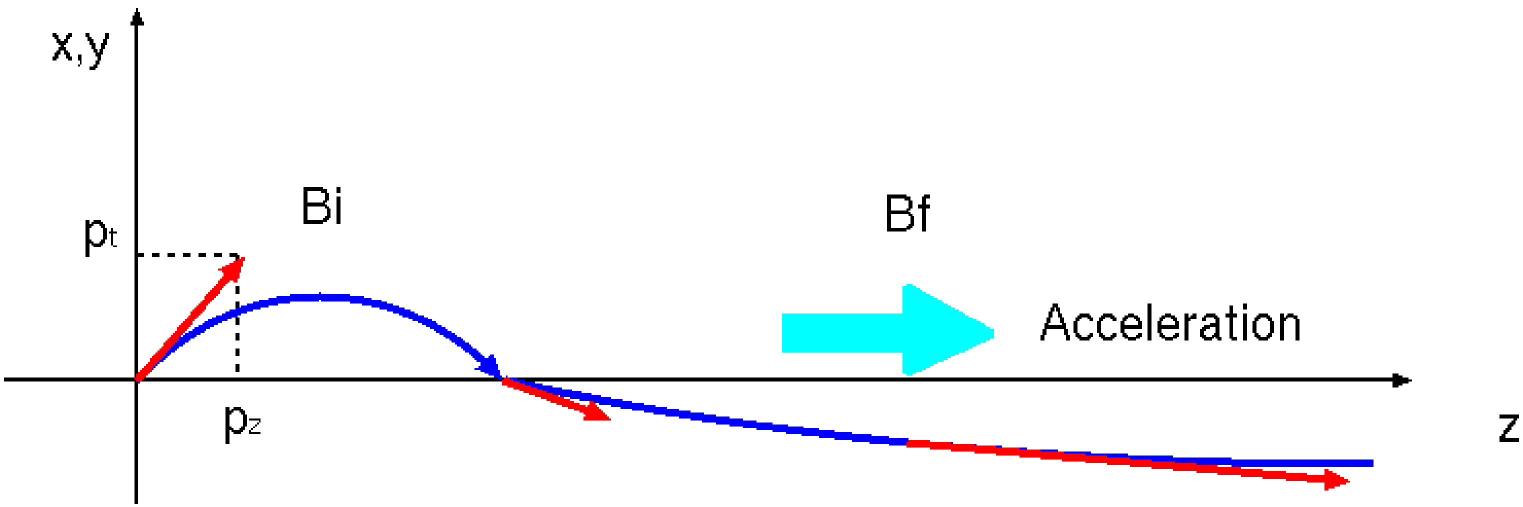
QWT(6)

- Kick to off momentum positrons, which is not circulate $\rho\pi$, 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 positrons only with the appropriate condition are captured by QWT.

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

- Acceptance

Energy :

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

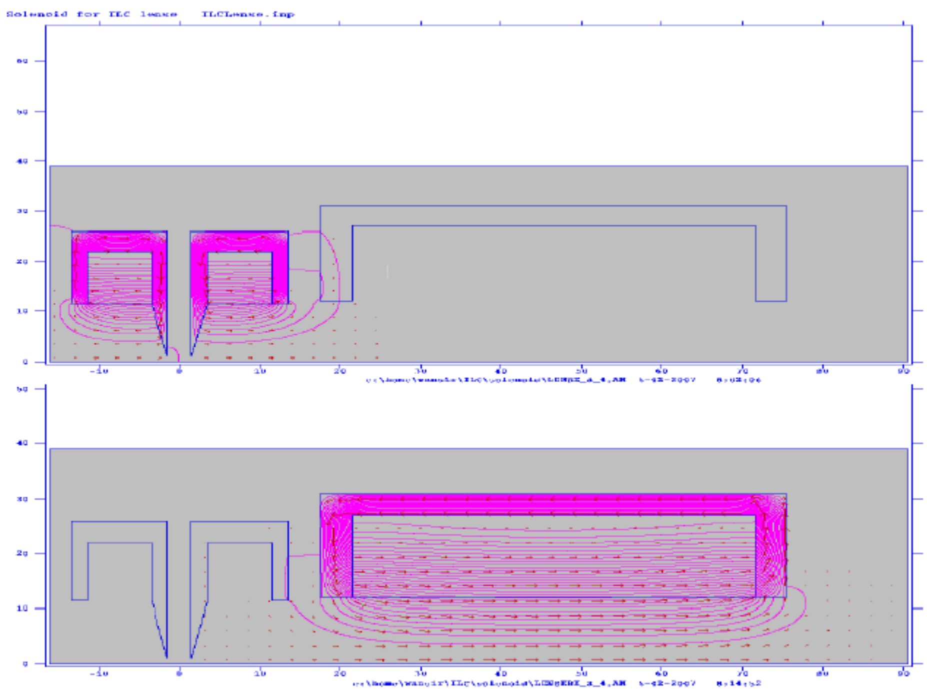
The circulating motion should be within the radius of accelerating structure, a, then

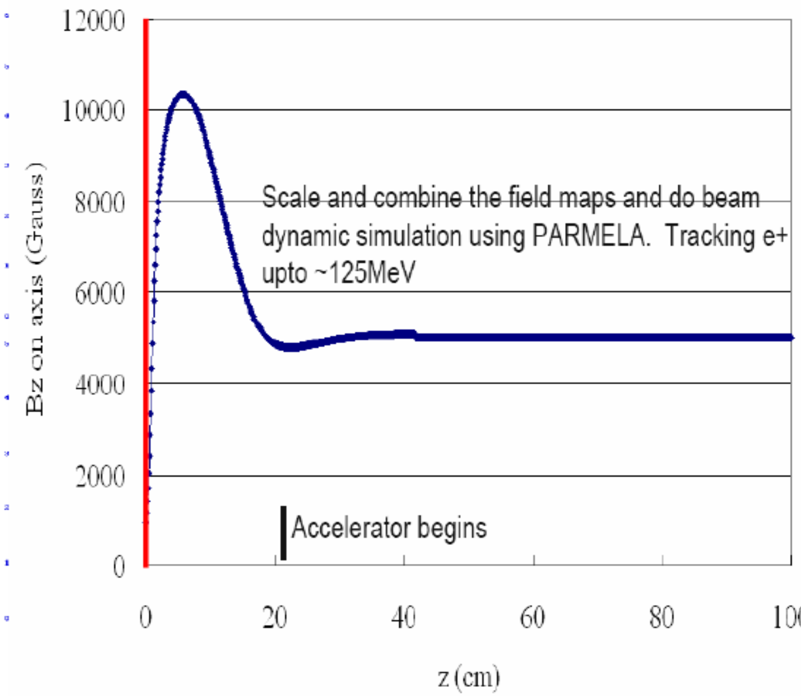
$$2\rho = \frac{2p_t}{eB_i} < a \quad (2-16)$$

Acceptance on pt is

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

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 B_f region.

Acceptance by QWT

- Bi=1.0 Tesla
- Li=0.1m
- Bf=0.5 Tesla
- A=0.02

Longitudinal momentum captured by the QWT is obtained from eq (2-14) as

$$p_z(MeV/c)=\frac{L_i e B_i}{\pi}\frac{c}{e}=\frac{c L_i B_i}{\pi}\sim 9.5$$

Upperlimit of transverse momentum is obtained from eq (2-17)

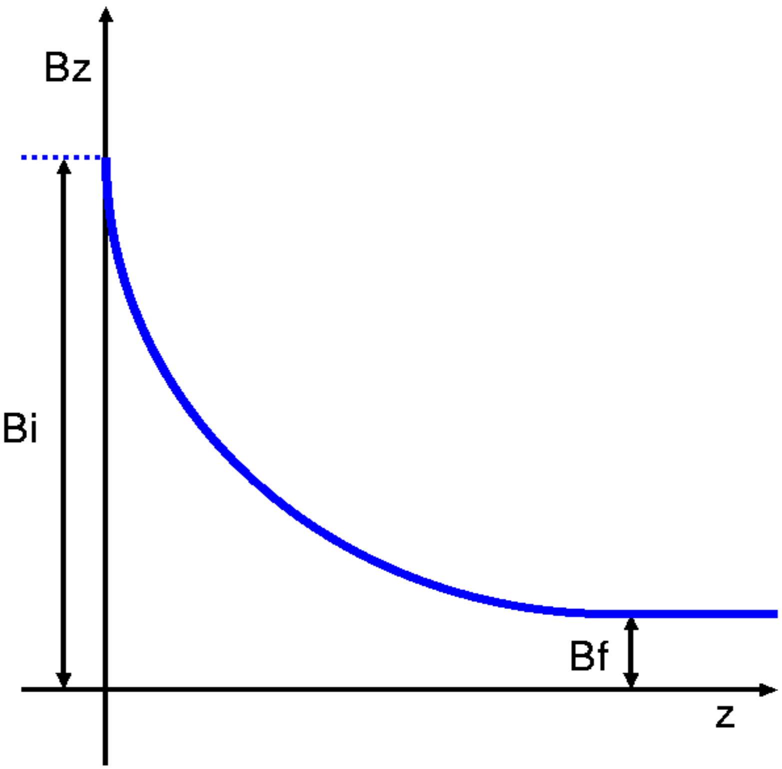
$$p_t(MeV/c)<\frac{eB_i a}{2}\frac{c}{e}=\frac{cB_i a}{2}\sim 3.0$$

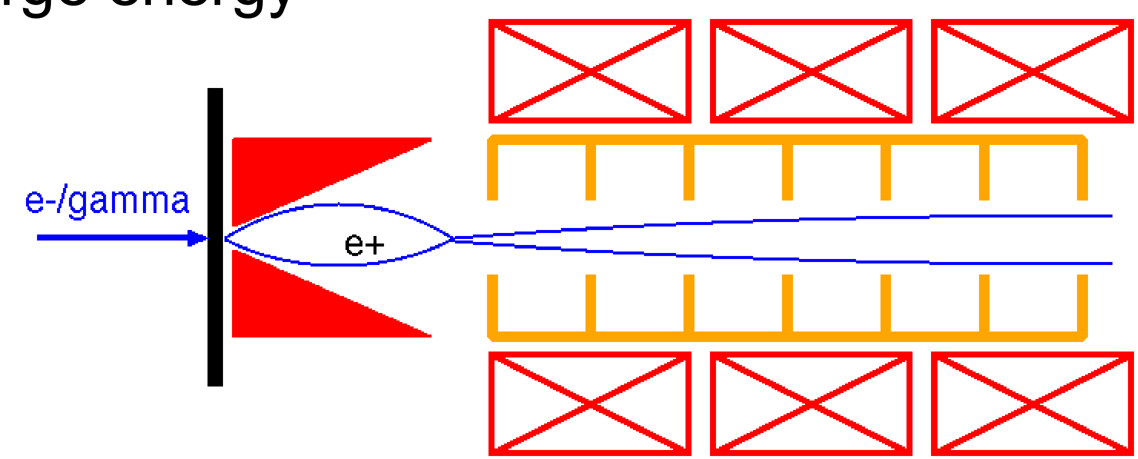
AMD(1)

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

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

- The magnetic field variation should be even slow comparing to the electron spiral motion.
- AMD has relatively large energy acceptance.





AMD (2)

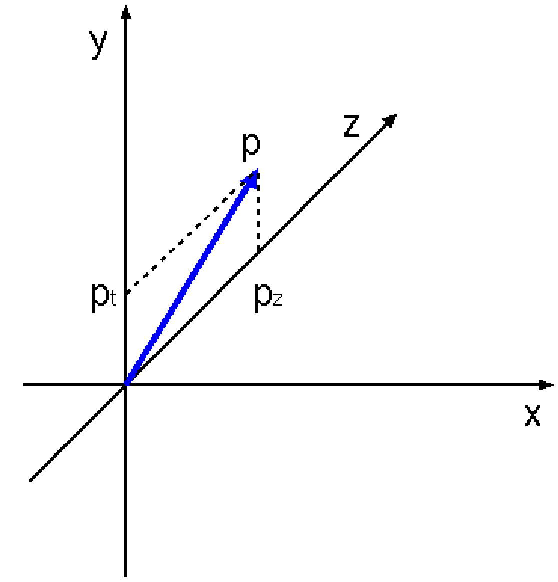
Assume positrons start at $(x,y,z)=(0,0,0)$ with momentum $p=(0,p_{t0},p_z)$.

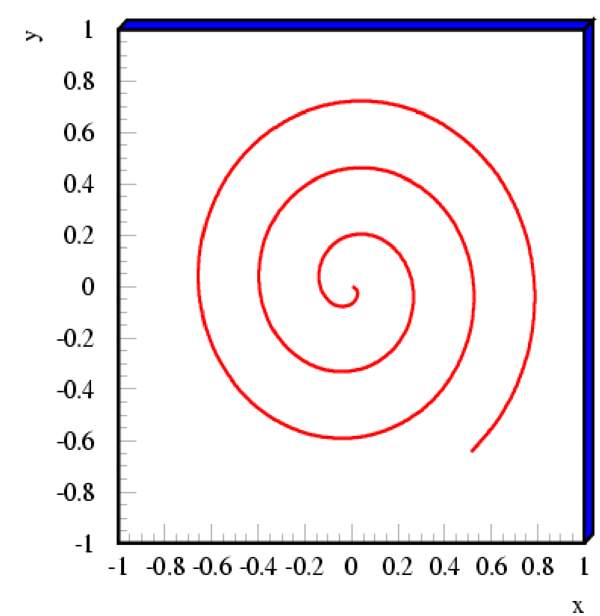
In xy plane, positrons are deflected by $B(z)$ and circulated with radius $\rho(z)$, but it is now a function of z.

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

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

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





AMD(3)

Due to the adiabatic motion,

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

Then $p_t(z)$ is expressed as

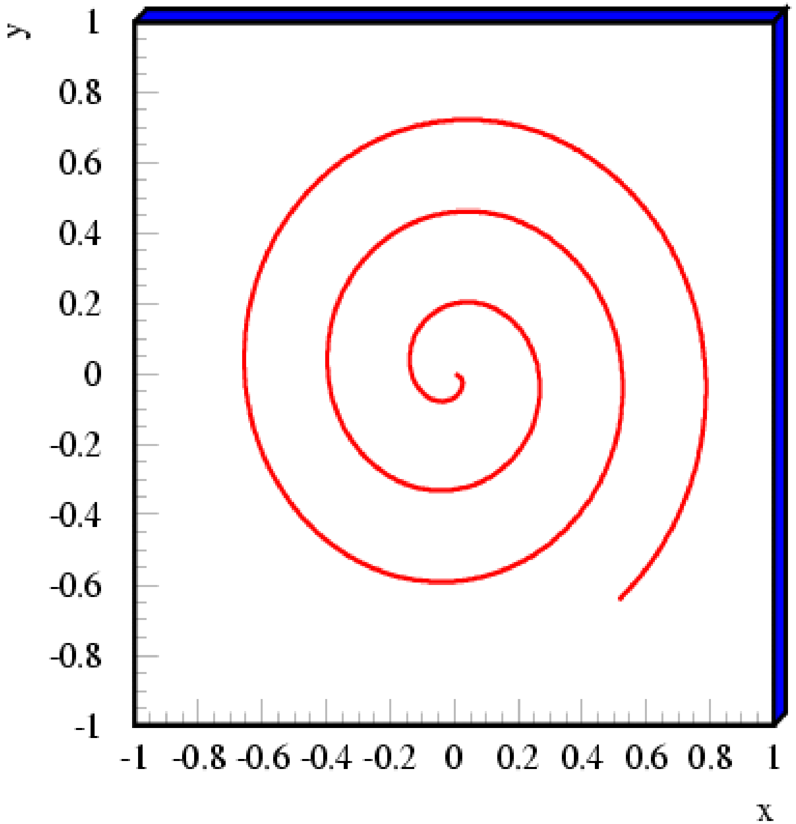
$$p_t(z) = \sqrt{\frac{B(z)}{B_i}}\, p_{t0} \qquad (2-22)$$

The radius of the circular motion is

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

The radius is increased up to

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



AMD(4)

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

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

Adiabatic case

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

The difference is coming from the adiabatic motion and transverse momentum is transfered to the longitudinal direction.

AMD(5)

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

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

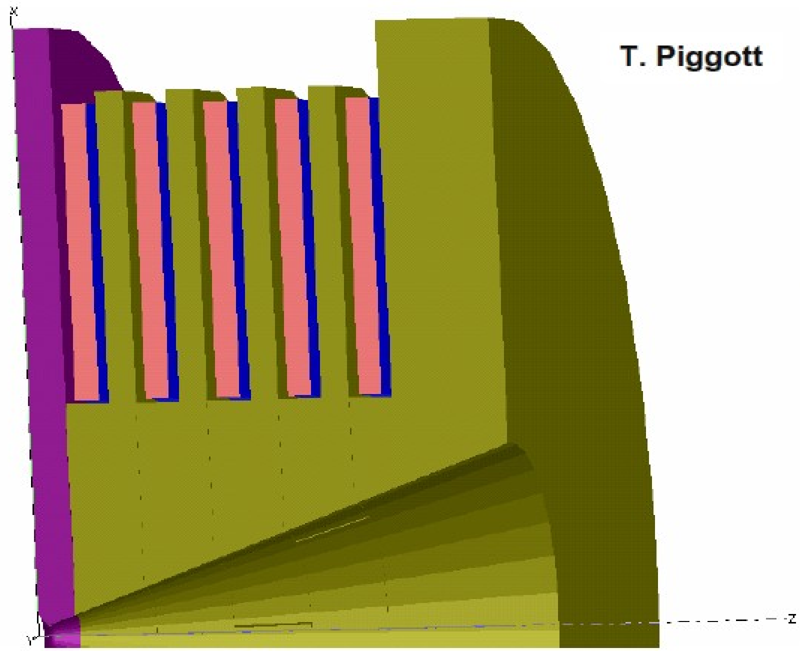
If the longitudinal momentum is too large, the variation of the solenoid field, B(z), becomes too fast to break the adiabatic condition.

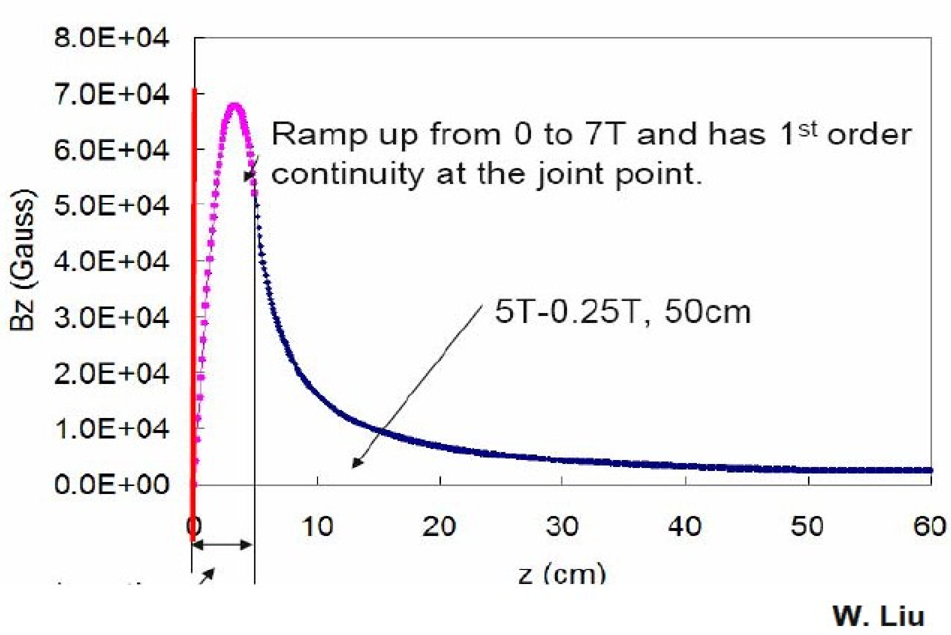
$$p_z < 0.5 \frac{eB_i}{\mu} \qquad (2-28)$$

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

AMD(6)

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



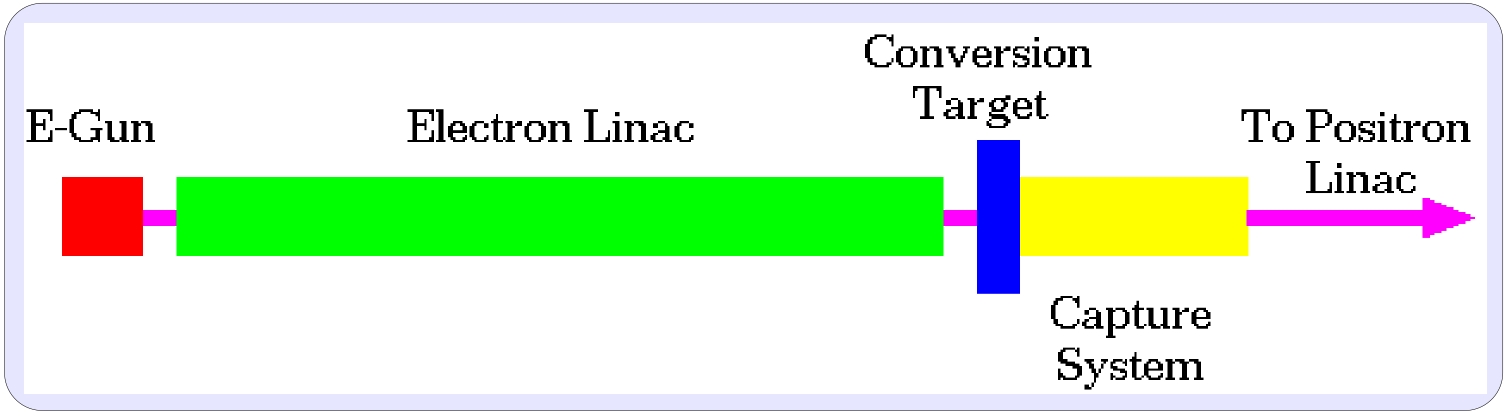


- AMD field is produced by flux-concentrator.
- Primary coil induces eddy current in the inner conductor.
- Because of the tapered shape of the inner conductor, the magnetic field is concentrated.
- Ramping from 0T to 7 T in 2cm (no field on target).
- B_i=5T and B_f is 0.25T.

Positron Source

Electron Driven (1)

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



Electron Driven (2)

Positron Generation
Positron Capture
Positron Source
Positron Source for LC
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, ε_0 is critical energy, in where energy loss by scattering and radiation is same.

The positron yield is

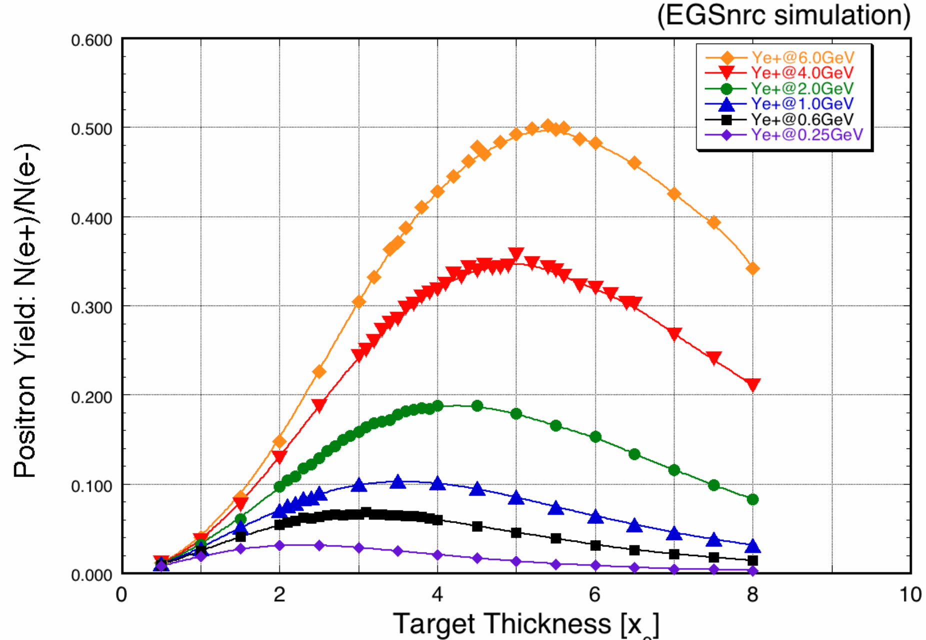
$$\eta = \frac{N_{pos}}{N_{ele}} \qquad (3-2)$$

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

where η is simple yield and

η_n is the normalized yield.

(EGSnrc simulation)



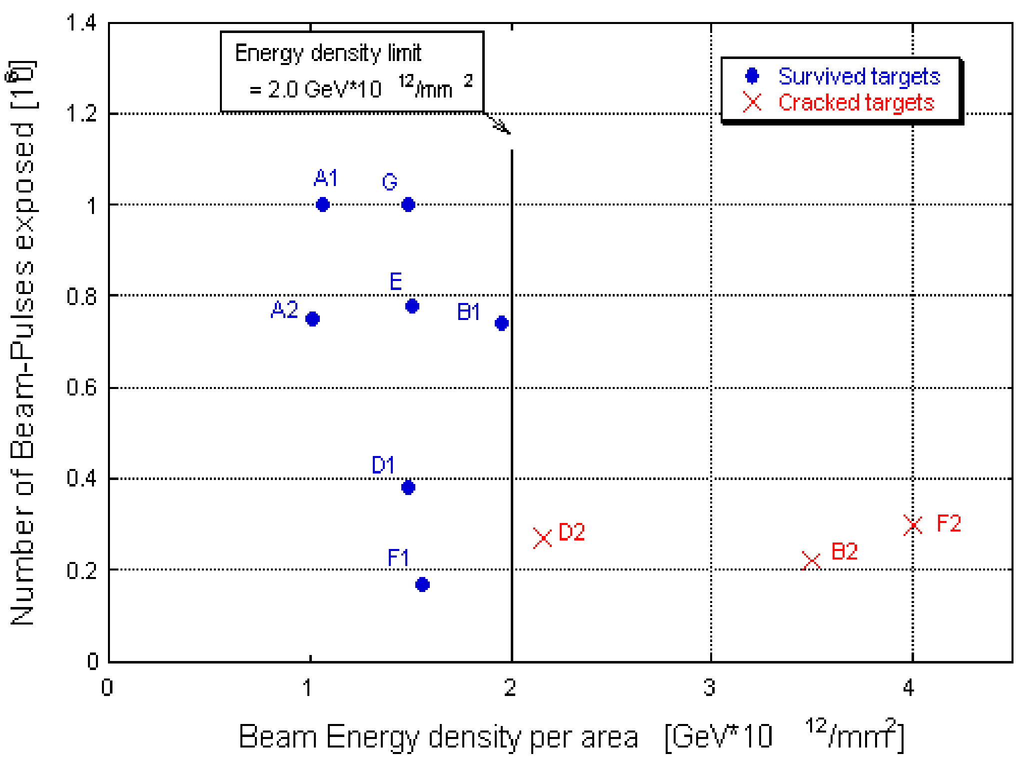
Courtesy of T.Kamitani

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 of this thermal energy.
- The destruction can be occurred several processes,
  - Melting,
  - Fatigue,
  - Mechanical destruction by shock wave,etc.
- Several novel ideas are proposed to solve this issue.

Damage Threshold (1)

- 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}/mm^2 or 320J/mm^2 .



S. Ecklund, SLAC-CN-128

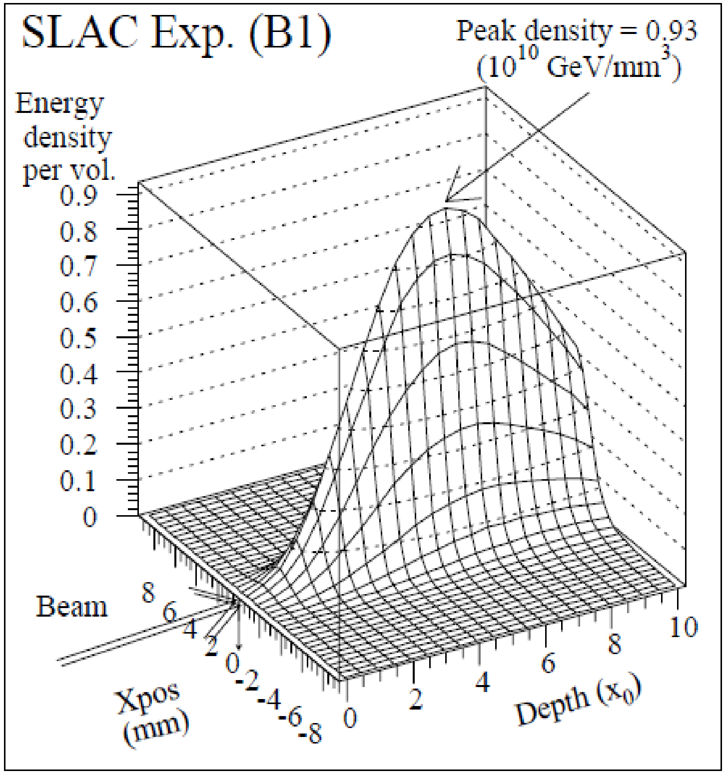
To evaluate the damage threshold in more general way, the energy deposited density at SLAC experiment is extracted.

$$\rho = 0.93 \times 10^{10} \ [GeV/mm^3]$$

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

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

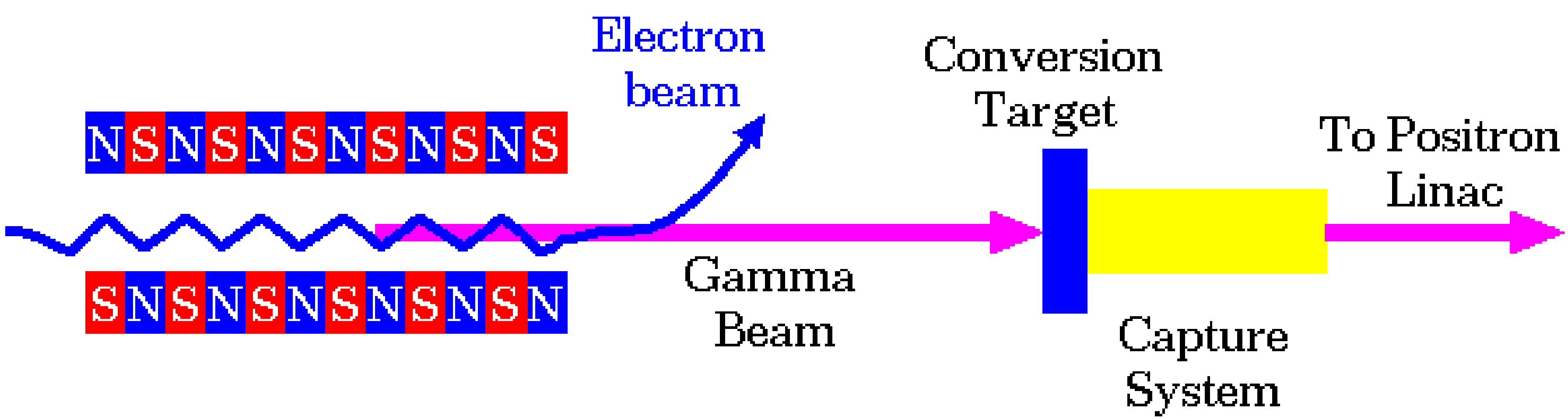
$$\rho = 35 [J/g]$$



T. Kamitani

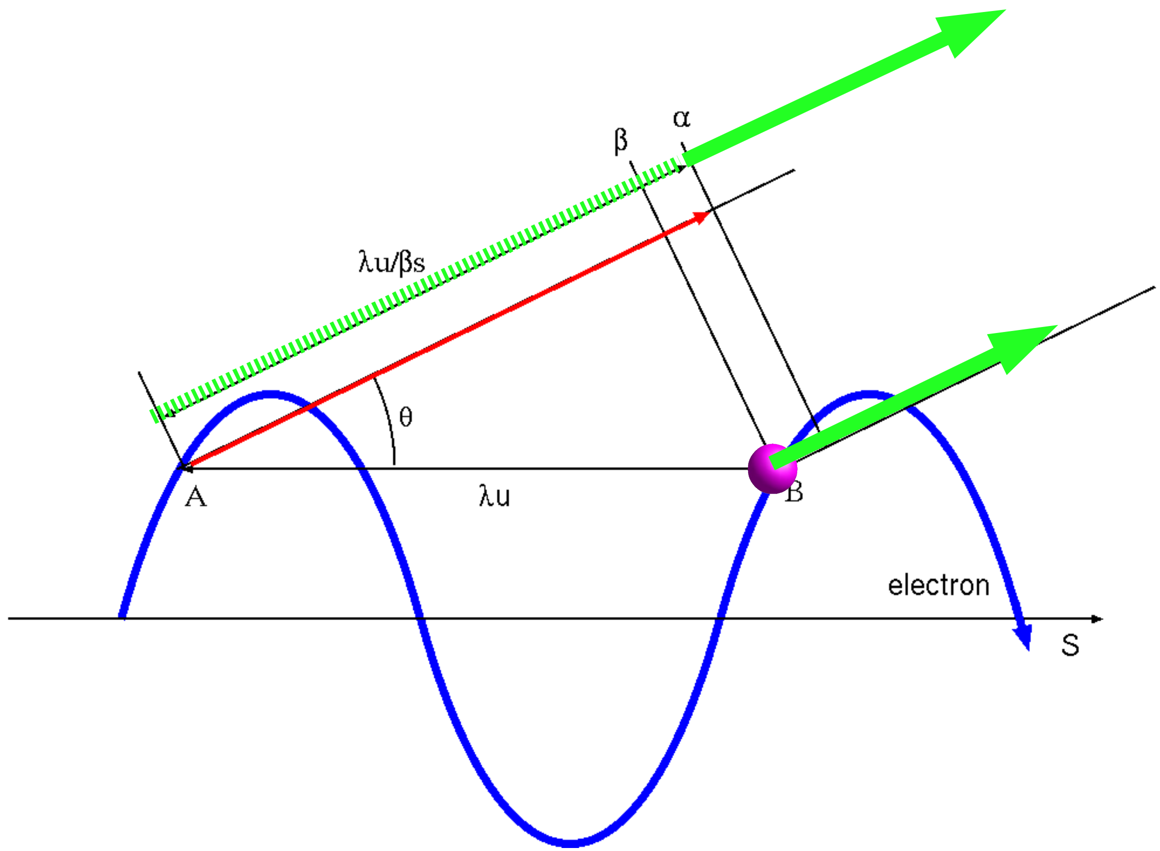
Undulator Scheme

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



Undulator Radiation (1)

- 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.



Undulator radiation (2)

Field of helical undulator is given by

$$\boldsymbol{B}=B_0\cos\left(2\pi\frac{z}{\lambda_u}\right)\boldsymbol{e}_i+B_0\sin\left(2\pi\frac{z}{\lambda_u}\right)\boldsymbol{e}_i \qquad (3-4)$$

Electron trajectory is given by

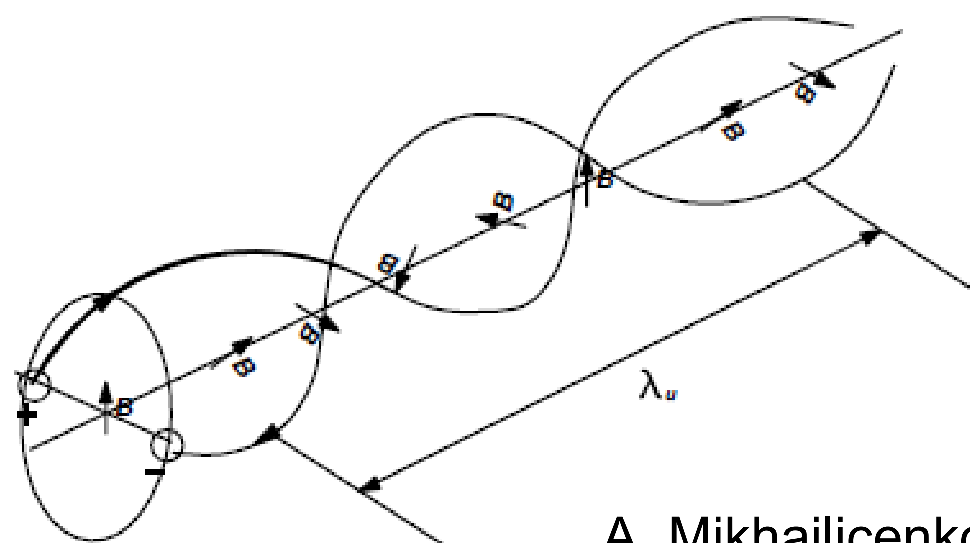
$$\boldsymbol{r}(s)=r\sin\left(\frac{2\pi\bar{\beta}}{\lambda_u\beta}s\right)\boldsymbol{e}_i+r\cos\left(\frac{2\pi\bar{\beta}}{\lambda_u\beta}s\right)\boldsymbol{e}_j+s\,\boldsymbol{e}_k \qquad (3-5)$$

$$\bar{\beta}=\beta\sqrt{1-\frac{K^2}{\gamma^2}} \qquad (3-6)$$

$$K=\frac{eB\lambda_u}{2\pi mc}$$

$$=93.4\,B[T]\lambda_u[m] \qquad (3-7)$$

$$r=\frac{K\lambda_u}{2\pi\gamma} \qquad (3-8)$$



A. Mikhailicenko

Undulator radiation (3)

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

$$\lambda_1=\frac{\lambda_u}{2\mathrm{n}\,\gamma^2}\left(1+K^2+\theta^2\gamma^2\right) \qquad (3-9)$$

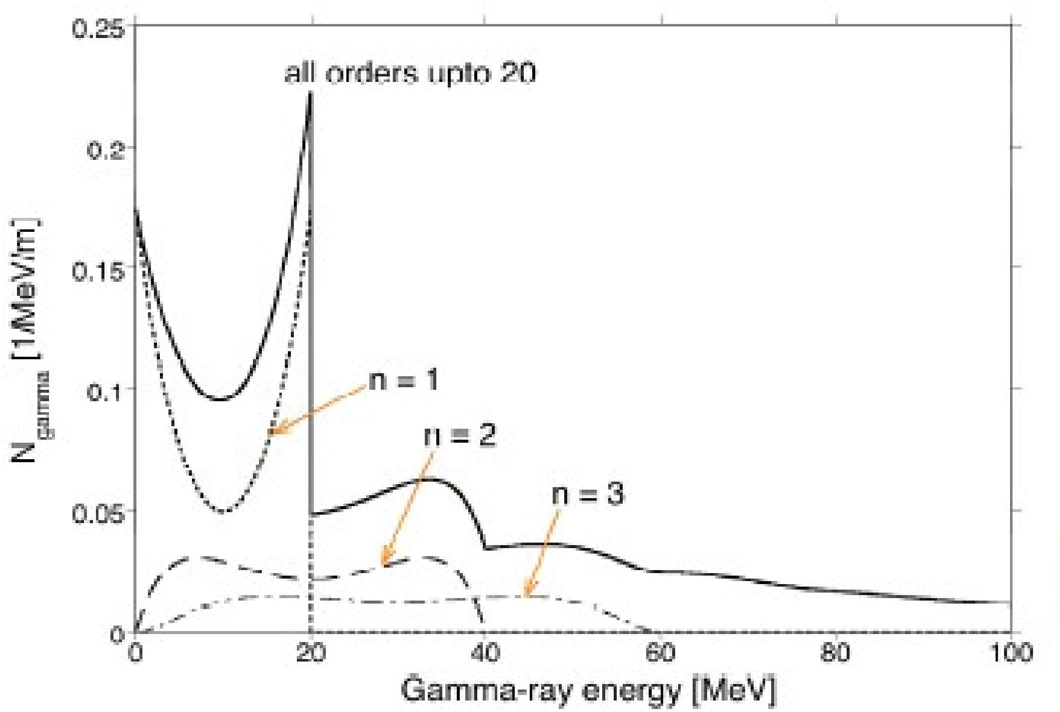
$$E_1[eV]=9.50\frac{nE^2[GeV^2]}{\lambda_u[m](1+K^2+\theta^2\gamma^2)}$$

$$\sim 9.50\frac{nE^2[GeV]}{\lambda_u[m](1+K^2)} \qquad (3-10)$$

Undulator Radiation (1)

Number of photons emitted from undulator (nth harmoincs) integrated over all solid angle is

$$\frac{d^2 N_{ph}}{dEdL}\left[\frac{1}{m.MeV}\right]=\frac{10^6 e^3}{4\pi\epsilon c^2 h^2}\frac{K^2}{\gamma^2}\left[J_n^{'}(x)^2+\left(\frac{\alpha_n}{K}-\frac{n}{x}\right)^2 J_n(x)^2\right] \quad (3-11)$$



Undulator Radiation (2)

The cut off photon energy from undulator is rewritten as

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

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

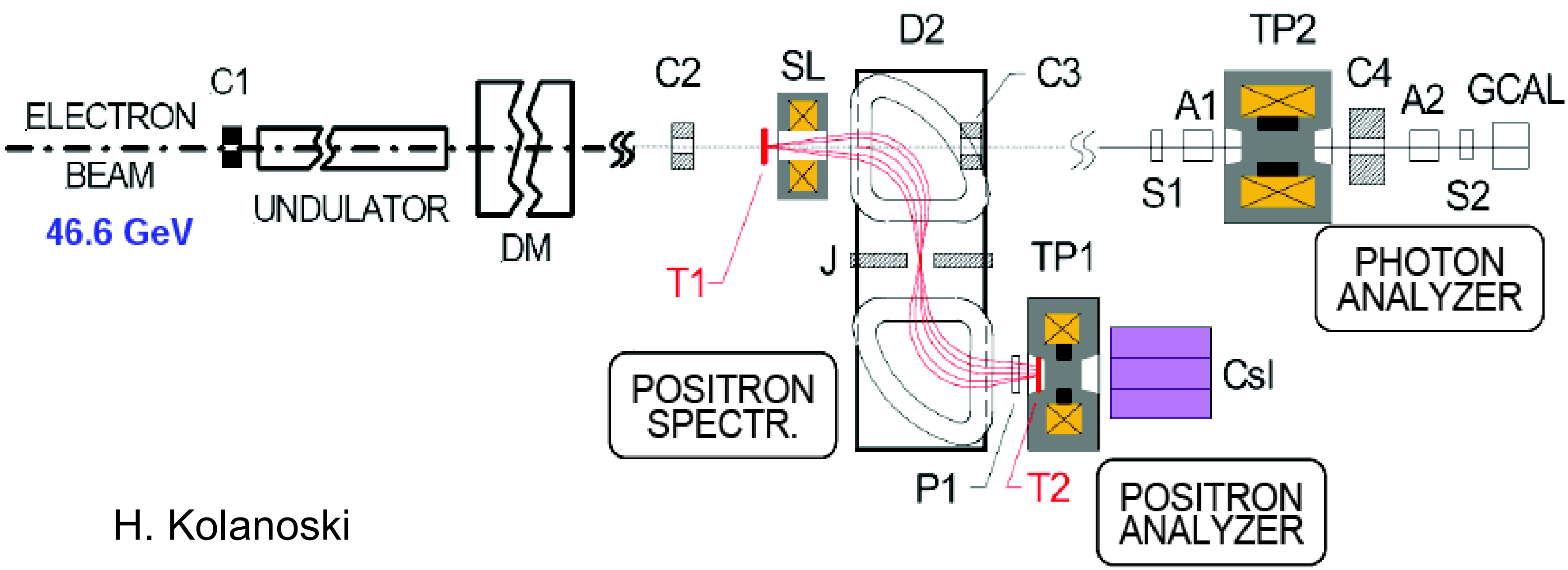
where ω_0 is photon energy, whose wave length is undulator period. The undulator radiation can be interpreted as scattering between electron and photon. The photon energy is boosted by the electron scattering by factor γ^2.

The undulator period is very long as photon wavelength and the energy is very low. Then, we need high boost factor γ^2. In fact, the energy is more than 100 GeV and a dedicated electron linac is unrealistic. For ILC, we "share" the same electron linac for collision.

E166 (1)

Positron Generation
Positron Capture
Positron Source
Positron Source for LC
Summary

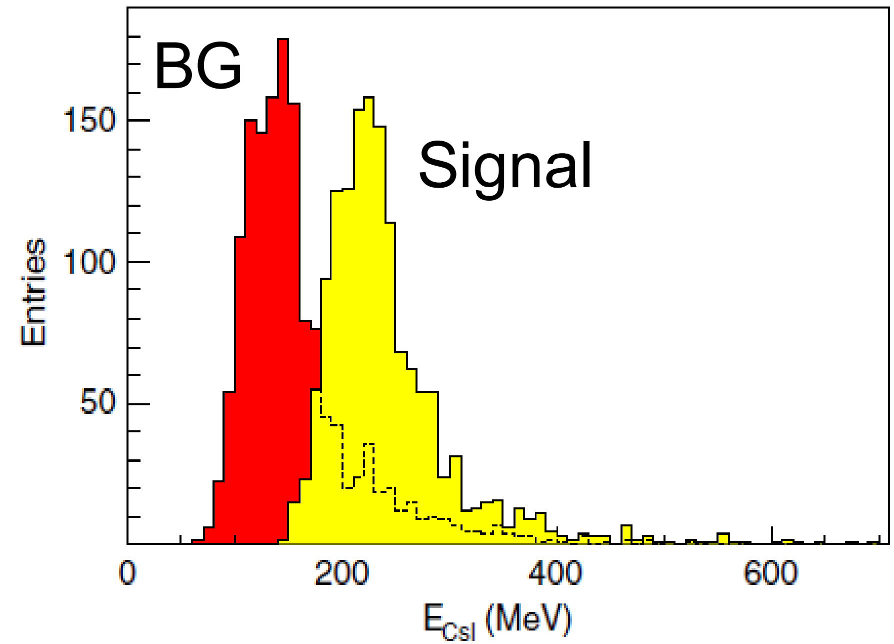
- E166 is an experiment, which was carried out at SLAC to demonstrate the polarized positron production with helical undulator.
- 46.6 GeV electron beam passes through 1m undulator, K=0.17 (0.71T, λ_u=2.54mm).
- γ and positron polarization is analyzed by transmission method.



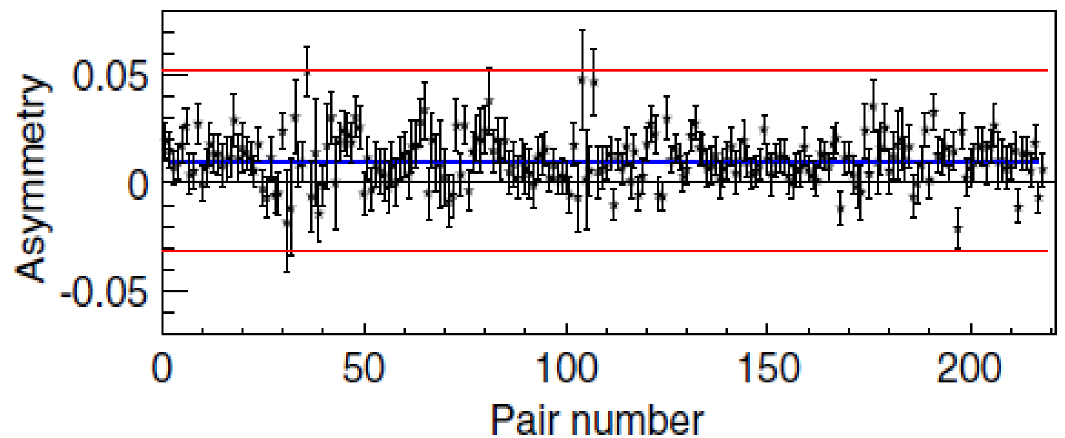
H. Kolanoski

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.



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



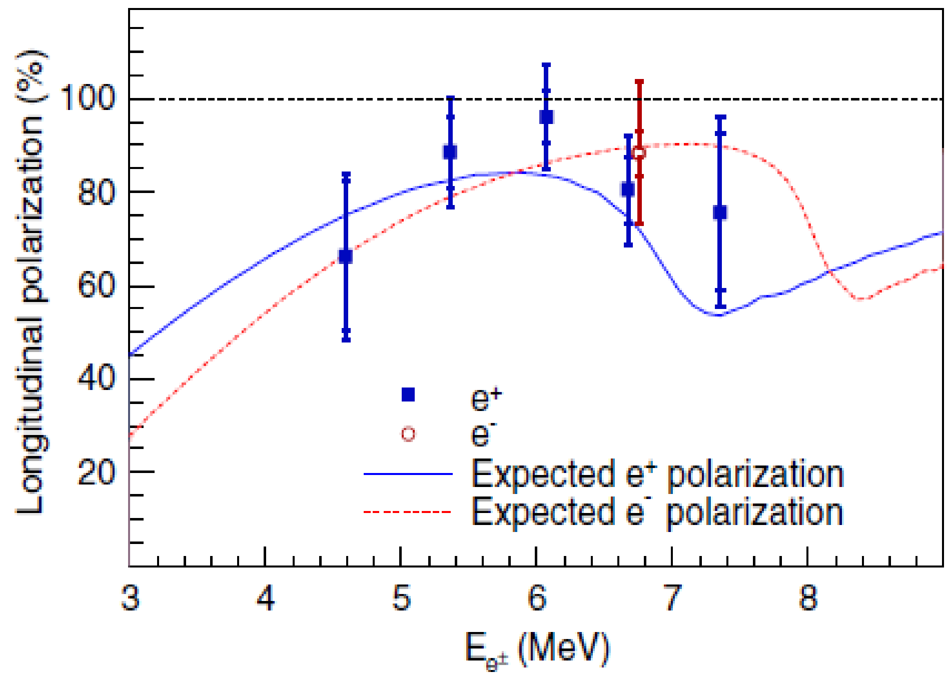
G. Alexander

E166 (3)

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.

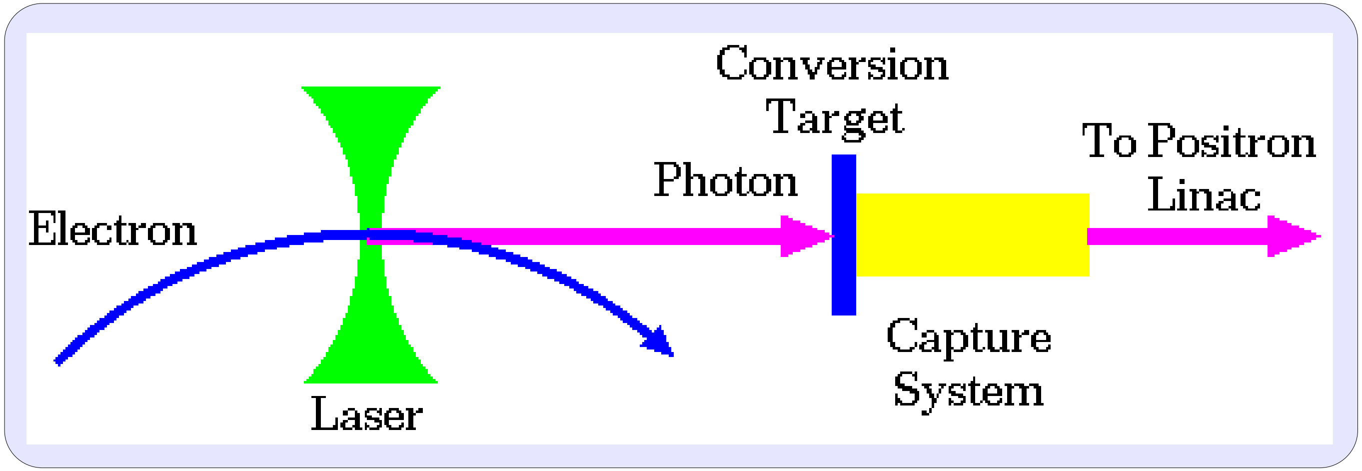


$E_{e^\pm}$	$\delta \pm \sigma_\delta(\text{stat})$	A	$P \pm \sigma_P(\text{stat}) \pm \sigma_P(\text{syst})$
4.6 (e^+)	0.69 ± 0.17	0.150	66 ± 16 ± 8
5.4 (e^+)	0.96 ± 0.08	0.156	89 ± 8 ± 9
6.1 (e^+)	1.08 ± 0.06	0.162	96 ± 6 ± 10
6.7 (e^+)	0.92 ± 0.08	0.165	80 ± 7 ± 9
6.7 (e^-)	0.94 ± 0.05	0.153	88 ± 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.
- If the laser is circularly polarized, positron can be polarized.

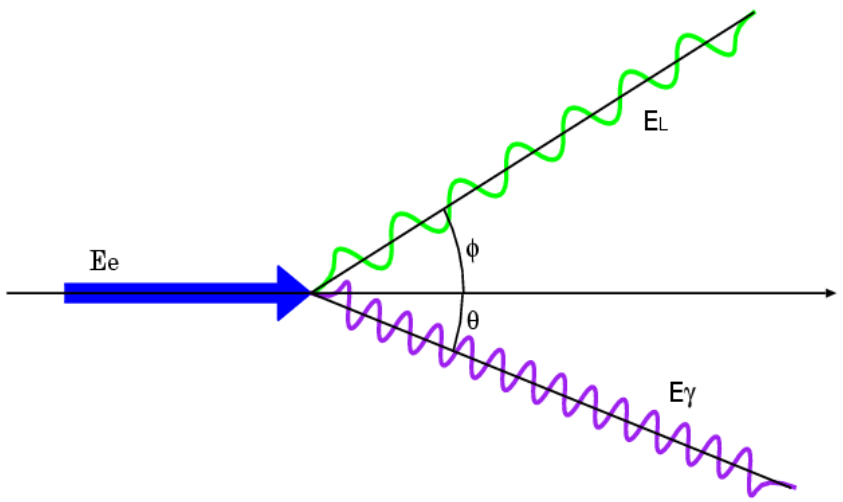


Compton Scheme (2)

- 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, γ=2000.
- E_γ ~ 16MeV



Compton Scheme (3)

Laser acts as a quite short period undulator.

The energy from Compton scattering is rewritten as

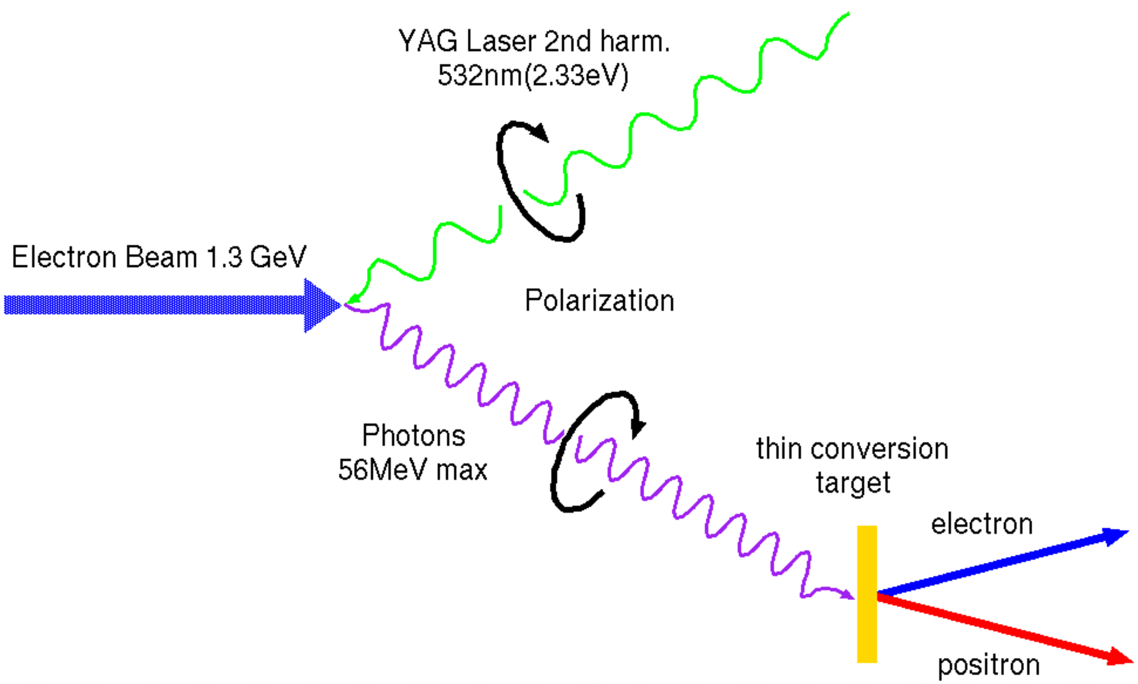
$$E_{\gamma} \sim 4\gamma^2 \hbar \frac{2\pi c}{\lambda_L} \qquad (3-17)$$

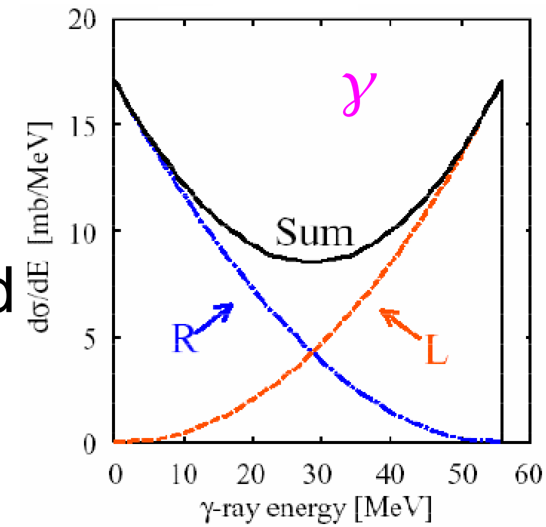
where λ_L is laser wave length. The laser photon is boosted by electron with factor $4\gamma^2$.

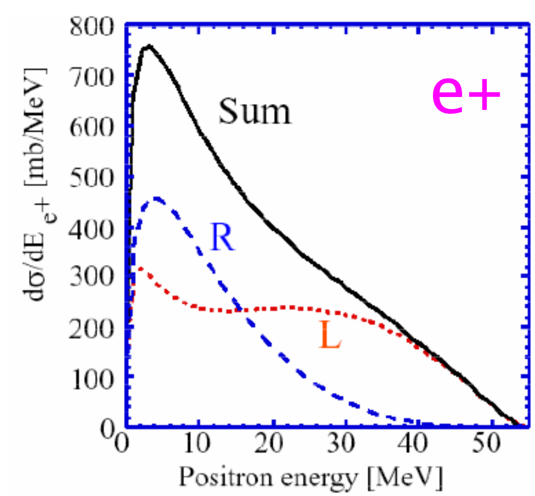
High energy gamma (several 10s MeV) is obtained with few GeV electron beam. A dedicated electron linac is a reasonable.

Compton Scheme (4)

- 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 polarize.

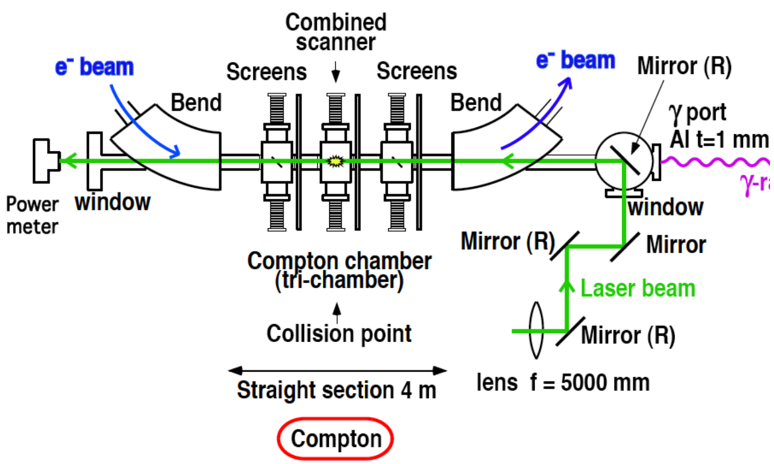


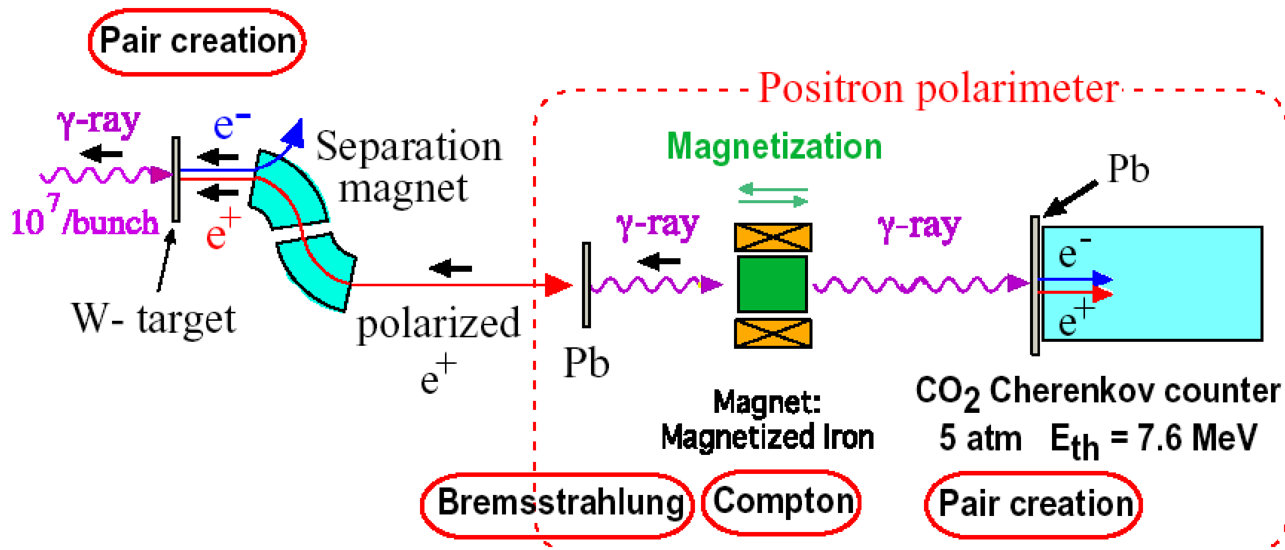


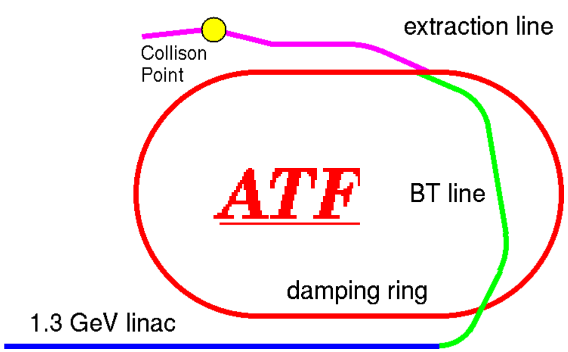


Compton Scheme (5)
Experiment at KEK-ATF

Positron: production, selection, and polarimetry







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

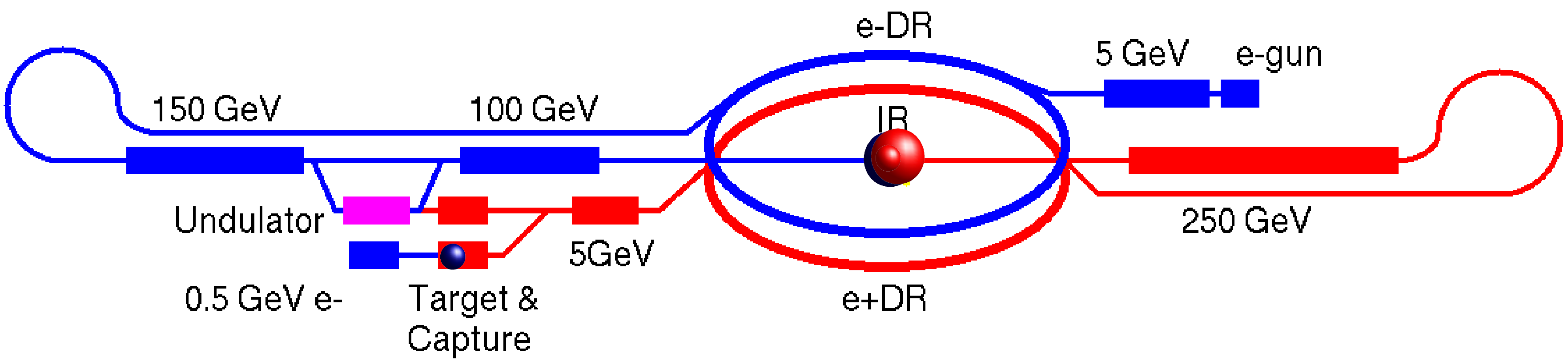
Positron Source For LC

ILC Positron Source

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

- Undulator scheme+ low intensity electron driven scheme (10%) is a baseline configuration.
- Compton scheme is an advanced alternative.
- Electron driven scheme is a fall back.

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



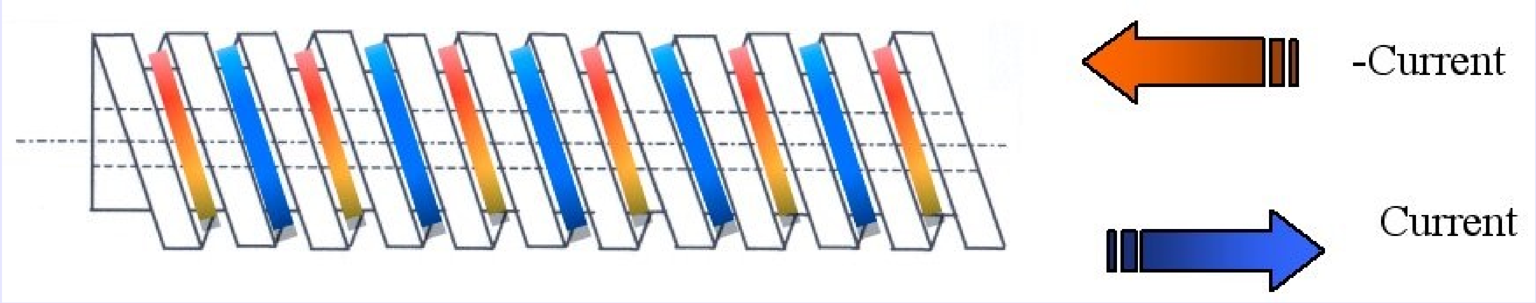
- Gamma rays for positron generation is produced by passing 150 GeV electron through undulator.
- Gamma rays are converted to positron.
- A positron source driven by 0.5 GeV electron is a back up for high availability.
- A common 5 GeV positron booster.

System Specifications

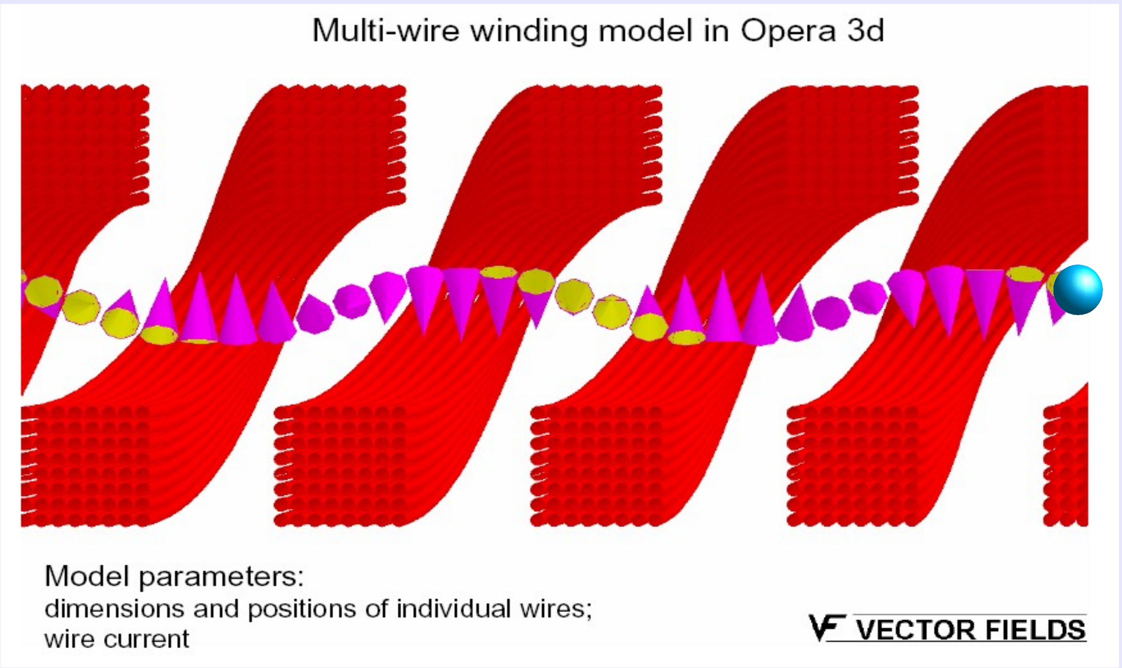
Positron Generation
Positron Capture
Positron Source
Positron Source for LC
Summary

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

Undulator Cryo-module Overview

Stainless steel vacuum vessel with Central turret

50K Al Alloy Thermal shield. Supported from He bath

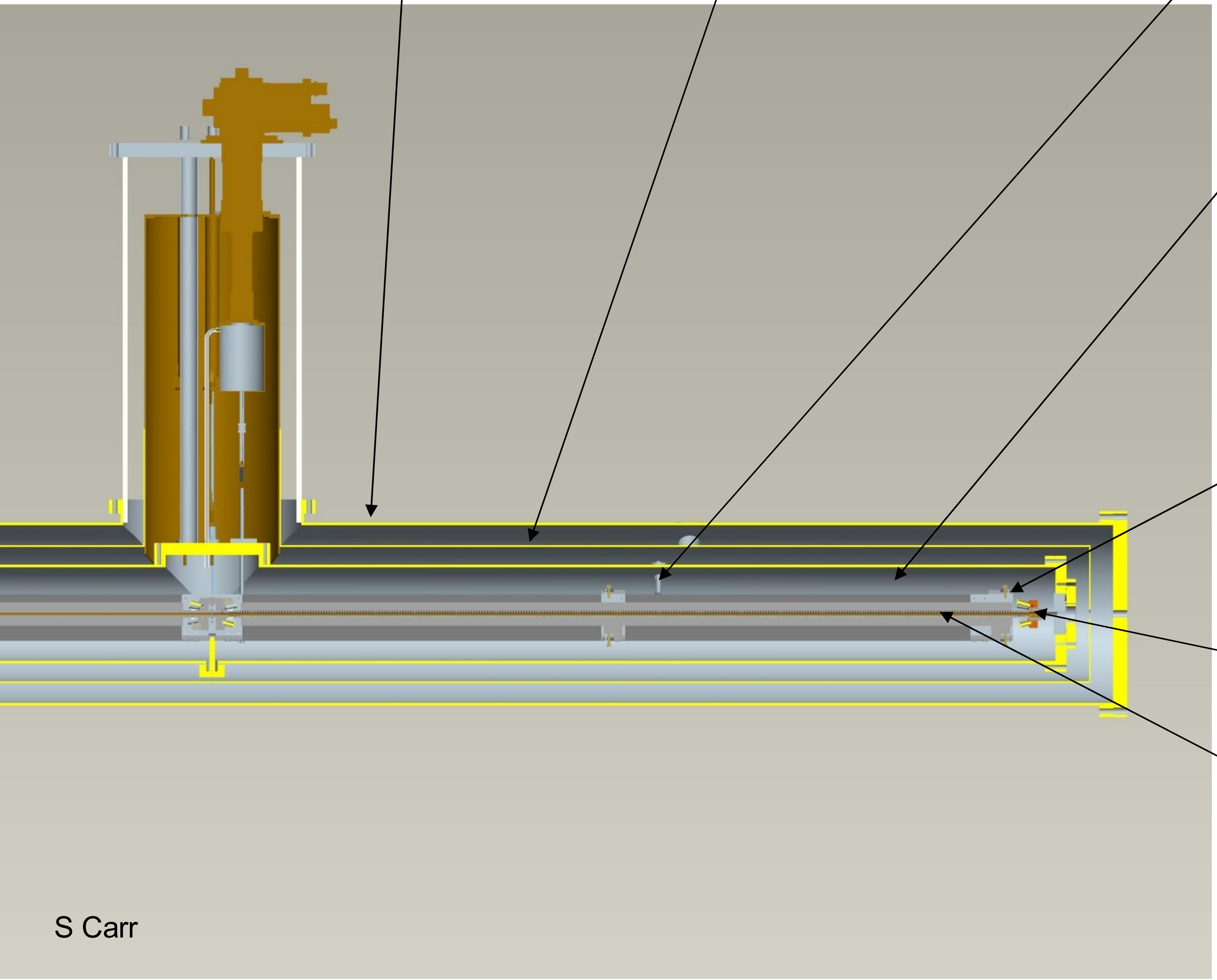
U beam Support rod

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

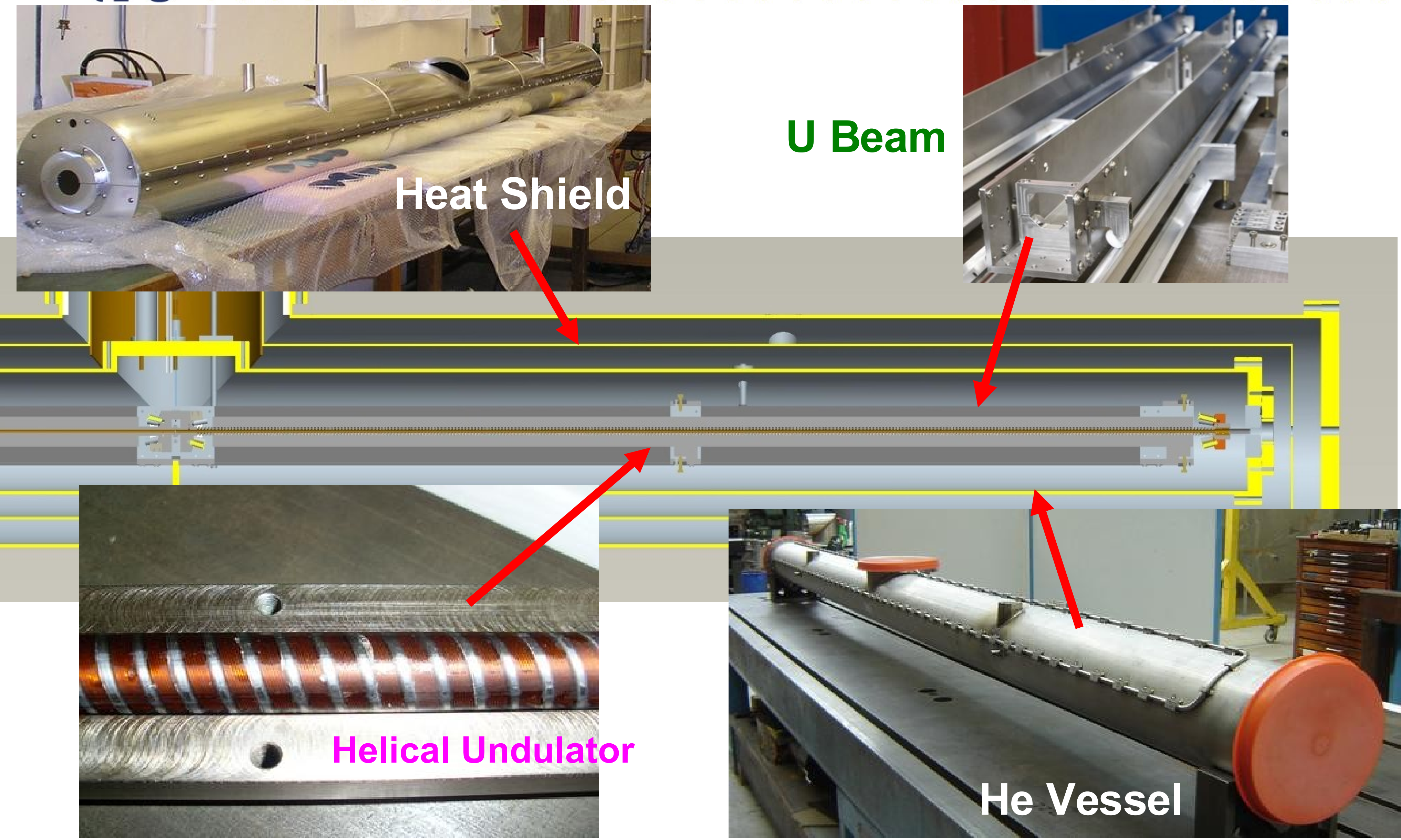
U Beam used to support/align the magnet.

Beam Tube

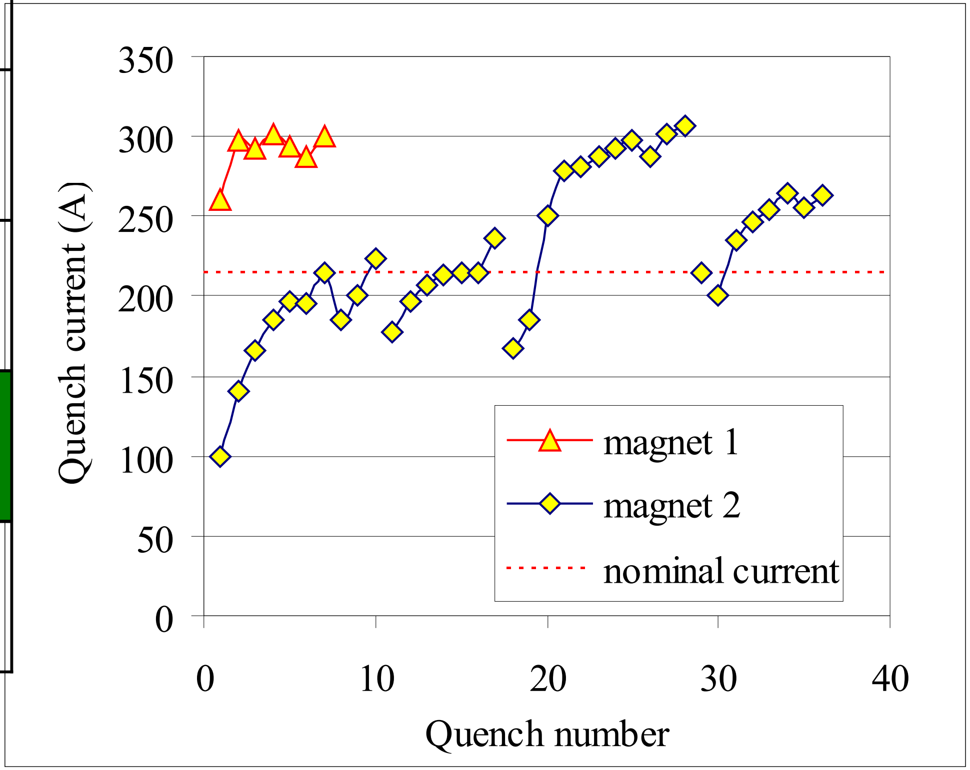
Magnet cooled to 4.2K by liq He in bath.

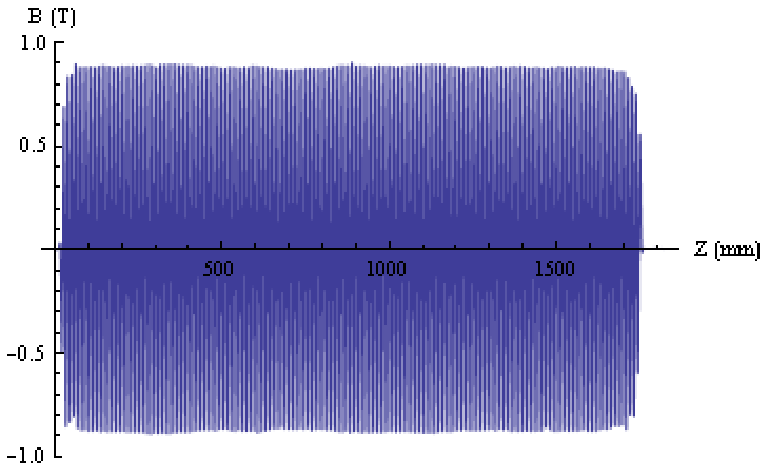


Undulator Cryomodule



Quench Test & Field Measurement





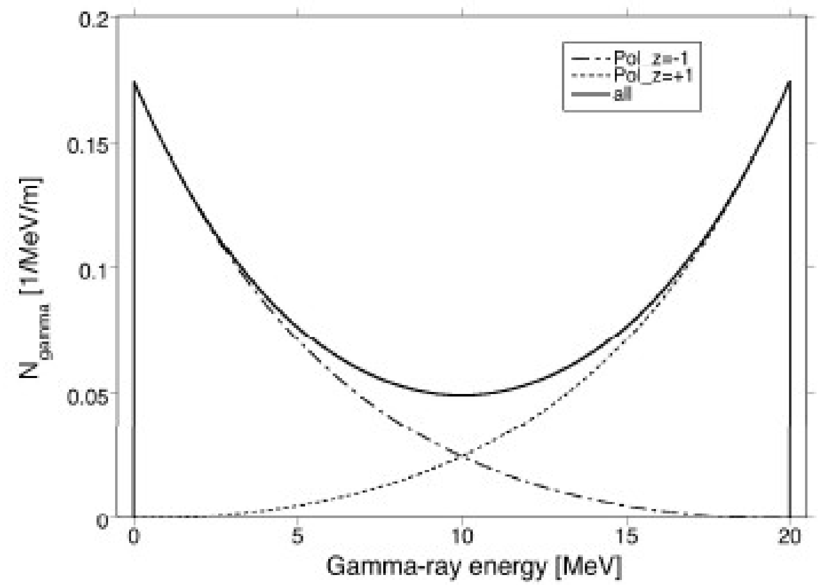
- All two magnets finally satisfied the specification.
- Field profile is measured by hall probe, showing a good quality.

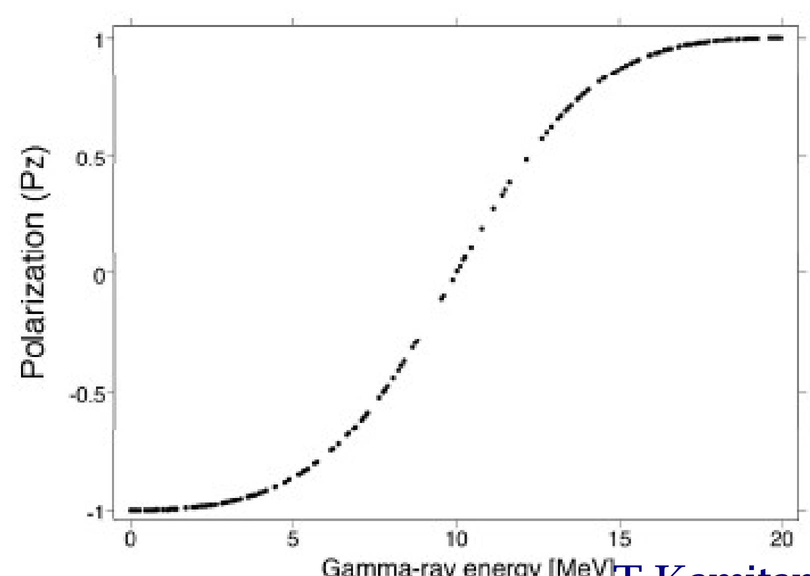
Polarized Positron

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

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

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

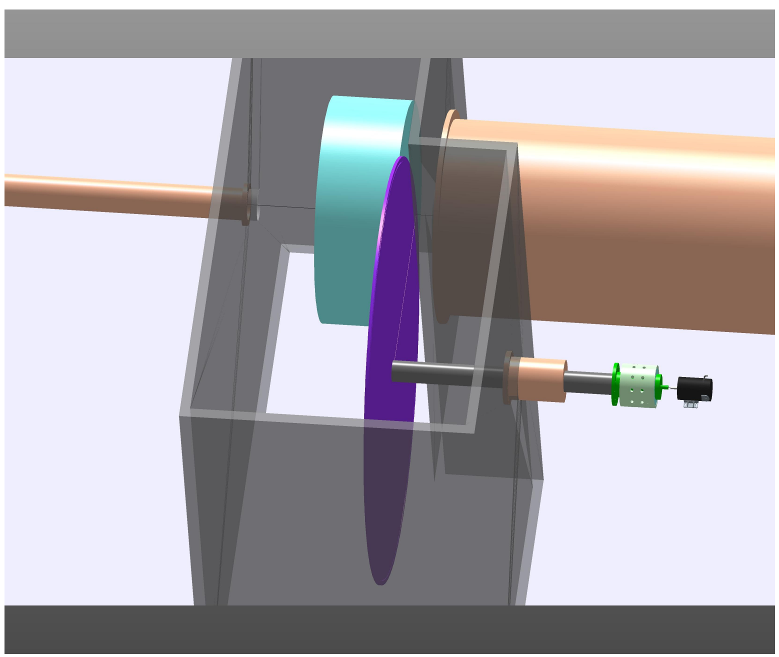


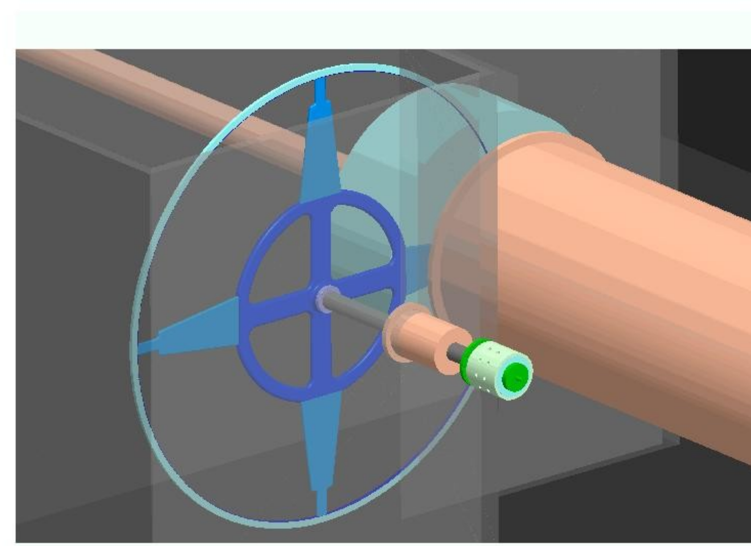


T.Kamitani

Target

- Target : Ti-6% Al-4% V with 0.4 X_0, rotating with tangential speed 100 m/s .
- Beam spot : 1.5 mm
- Heat load by gamma : 18 kW
- Heat load by Eddy current :20kW (rim) when the target is immersed in B field. Must be no B field.

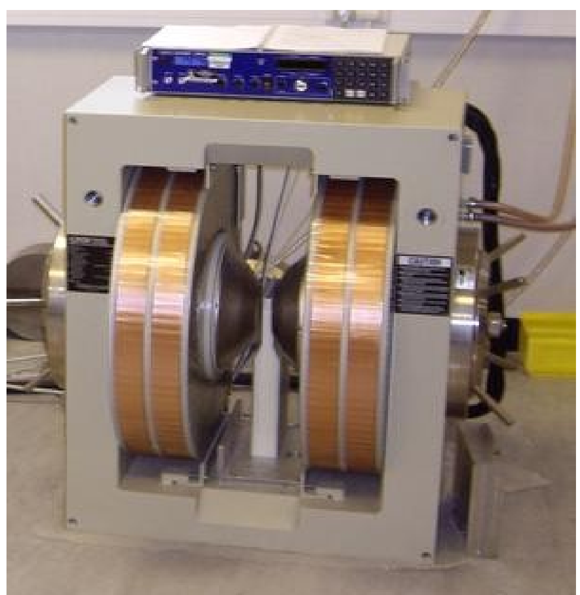




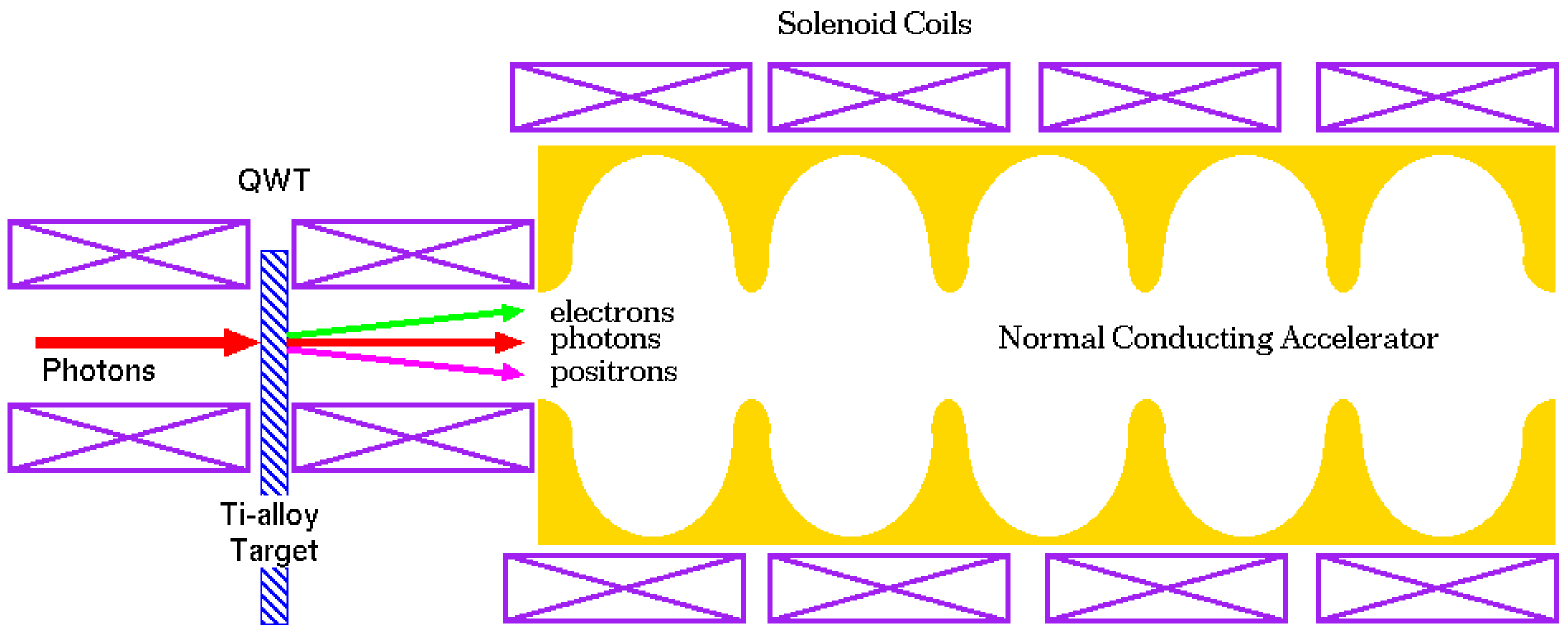
LLNL draft design

Target Prototype

Experiment in Cock-croft Inst. UK

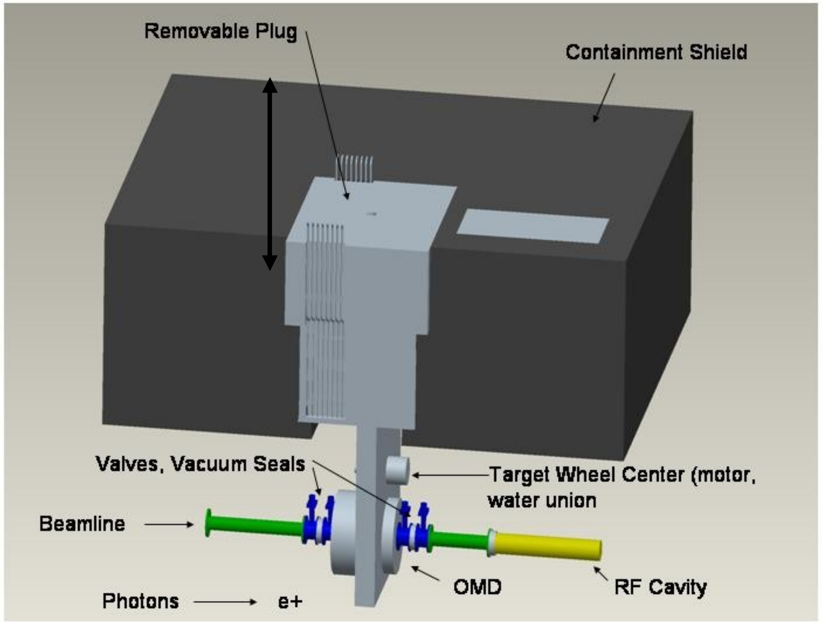


- QWT (B_i~1T, B_f~0.5T in 20cm): pulsed coil with bucking coil to shield magnetic field on target.
- L-Band NC accelerator tube with 12 ~ 15 MV/m.



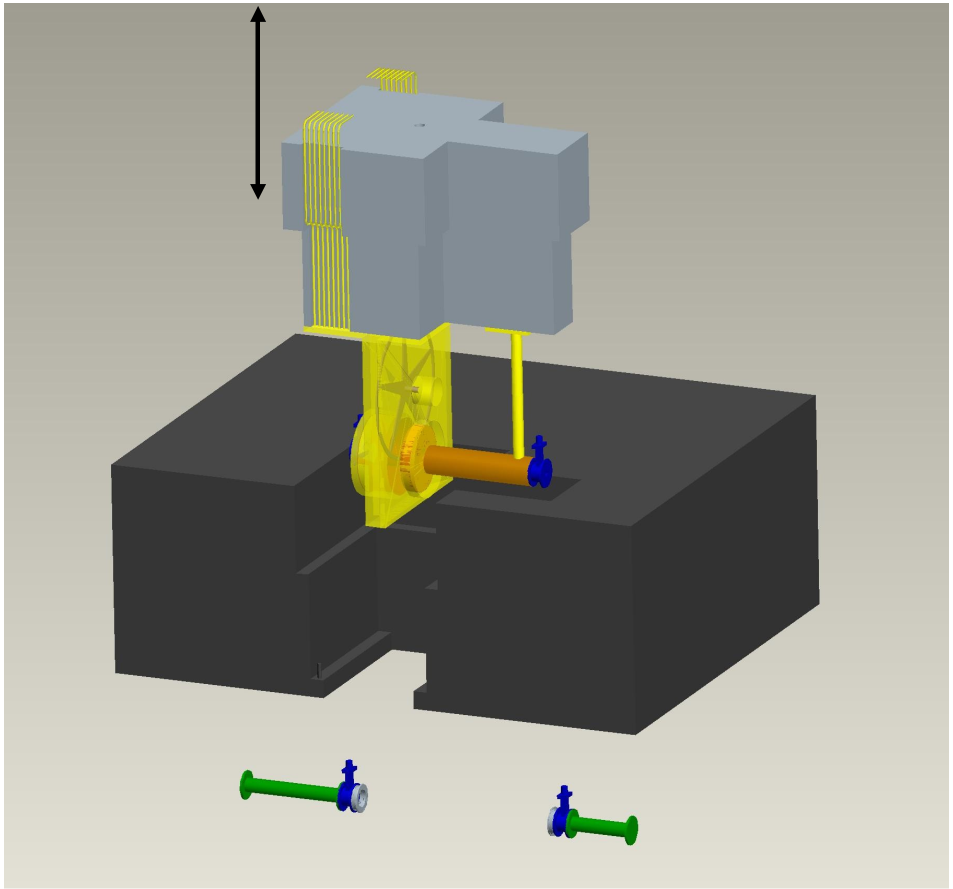
Remote Handling

Target Assembly In Place



1.25 m

Target Assembly Lifting Out

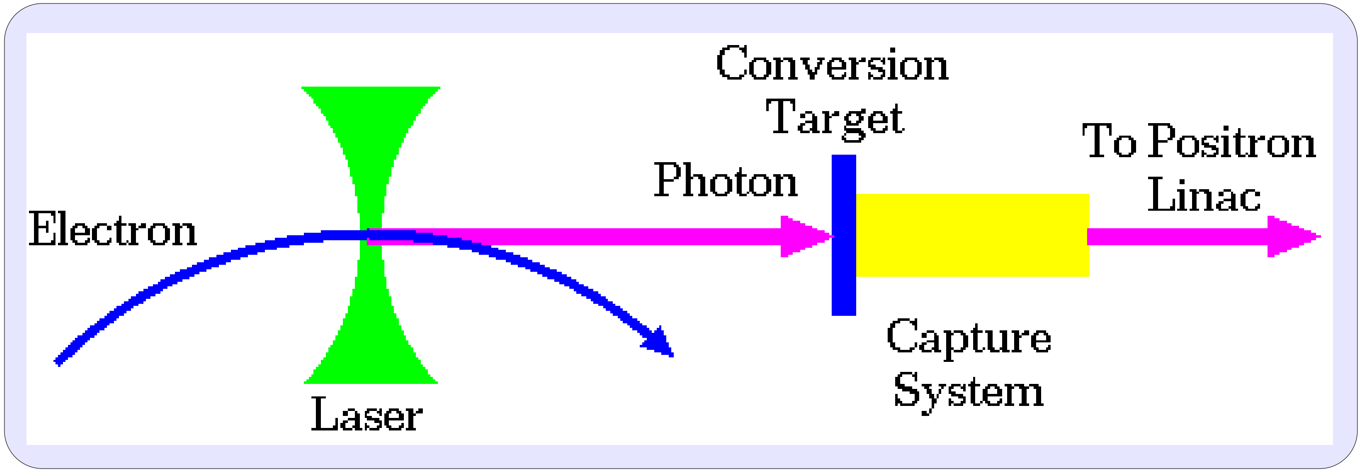


System consideration

- This system is a totally new approach; Feasibility of the system should be confirmed in various levels.
  - **Devices**
  - **System and sub-system**
- In addition, the ILC baseline e+ source is not an isolated system from the whole ILC and has inter-system dependencies.
- Careful considerations are necessary from the system point of view.
  - **E+ is generated at the same time for the collision.**
  - **E+ time structure is identical to that in ML.**
  - **For high availability, a backup source, which is independent and low intensity e+ source, is necessary.**

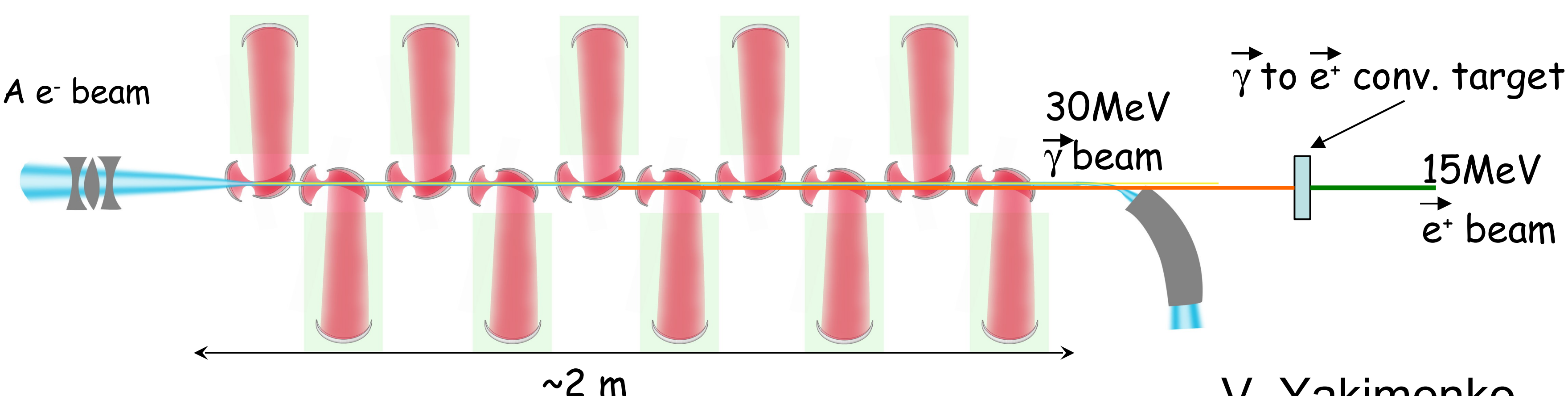
Laser Compton Scheme

- 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

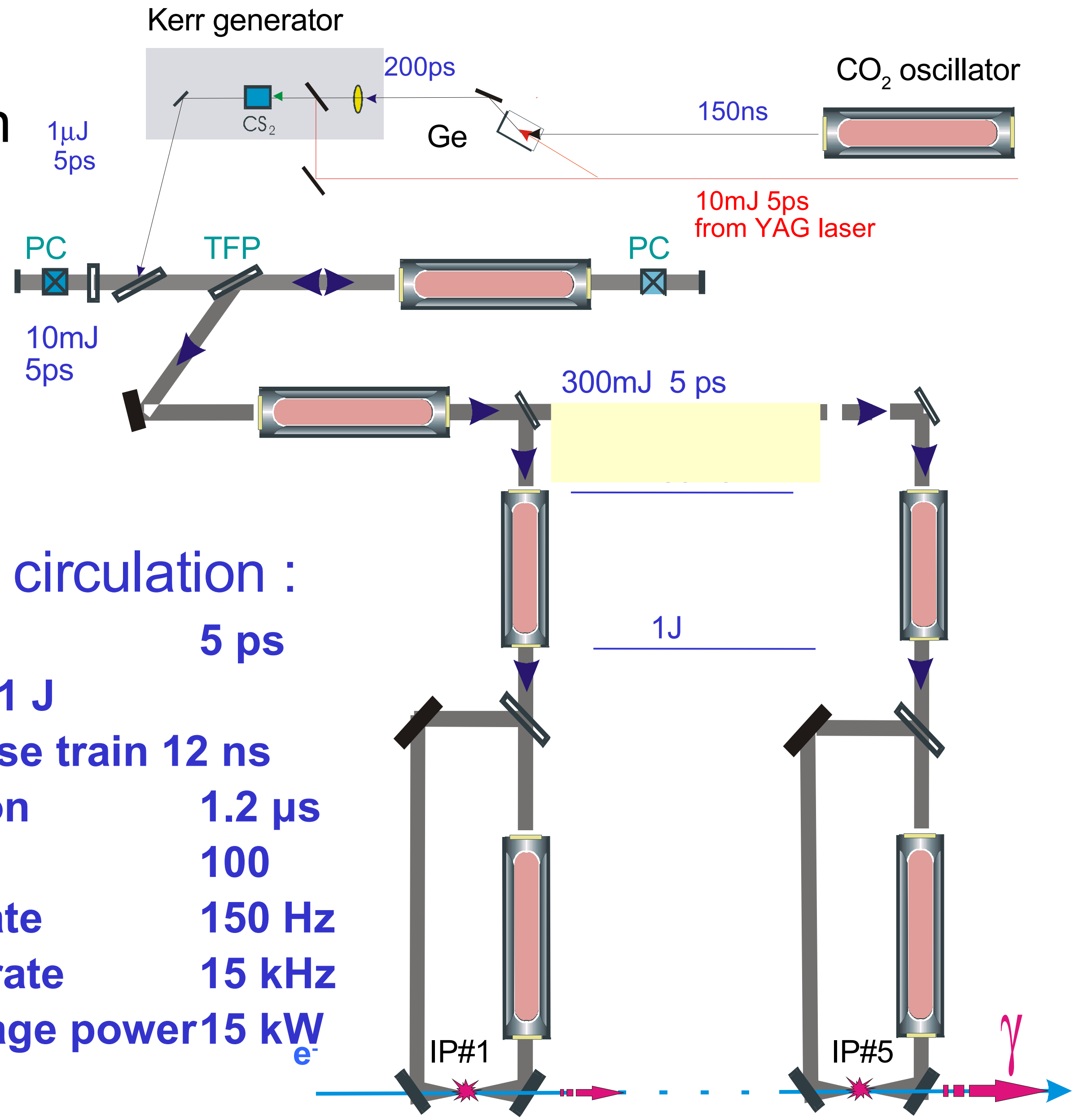
- Polarized gamma-ray beam is generated in the Compton back scattering inside optical cavity of CO_2 laser beam and 4 GeV e-beam produced by linac.
- Laser system relies on the commercially available lasers but need R&D for high repetition operation.
- Ring cavity with laser amplifier realizes the $C0_2$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



V. Yakimenko

Linac Laser Compton (2)

Linac Laser Compton scheme is designed with CO_2 laser system.



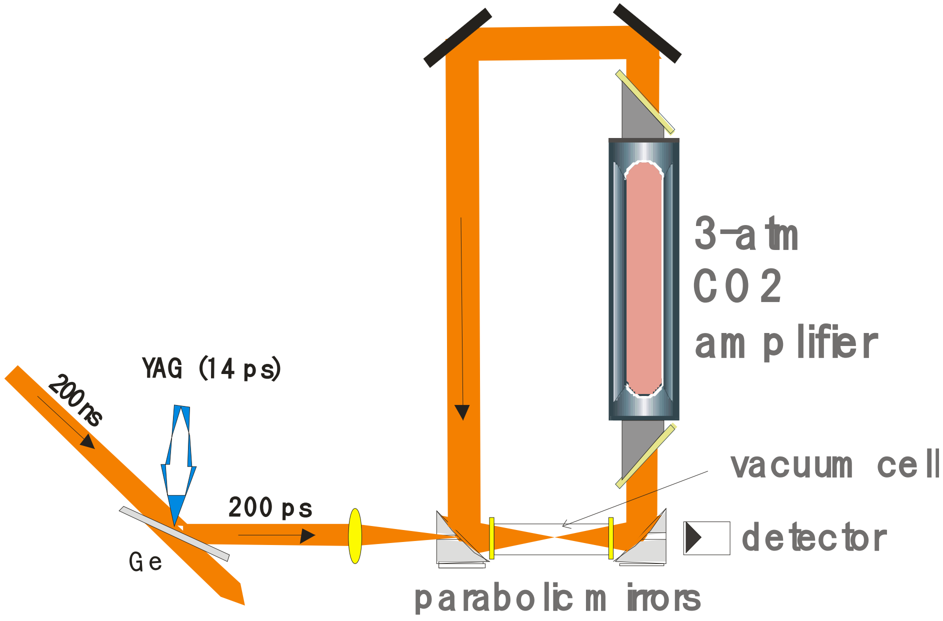
intra-cavity pulse circulation :

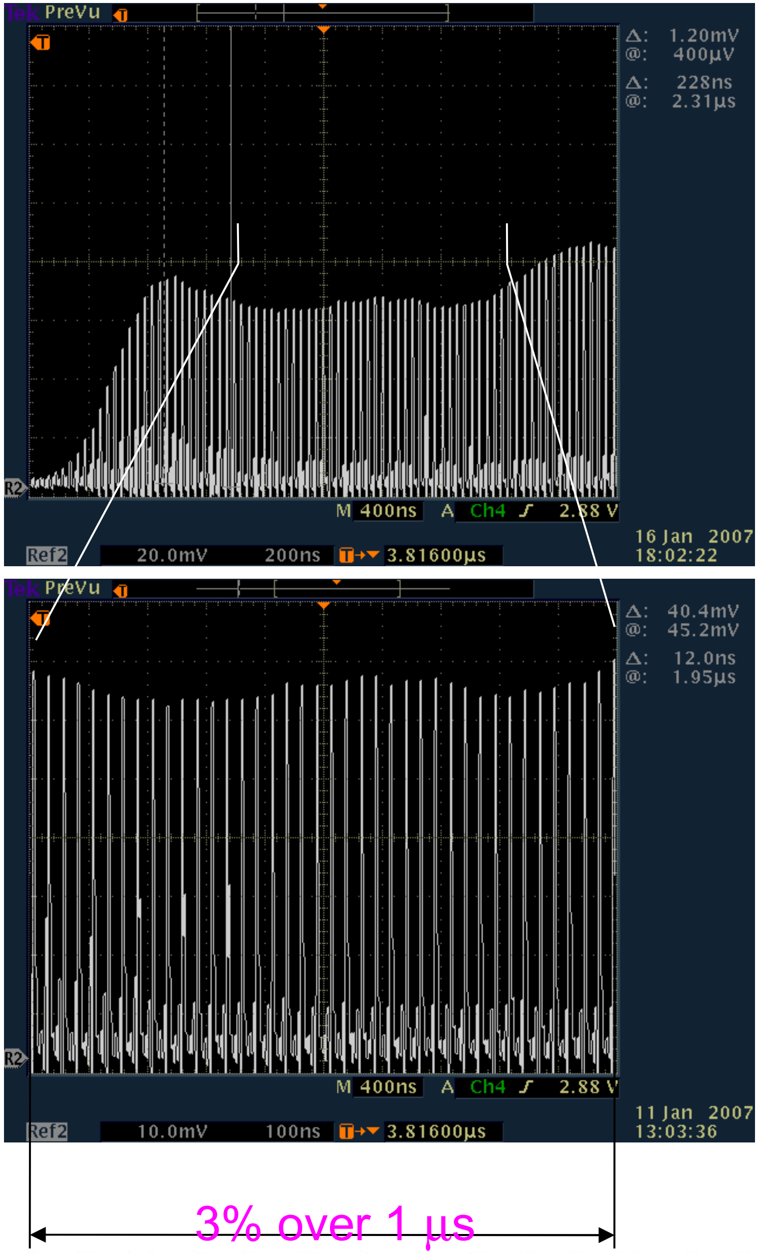
- pulse length 5 ps
- energy per pulse1 J
- period inside pulse train 12 ns
- total train duration 1.2 μs
- pulses/train 100
- train repetition rate 150 Hz
- Cumulative rep. rate 15 kHz
- Cumulative average power15 kW

V. Yakimenko, I. Pogorelsky

CO2 Laser Test Setup

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





Observations:

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

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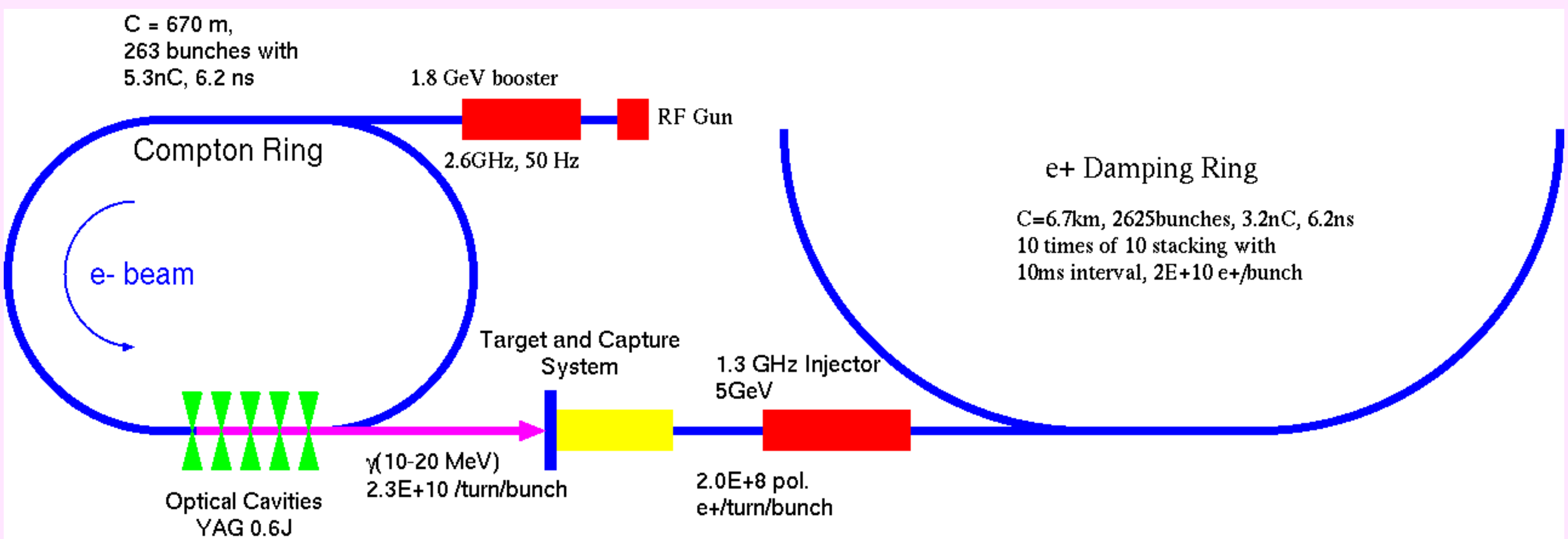
V. Yakimenko, I. Pogorelsky

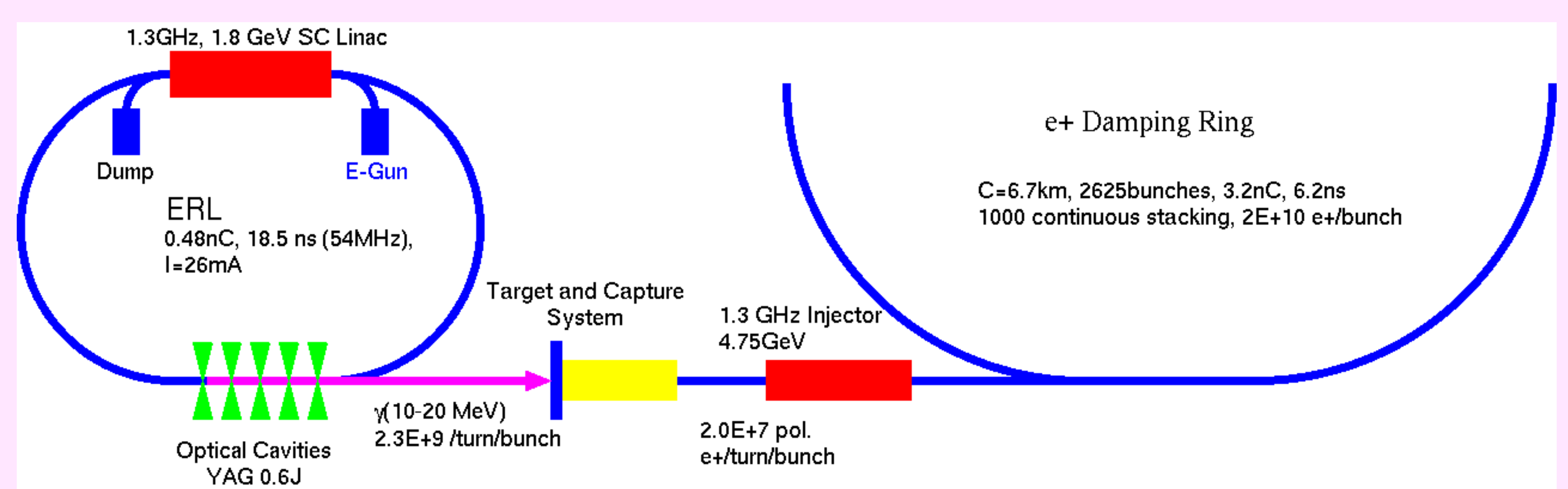
Compton Ring

- 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.



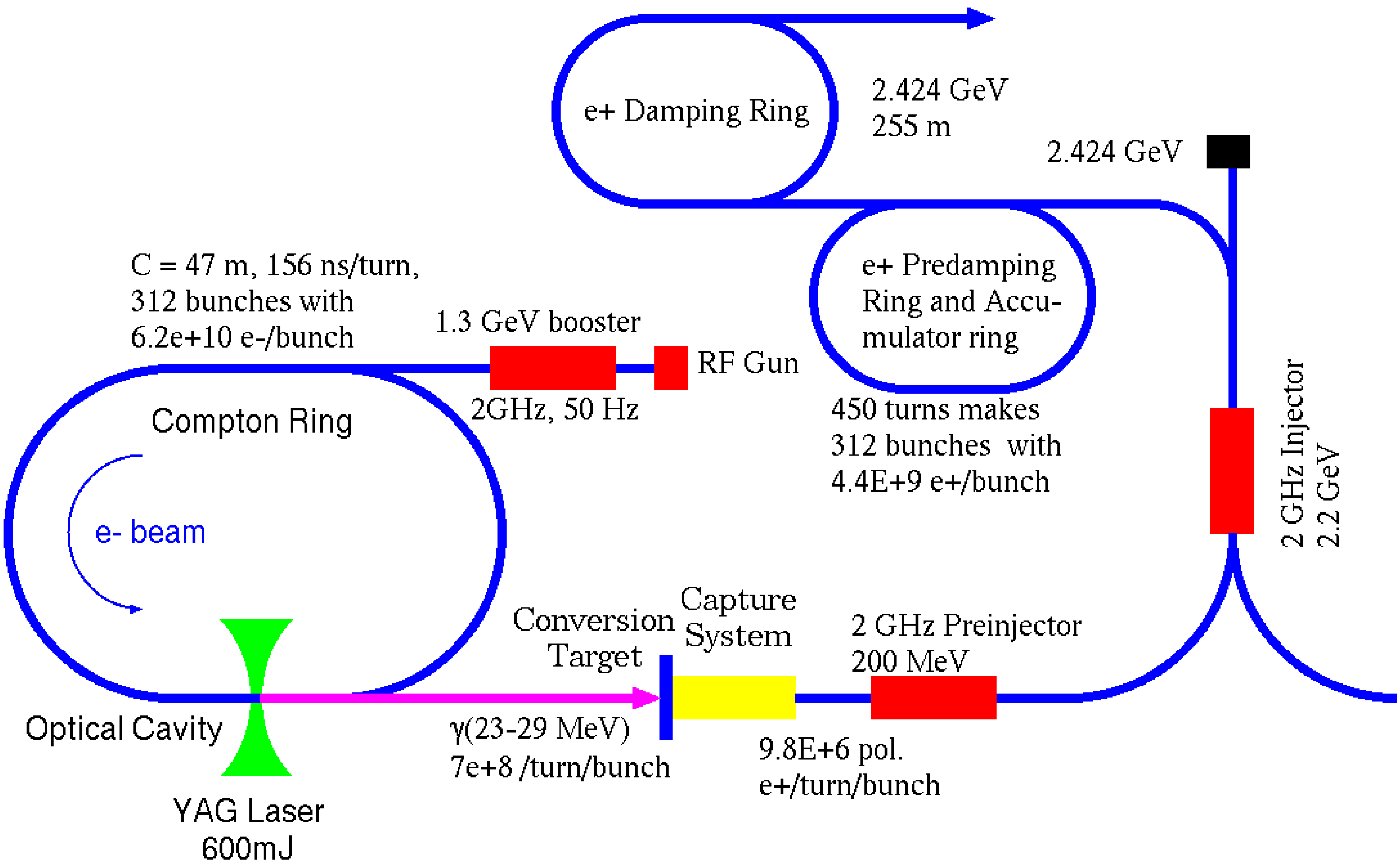
ERL

- 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.



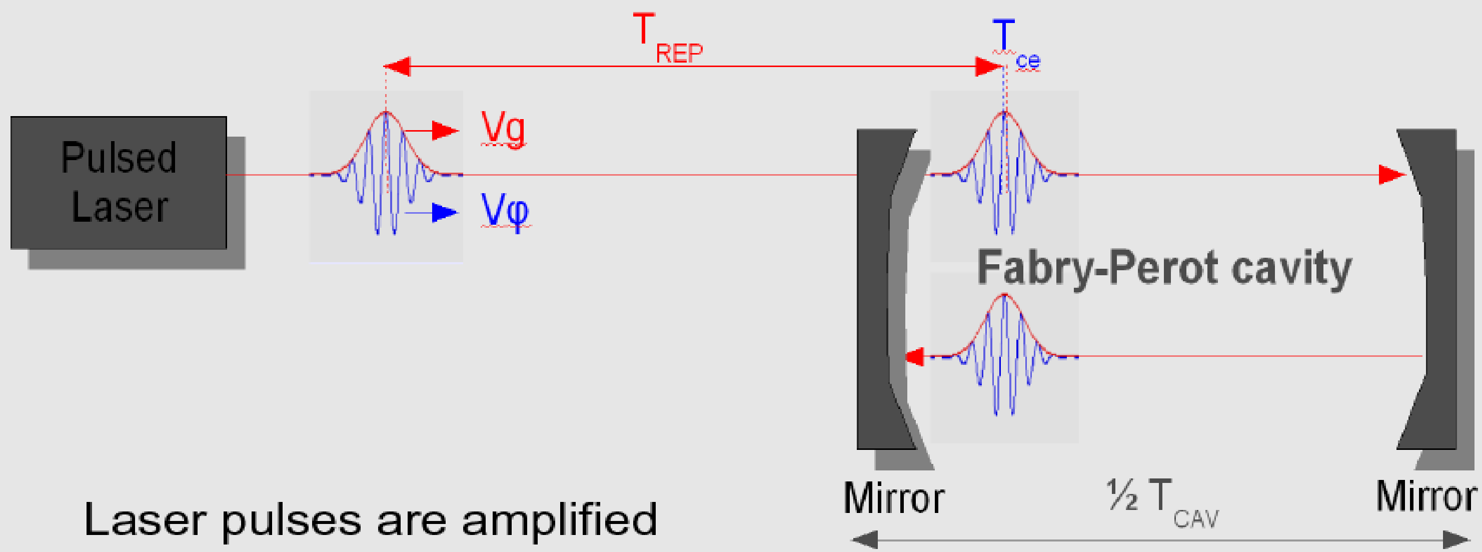
CLIC Compton Scheme

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



Pulse Stacking Optical Cavity

- Pulsed laser is stacked when appropriate conditions of the external cavity are satisfied.
- The peak power is enhanced by the pulse stacking.



Laser pulses are amplified
if laser field overlays with FP cavity field :

$$Trep \triangleq \frac{Lrep}{Vg} = Tcav \triangleq \frac{Lcav}{Vg} \quad \Rightarrow \quad \boxed{Lrep = Lcav}$$

$$Tce \triangleq Lrep\left(\frac{1}{Vg} - \frac{1}{V\varphi}\right) = k\frac{\lambda}{V\varphi} \quad \Rightarrow \quad \boxed{Vg = \frac{V\varphi}{1 + k\frac{\lambda}{Lrep}}}$$

$$k \in \mathbb{N}$$

Vg : Group Velocity
Vφ : Phase Velocity
Lrep : Laser repetition Length
Lcav : Fabry-Perot cavity Length

Optical Cavity (2)

Positron Generation

Positron Capture

Positron Source

Positron Source for LC

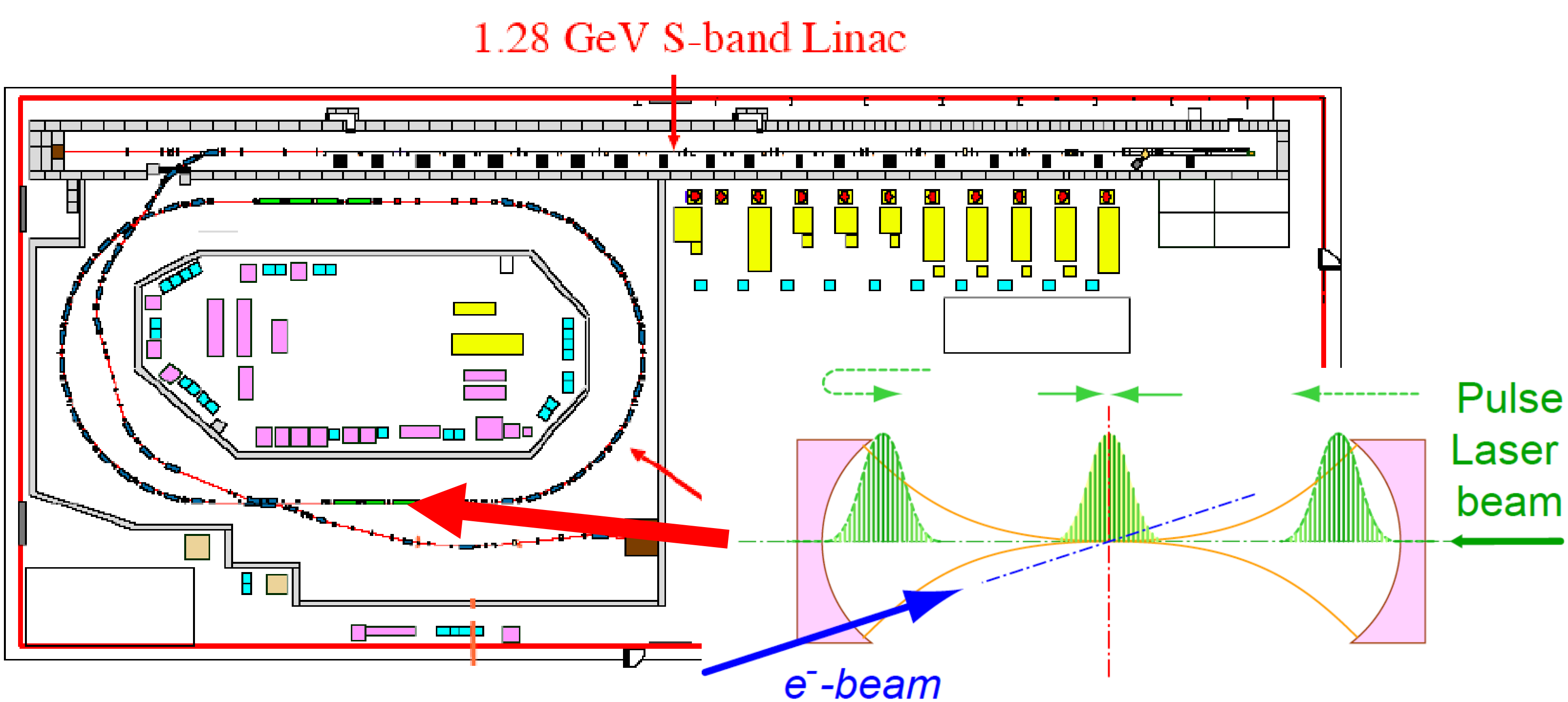
Summary

- 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.**

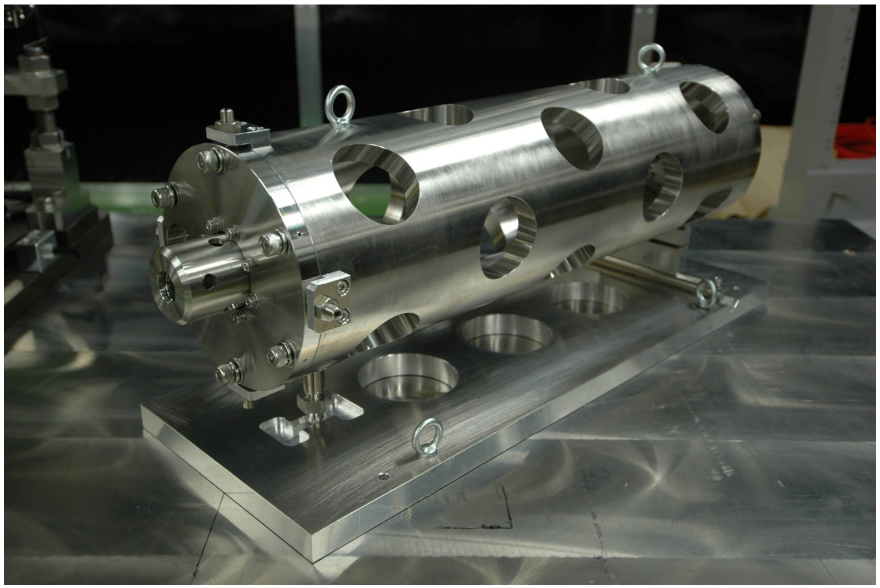
Lab.	LAL	KEK
Cavity	4-mirror confocal	2-mirror concentric
Finesse	10000	1000
Waist size (2σ)	<20um	60um

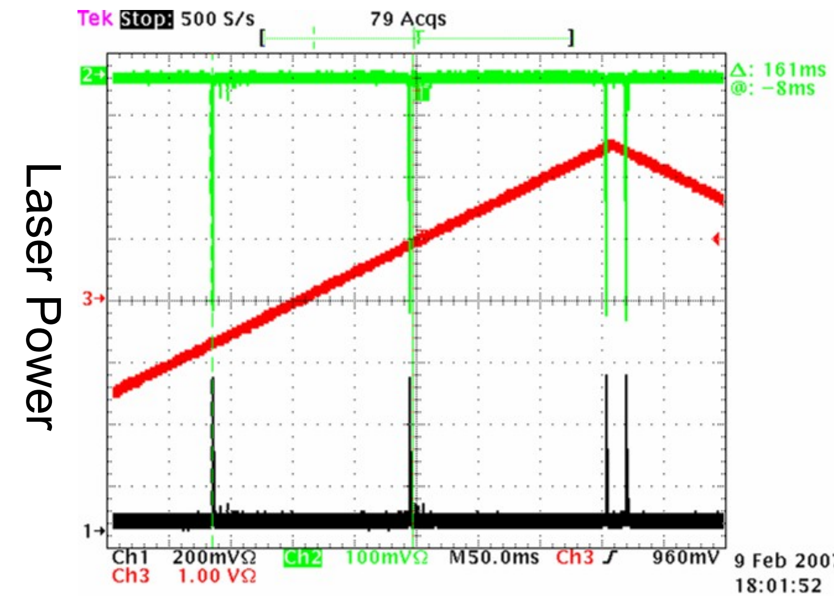
KEK-ATF experiment (1)

- 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.

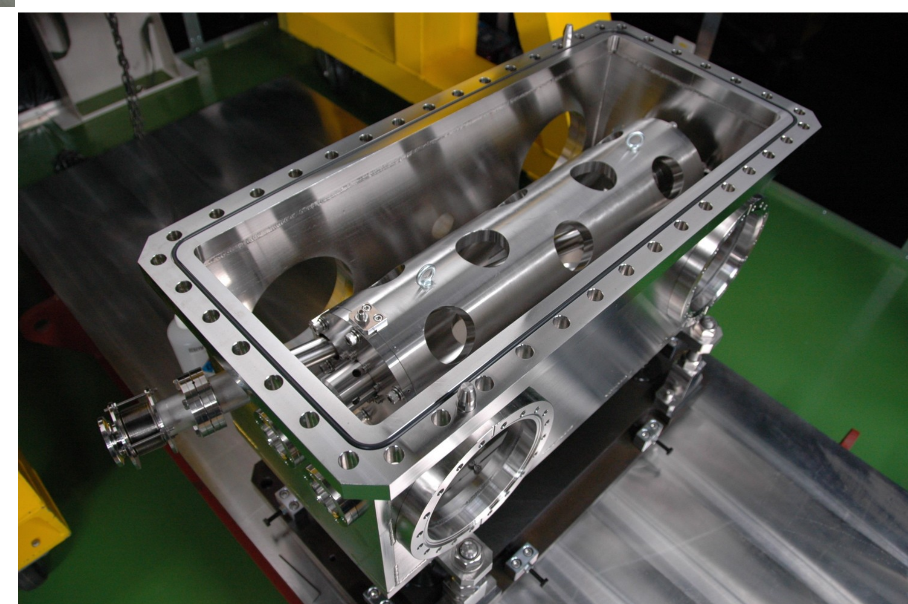


KEK-ATF experiment (2)

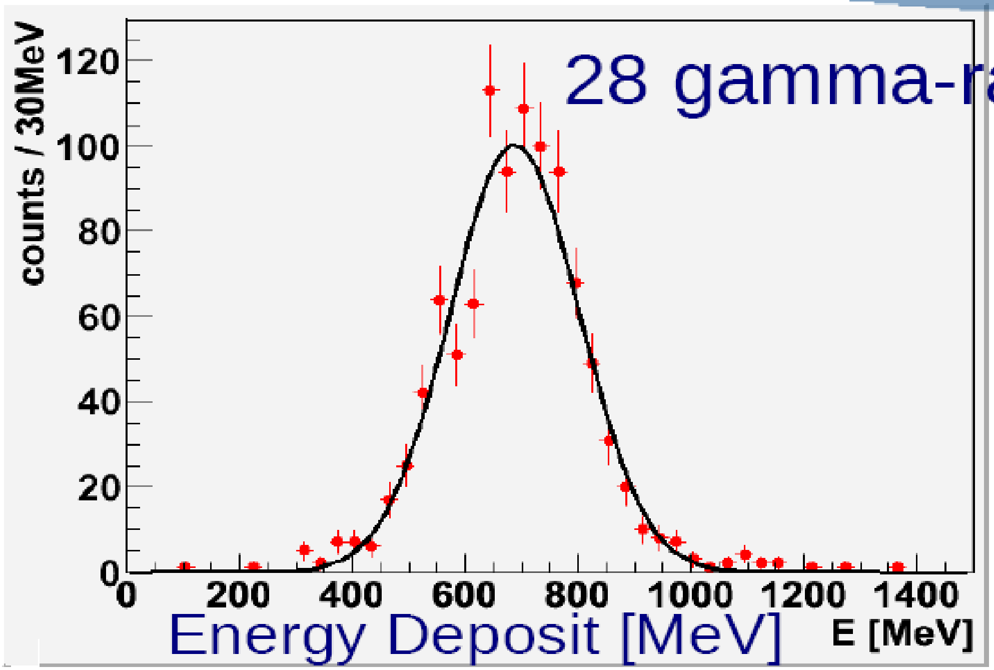




- Beam waist achieved inside the cavity is stably about 60μm.
- Cavity is “locked” for synchronization with the laser pulse.
- Finess ~ 600.



Observed Gamma-ray Spectrum



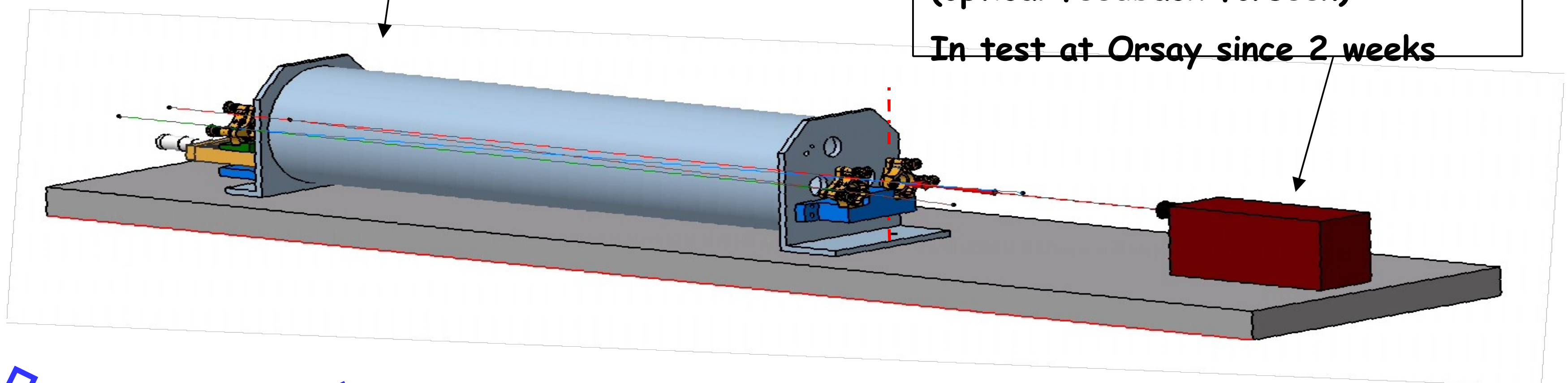
e- ring opr. mode
20 bunches / train

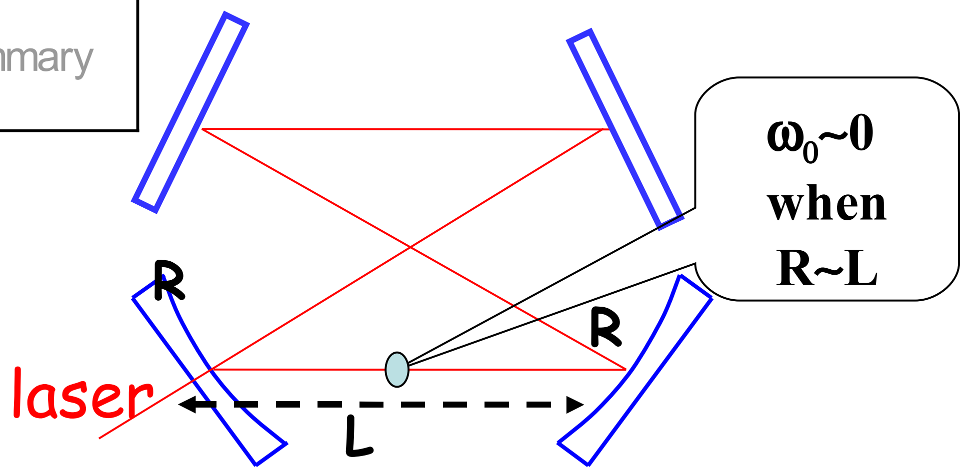
We observed 28.1±0.1 gamma-rays / train.
All solid angle → 60 gamma-rays / train

→ 60×2.16MHz ~ 1.2 × 10^8 [gamma / second]
Revolution

S. Miyoshi. Posipol09

LAL 4 mirrors cavity (1)





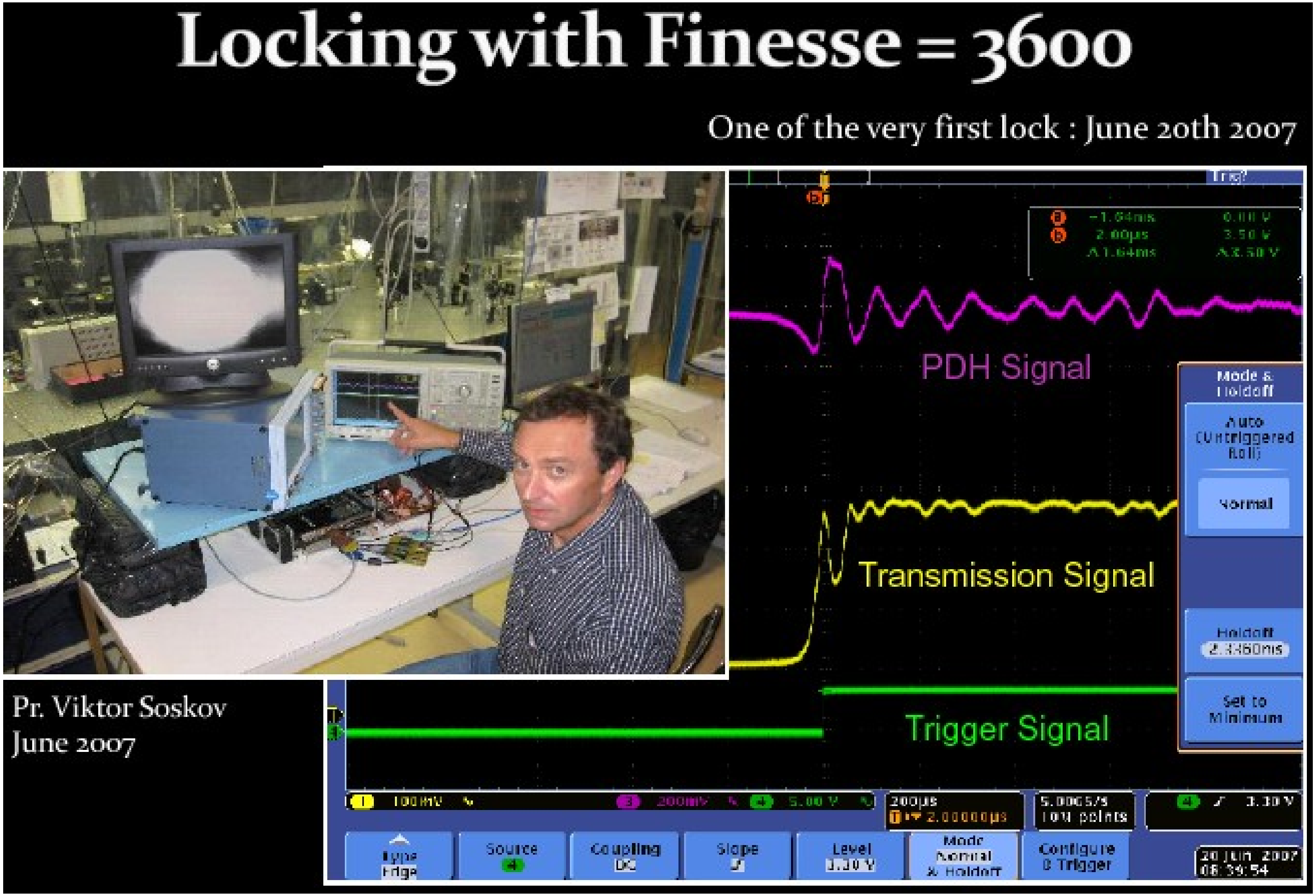
4 mirror non planar cavity

- 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)

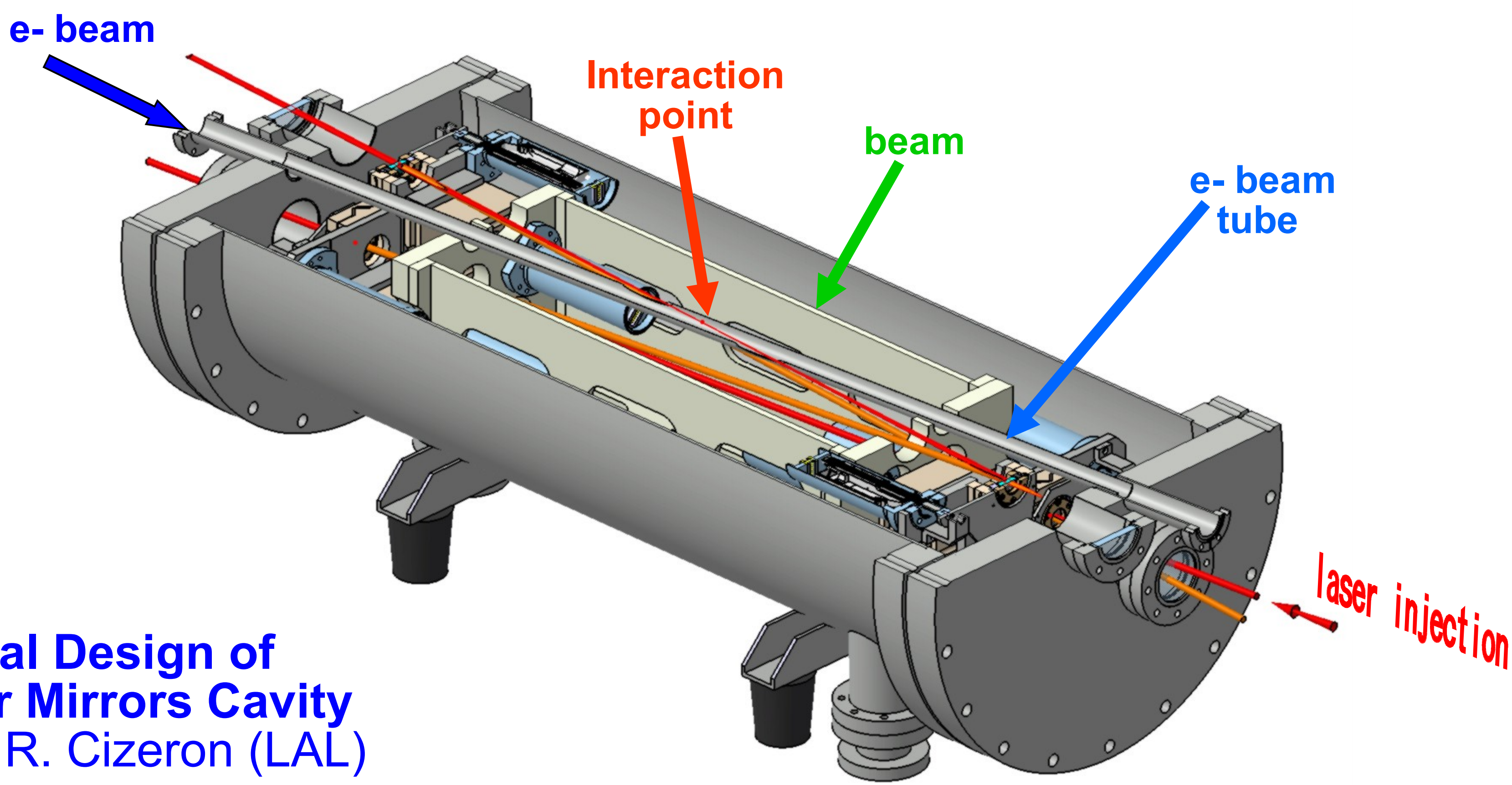
- Positron Generation
- Positron Capture
- Positron Source
- **Positron Source for LC**
- Summary



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)

Fibre Laser (1)

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

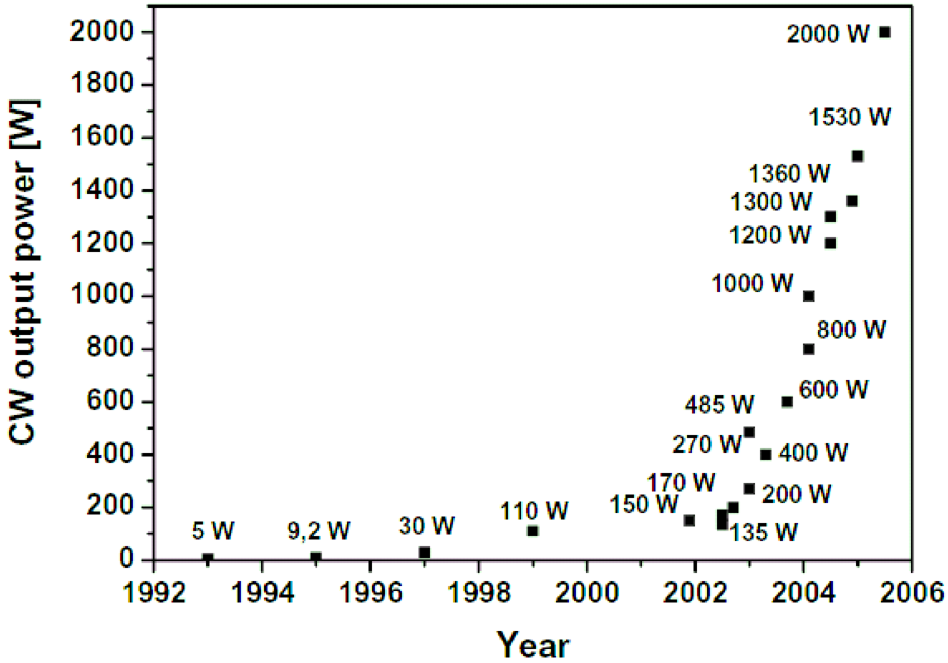
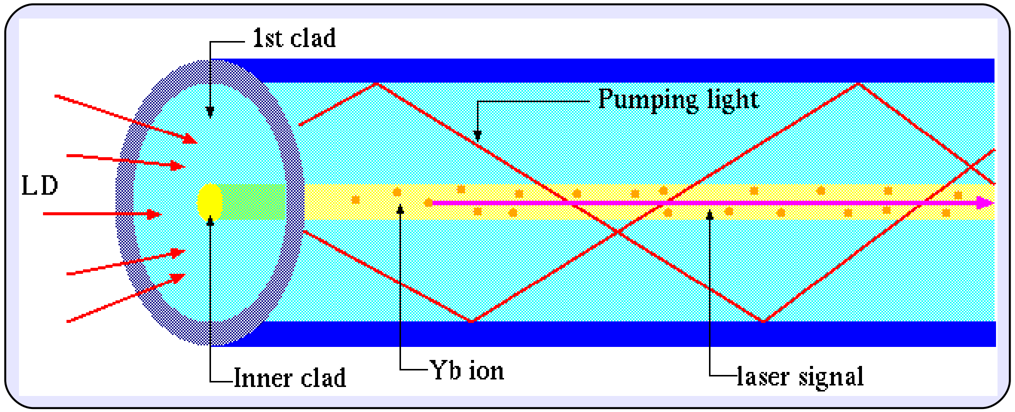


Fig. 4: Power evolution of cw double-clad fiber lasers with diffraction-limited beam quality over the last decade

J. Limpert

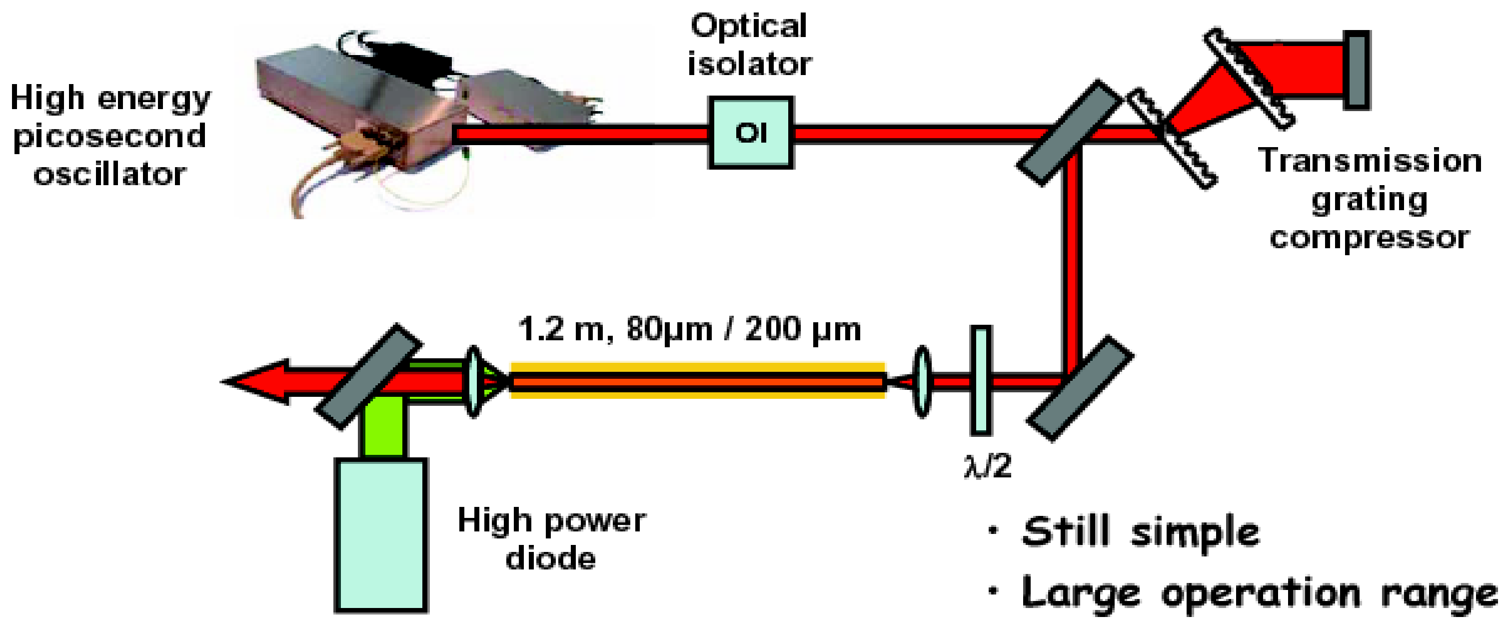


By M. Hanna

Fibre Laser (2)

E. Cormier

SPM induced spectral compression



- Still simple
- Large operation range

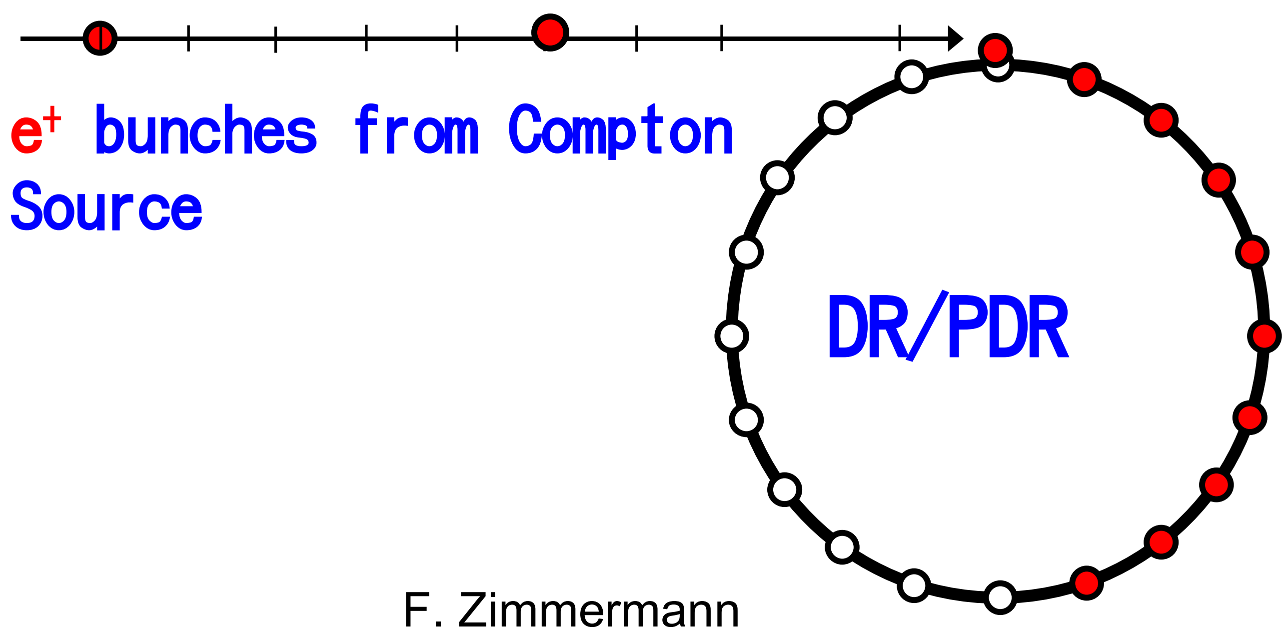
→ Max peak power = 0.21 MW
τ = 4 ps
E = 0.84 µJ
ν = 178.5 Mhz

P ~ 150 W

Optimal for cavity enhancement on ATF@KEK

Positron Stacking (1)

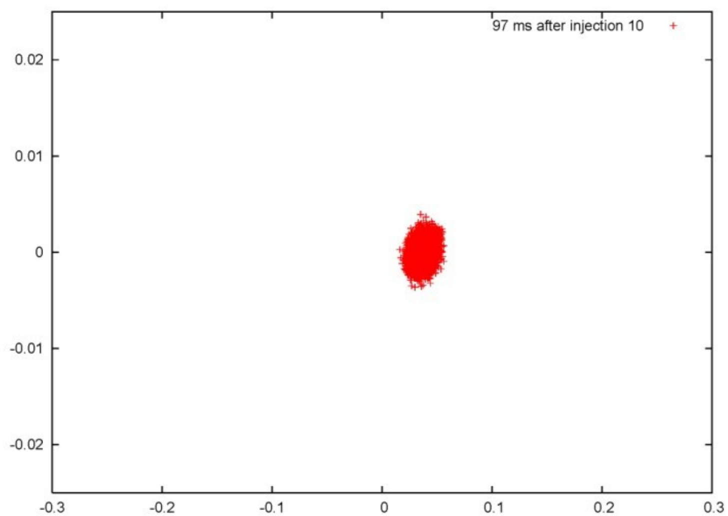
- Except linac scheme, # of positron by a single collision is not sufficient.
- We need accumulate positrons from many collisions to achieve the required bunch intensity for ILC and CLIC.
- Positron stacking: many positron bunches are injected to a same bucket in DR/PDR.



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.



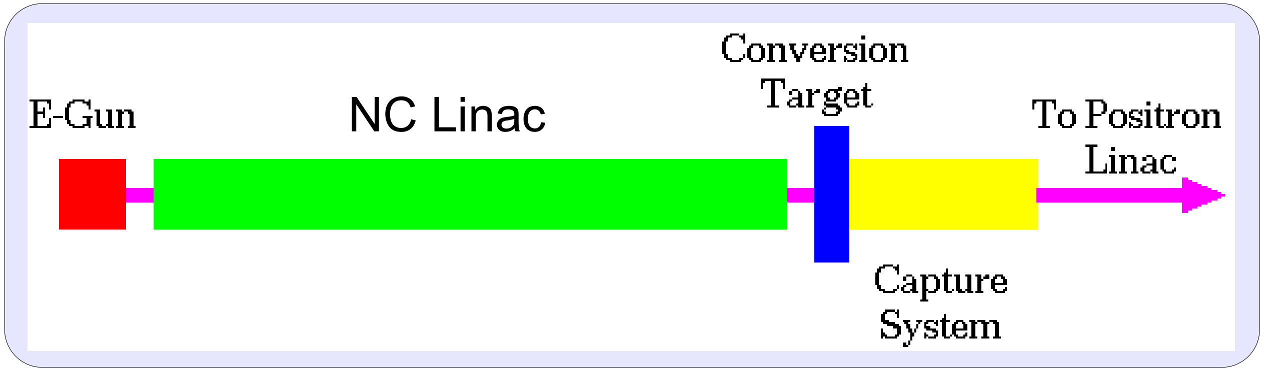
cycle 1, before 1st injection
cycle 1, after 5th injection
cycle 2, after 1st injection
cycle 10, after 30th injection
cycle 1, after 10th injection
10 ms after cycle 10
cycle 2, after 5th injection
97 ms after cycle 10
cycle 1, after 30th injection
cycle 2, after 30th injection

z_{off}=0.045 m, δ_{min}=5.7x10^{-3}, δ_{step}=0.175x10^{-3}/turn

F. Zimmermann

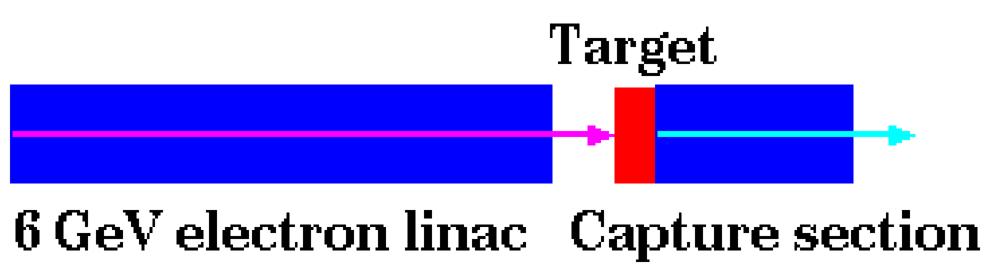
Electron Driven Scheme (1)

- Electron driven is the only scheme, which is ever been built and 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

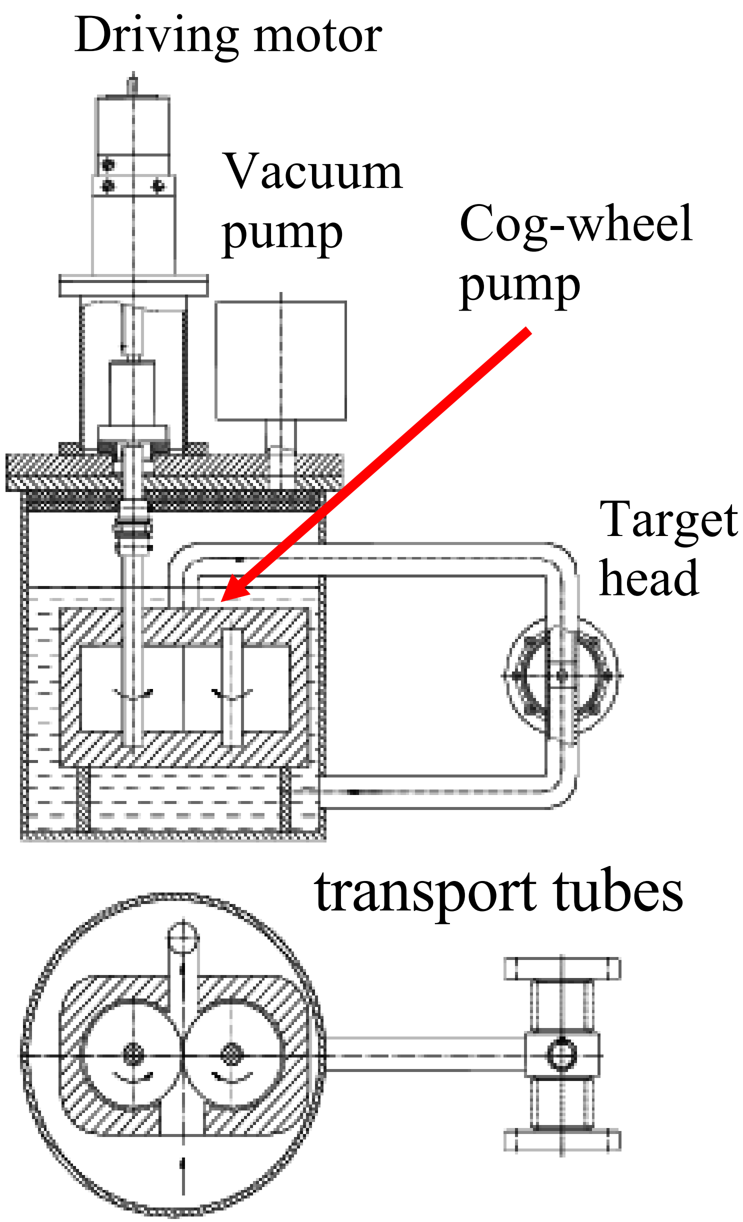


Electron Driven Scheme (2)

- Drive beam : 6 GeV, 3nC/bunch, 340ns spacing, 1ms duration.
- Production target: $4.5X_0$ (1.5cm) W-Re rotating with 50m/s or more (17um for every 340ns).
- 18J/bunch and 71 bunch overlaps makes energy density of 1270 $J/mm^2/24us$.
- Capture section: 1.0 of e+/e- yield.
- Target damage is a key factor on the realization.

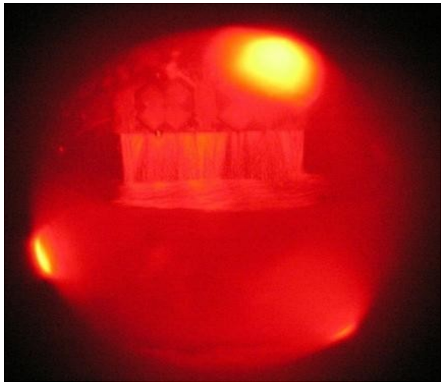


Liquid lead target



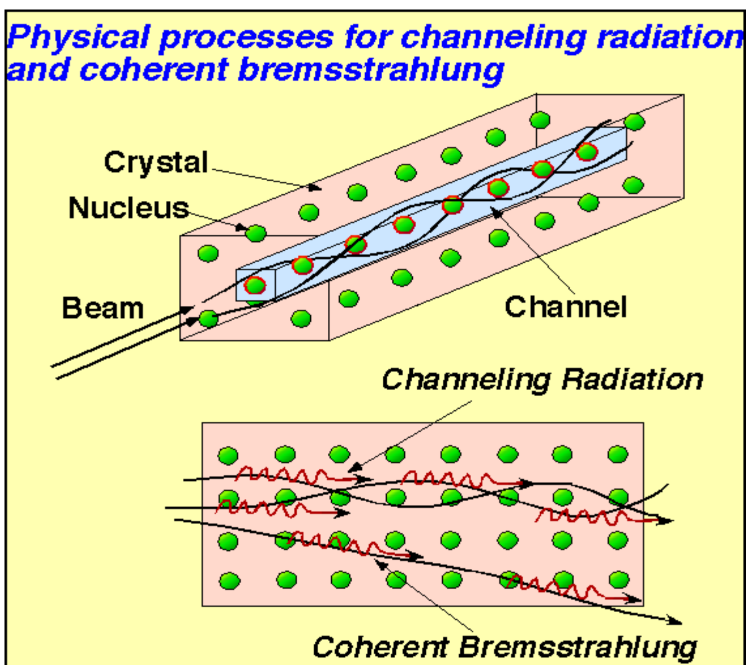
- Liq. Pb target system avoid fear for target damage.
- A prototype in BINP has been operated 20000h without any troubles.
- Damage for isolation window , which is light material, is an issue.
- Another issue is Pb boiling at 2200K.

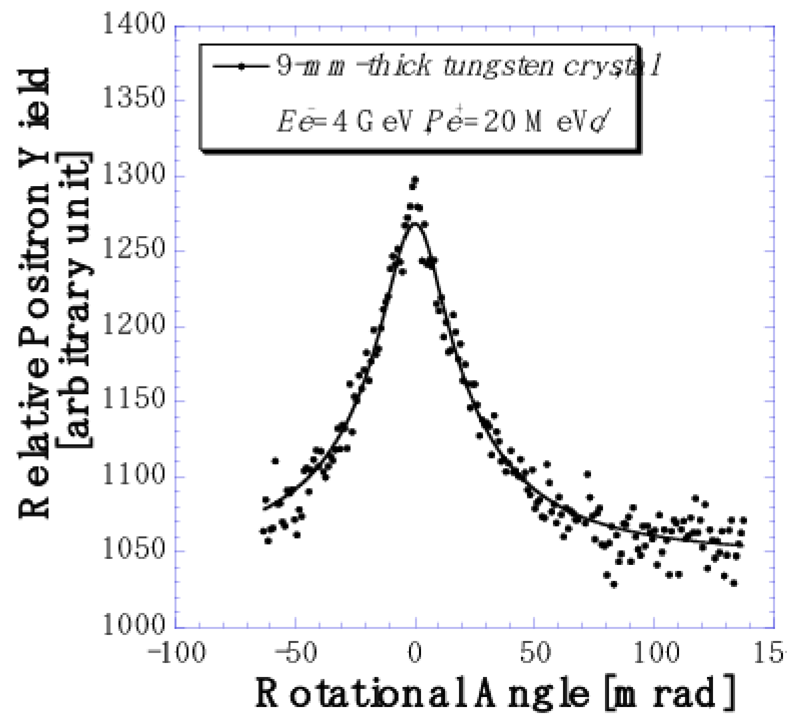
Pb 90% Sn 10%, 300˚C, in vacuum



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.

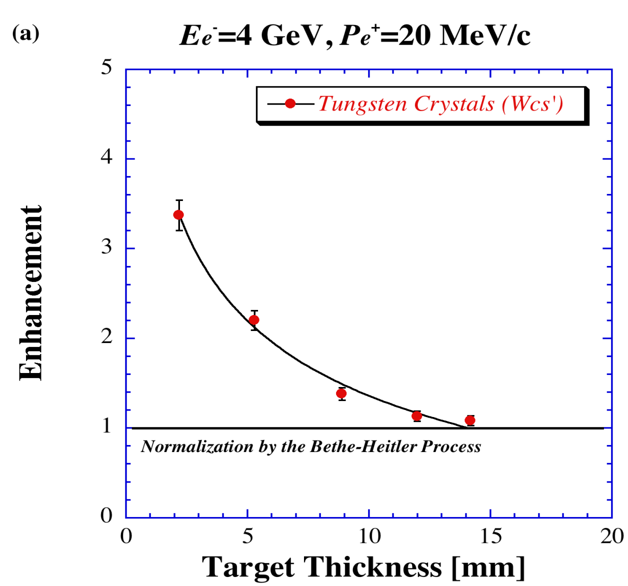


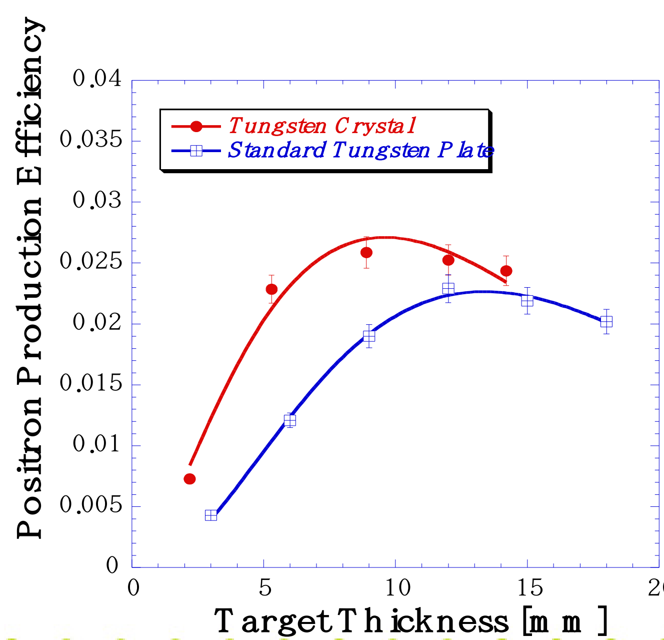


Crystalline Target (2)

- Positron Generation
- Positron Capture
- Positron Source
- **Positron Source for LC**
- 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.

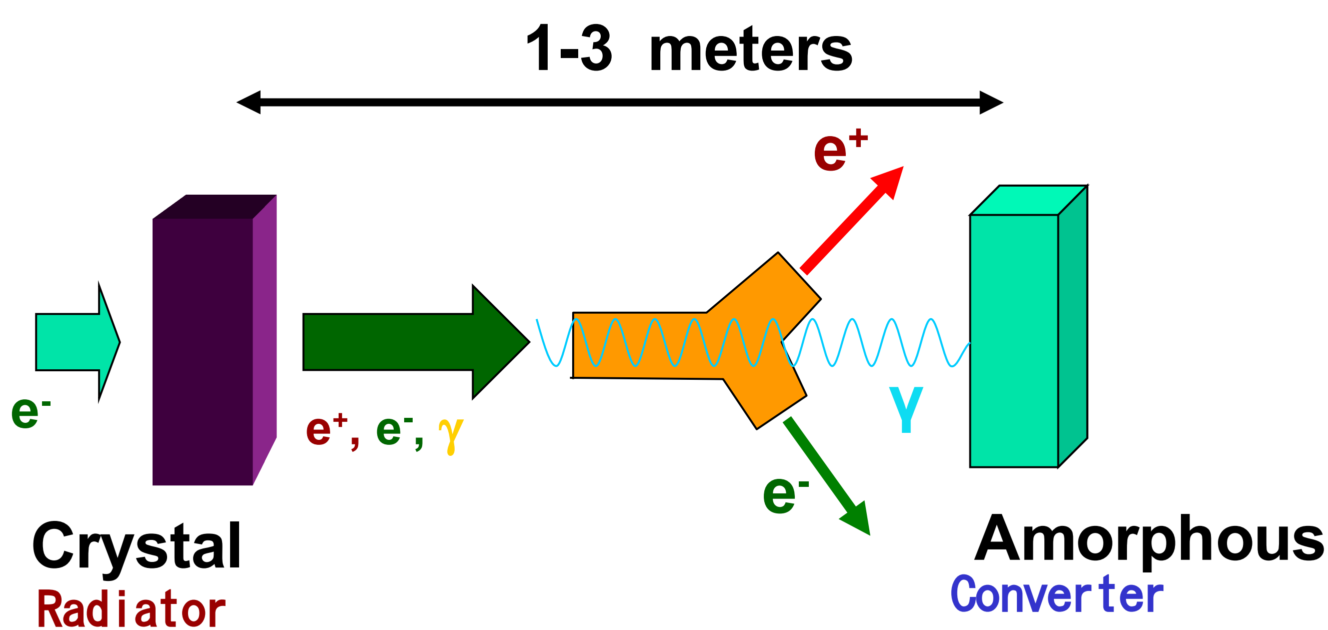




Crystalline Target(3)

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

- 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: that limits the energy deposition in the amorphous target.

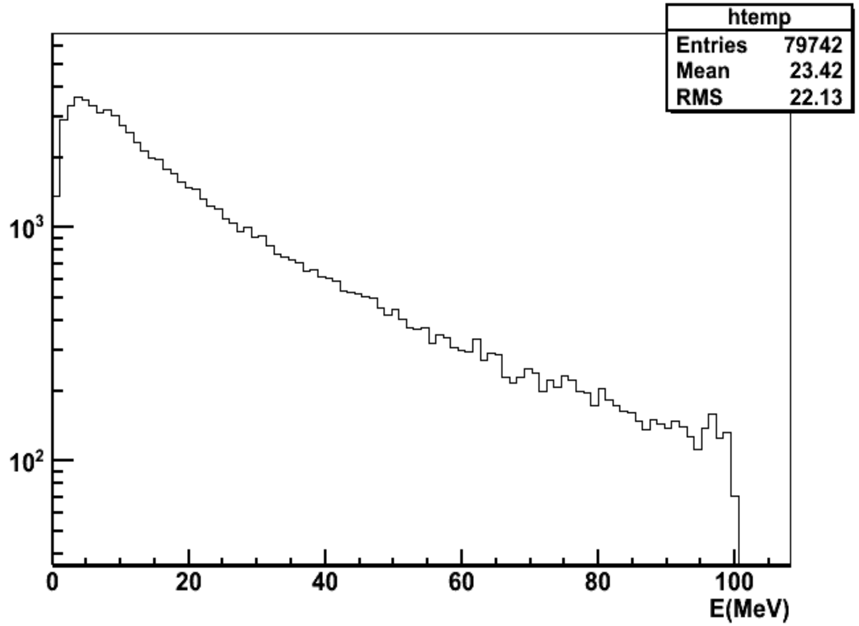


R. Chehab

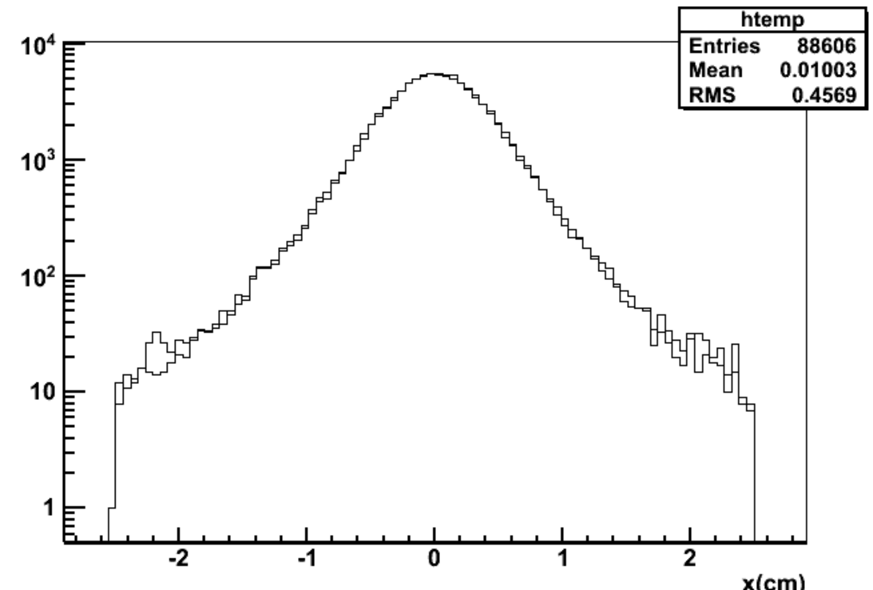
Crystalline Target(4) Positrons phase space

Incident E_{e^-} (GeV)	Incident P_{e^-} (kW)	P_γ (kW)
3	54	32
4	72	45
5	90	58
10	190	130

E_{e^-} (GeV)	N_{e^-}	N_γ	$\bar{E}_\gamma$ (MeV)
10	5×10^3	112098	304
5	6×10^3	119813	160
4	6.5×10^3	118312	136
3	8×10^3	125810	115



<E> ~ 23.5 MeV

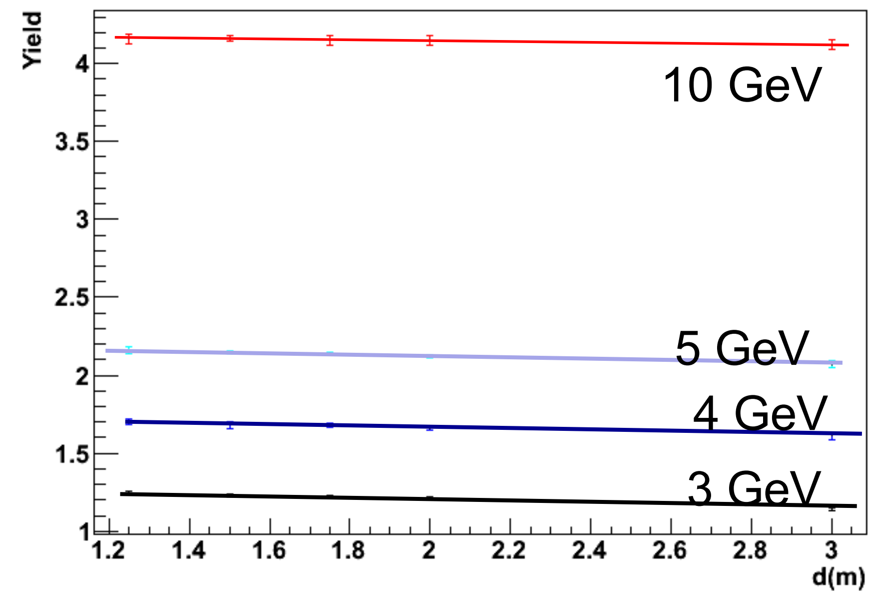


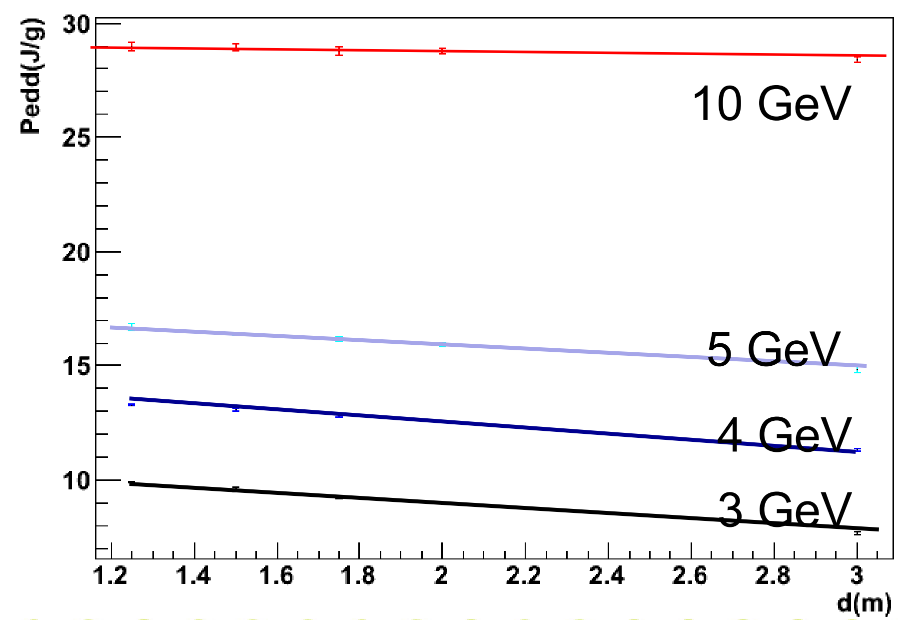
$\sigma_{x,y} \sim 4.5$ mm

O. Dadoun, Posipol09

Positron Yield and PEED

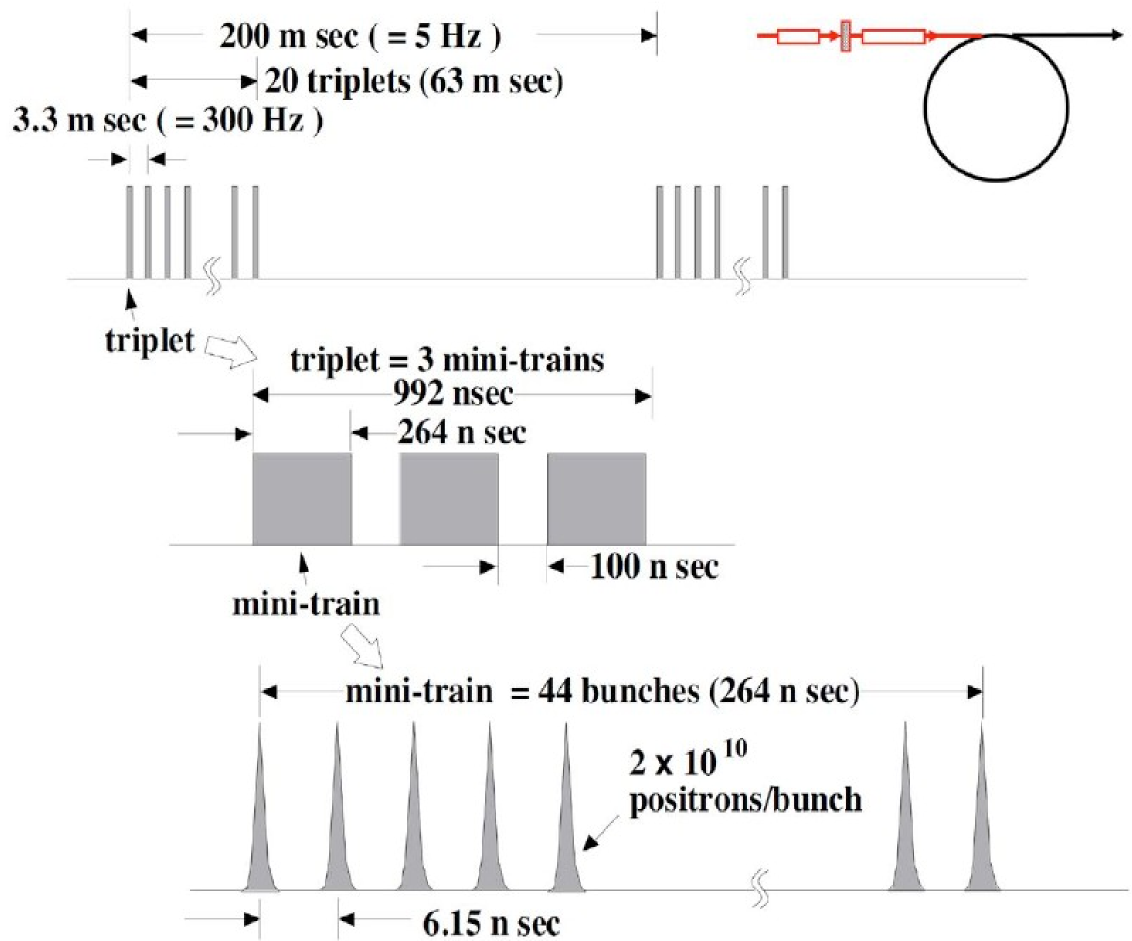
- Positron yield after the AMD r < 2.0 cm (e=10mm of amorphous)
- Positron yield not so affected by the distance.
- PEDD for 10mm of amorphous (elementary volume few mm^3)
- PEDD decrease as the distance "d" increases, because the incident photon spot size increases.
- PEDD is suppressed below the limit, 35 J/g.





300Hz Generation (1)

- To mitigate possible damage on the target, the positron is generated in 63ms duration, instead of 1ms .
- The bunch format is in mini-train. 3 mini-train compose one triplet.
- The positron is generated and injected to DR in the form of the triplet. The triplet format is identical that in DR.



T. Omori

300Hz Generation (2)

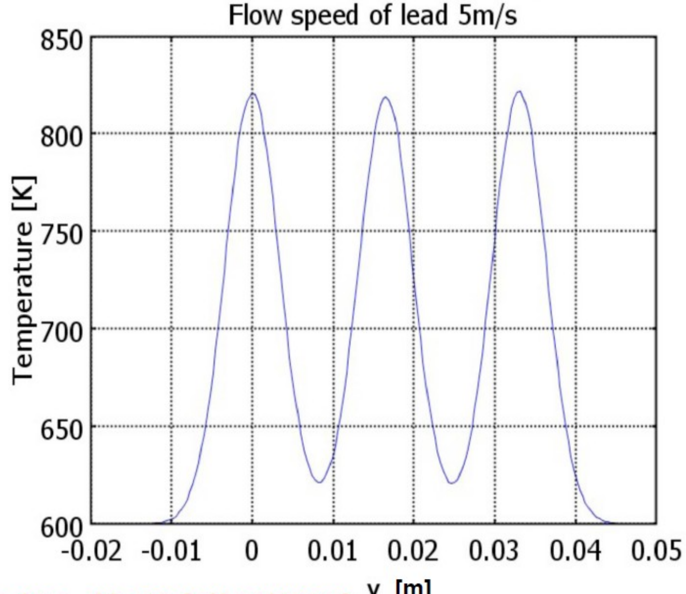
- Positron Generation
- Positron Capture
- Positron Source
- **Positron Source for LC**
- Summary

Simulation of heating by beam (Wanming-san)

Model

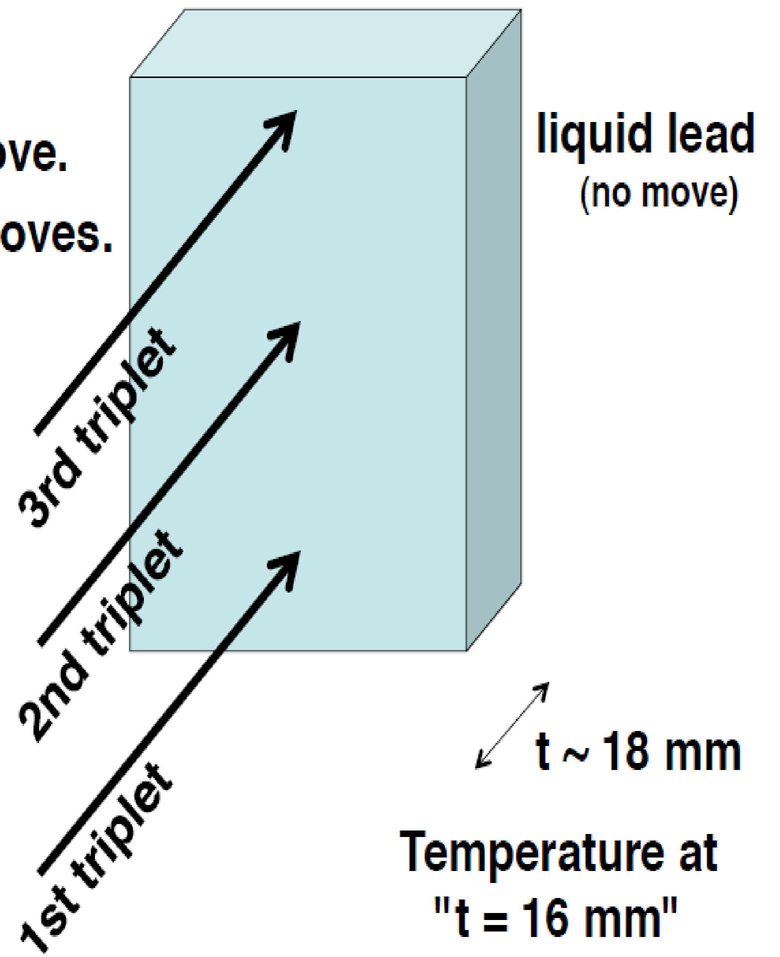
- Liquid Lead doesn't move.
- Beam injection point moves.

5 m/s, after 3 triplets



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

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.
- A common effort for ILC-CLIC on positron source R&D is ongoing.

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Positron Generation

Positron Capture

Positron Source

Positron Source for LC

Summary

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