Positron Source for Linear Colliders

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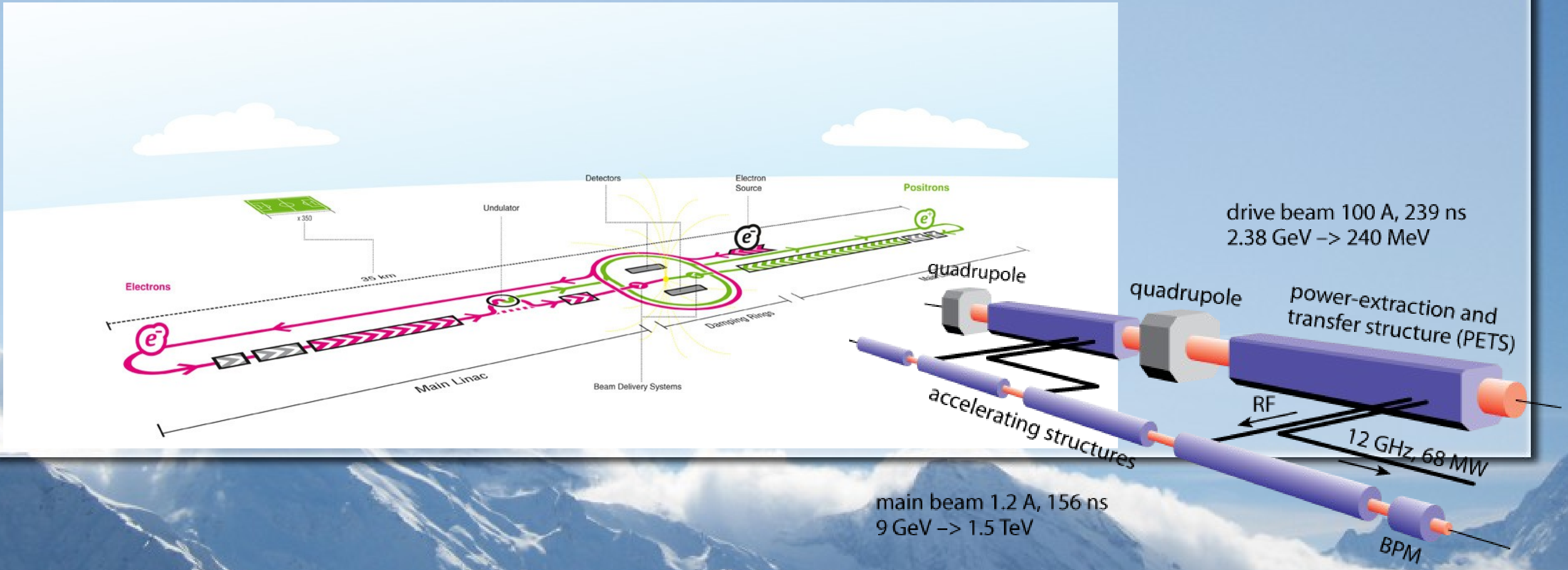

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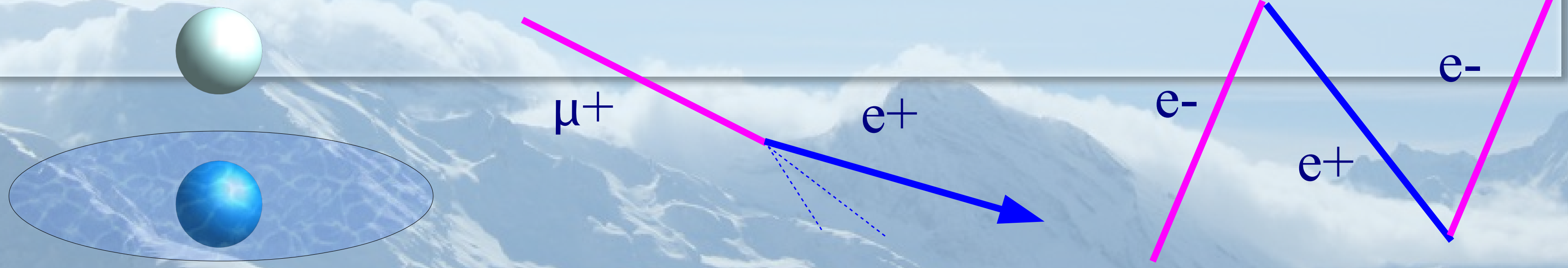
Introduction

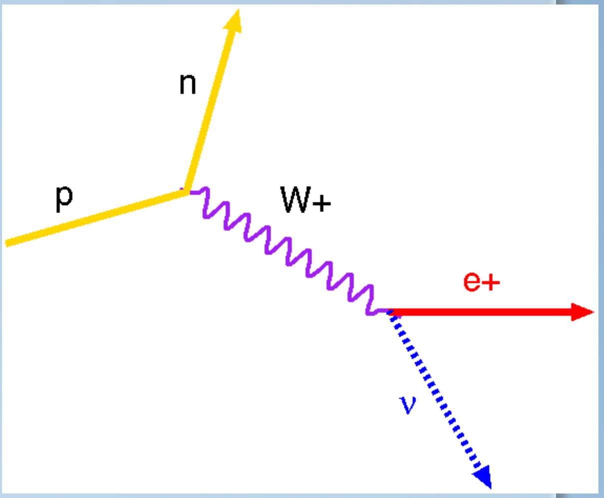
What is Positron?

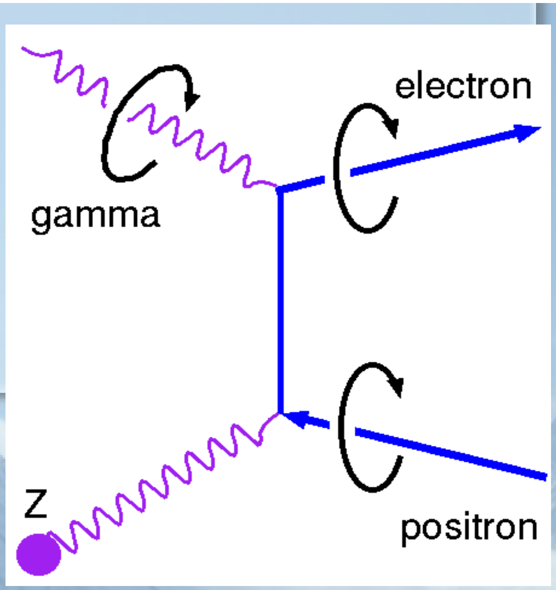
- 1928: Dirac equation suggested electrons with negative energy. Hole hypothesis: "vacuum" is filled with this negative energy electrons to prohibit Klein's paradox. "hole" in the see of this electrons, acts as positrons.
- 1932:Anderson discovered positrons in cosmic rays with cloud chamber.
- In the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



Positron Production (1)

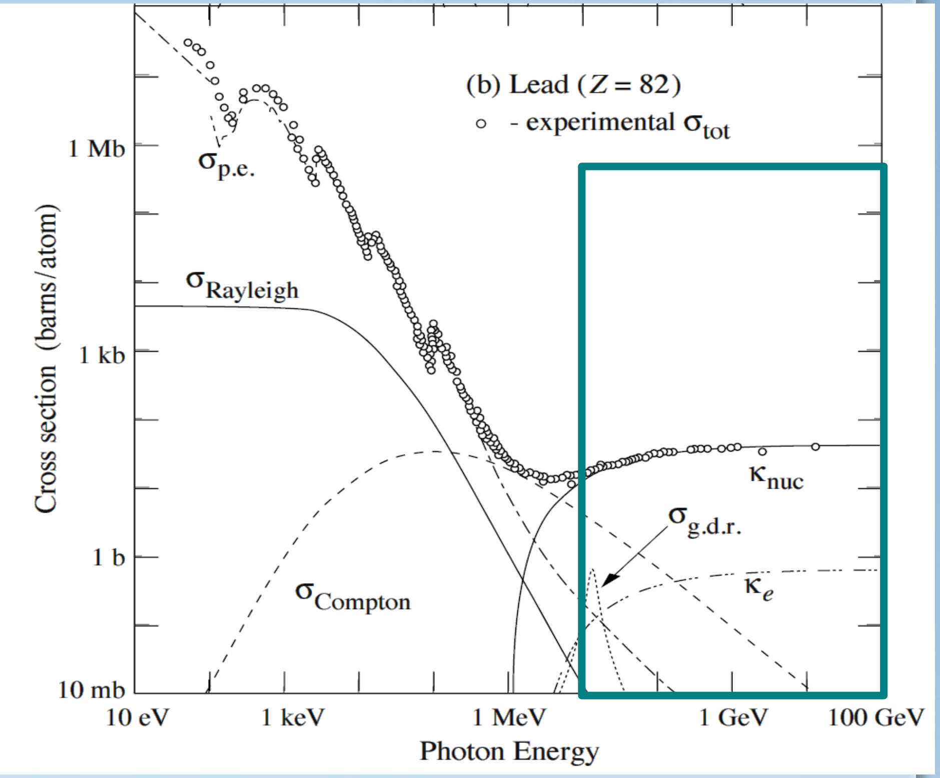
- There is only few positrons in nature.
- Two ways to produce positrons :
  - Create radio-active elements, which beta + decays; p ->n e+ neutrino.
  - Pair-creation ; gamma -> e+ e-
- All of the positron beam sources with a time structure, employ the pair-creation process.





Positron Production (2)

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



$\sigma_{p.e.}$: photo-electron

$\sigma_{Compton}$:Compton scattering

κ_{nuc}, κ_e: pair creation

(from Particle Data Group, http://pdg.lbl.gov)

Need Photon?

- We need many photons to create enough amount of positrons through the pair creation.
- How to create the photons?
  - Brems-strahlung, channeling radiation : electron interaction in material.
  - Undulator radition: Synchrotron Radiation by high energy electron.
  - Inverse Compton scattering : Laser and electron ineraction.

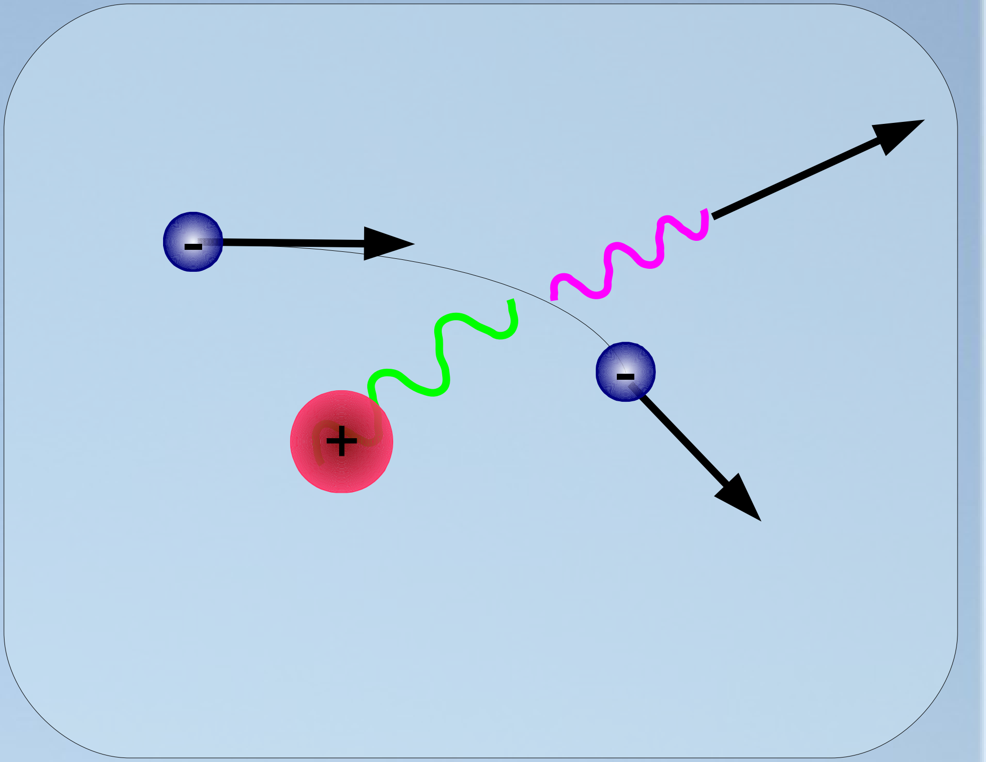
Positron Generation

Positron Generation

- Positron beam is generated by the pair-creation process.
- There are several schemes for positron generation, depending on way to generate high energy gamma rays.
- Electron driven
  - Authentic
  - Channeling radition
- Direact Pair-creation
  - Undulator
  - Laser-Compton

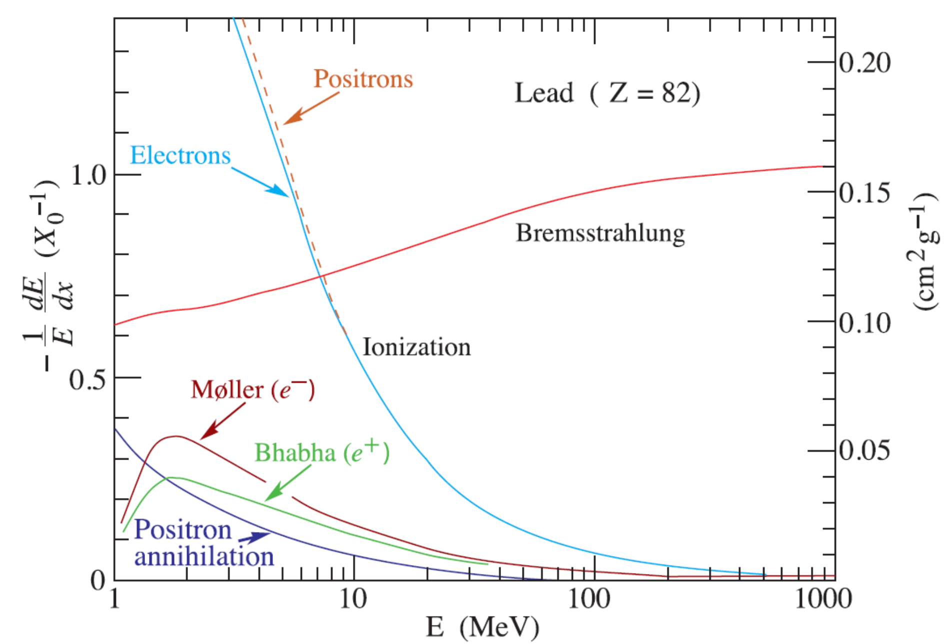
Bremsstrahlung (1)

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



Bremsstrahlung (2)

- Bremsstrahlung is dominant in high energy region.
- Below some energy (E_c critical energy) ionization is dominant.
- When high energy electrons are injected into matrial, electrons loose their energy by Brems-strahlung.
- When the energy becomes less than E_c, no more Brems-strahlung is occured.



Critical Energy E_c

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

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

Cascade Shower

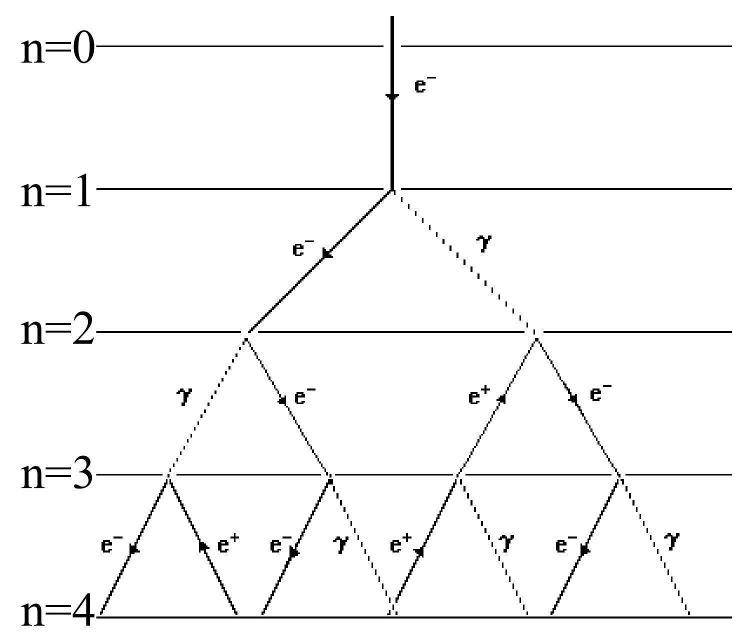
Radiation length X0: $\frac{dE}{dx} = -\frac{E}{X_0}$

Energy at each steps: $E_n = \frac{E_0}{2^n}$

This process is continued up to;

$$n_{max} = \frac{\ln\left(\frac{E_0}{E_c}\right)}{\ln 2} - 1$$

$$x_{max} = X_0\left[\ln\left(\frac{E_0}{E_c}\right) - \ln 2\right]$$

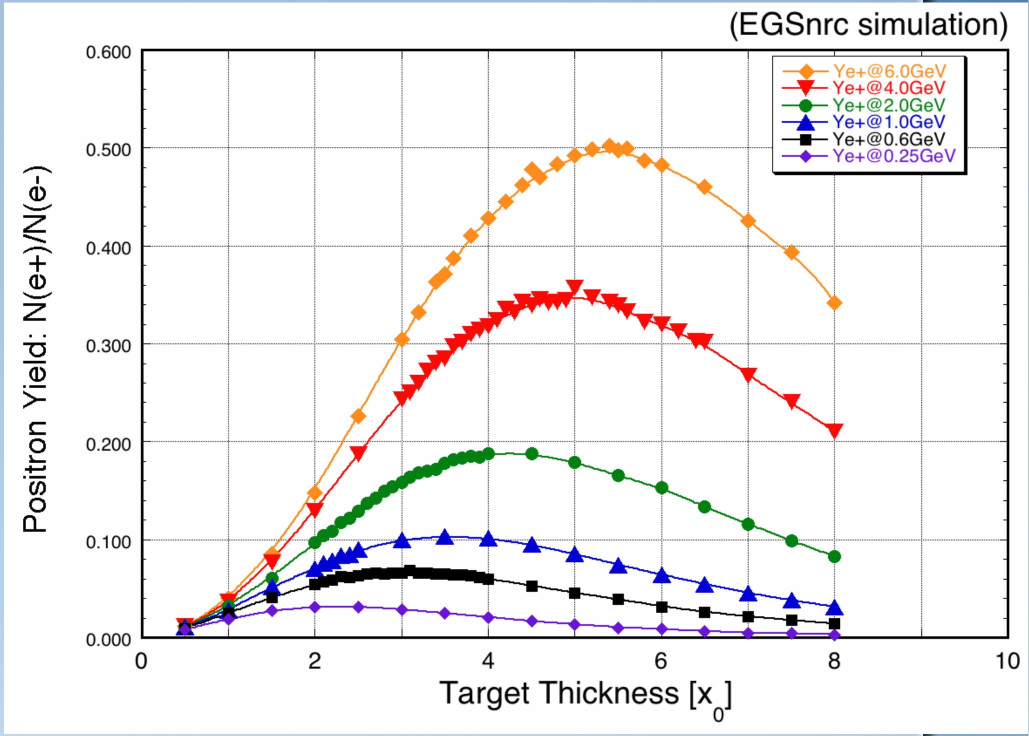


Cascde Shower (2)

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

$$x_{max}=X_0\left[\ln\left(\frac{E_0}{E_c}\right)-\ln 2\right]$$

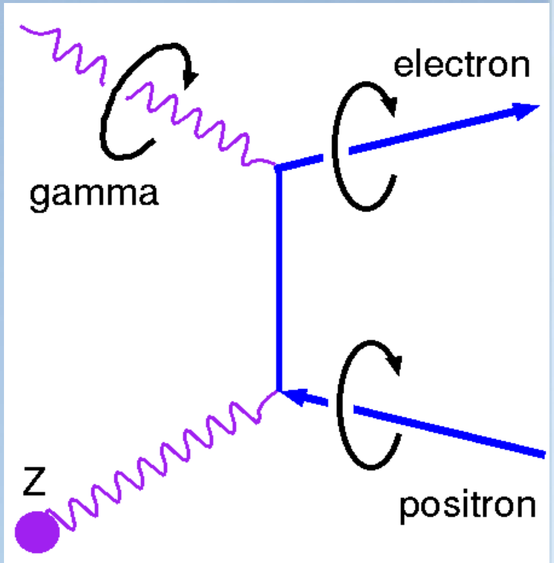
$$X_0=\frac{716.4[g.cm^{-2}]A}{Z(Z+1)\ln(287/\sqrt{Z})}$$



Courtesy of T.Kamitani

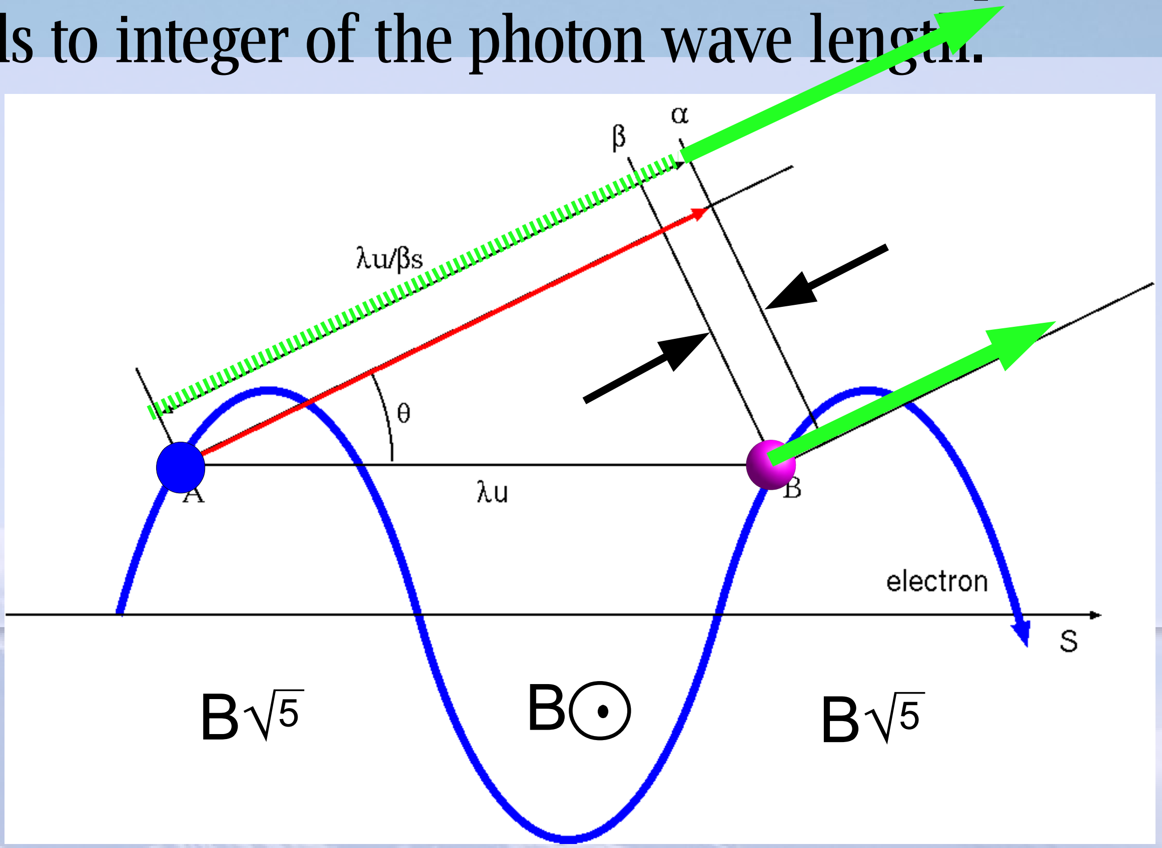
Direct Pair Creation

- 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 the zig-zag motion.
- Photons are emitted to the direction where wave-plane distance corresponds to integer of the photon wave length.



Undulator radiation (2)

The radiation spectrum is given by Lienard-Wiechert form

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

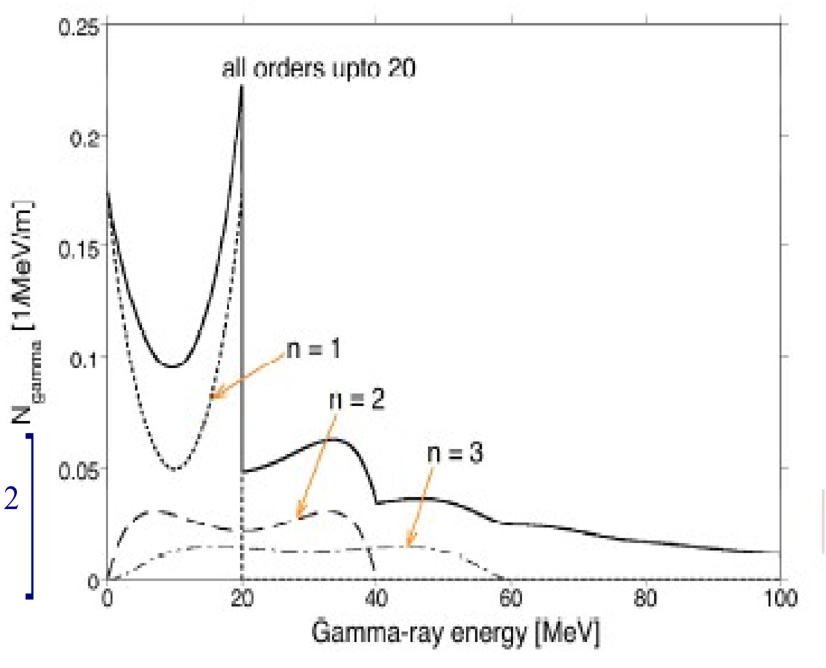
ω is angular frequency of photon, Ω is solid angle, **n** is unit vector to observation. The photon cut off energy is

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

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

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

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



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 $\hbar\omega_0$ is photon energy.

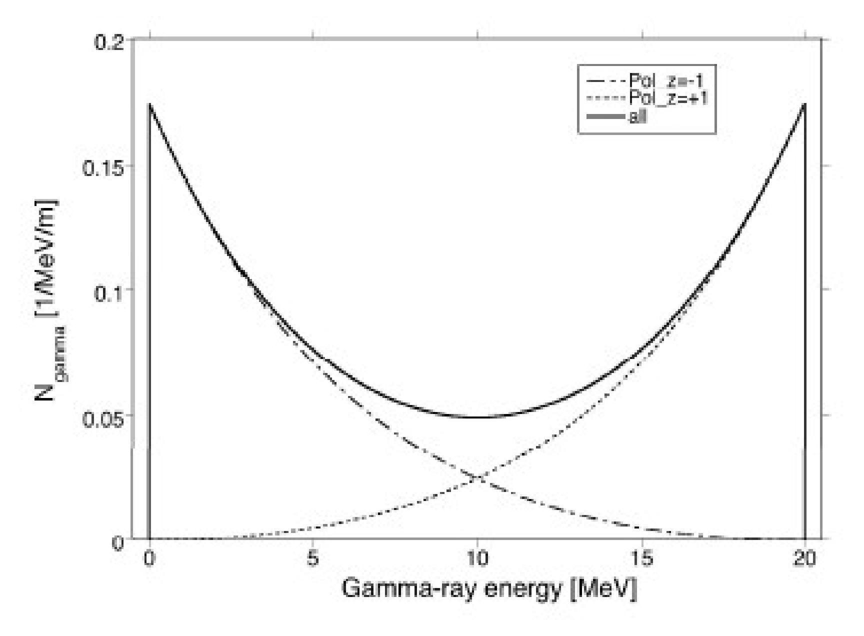
- The undulator radiation = electron and photon scattering.
  - Photon wave length = undulator period.
  - The photon energy is boosted by γ^2.
- ► Due to the long undulator period, high energy electron beam is necessary.

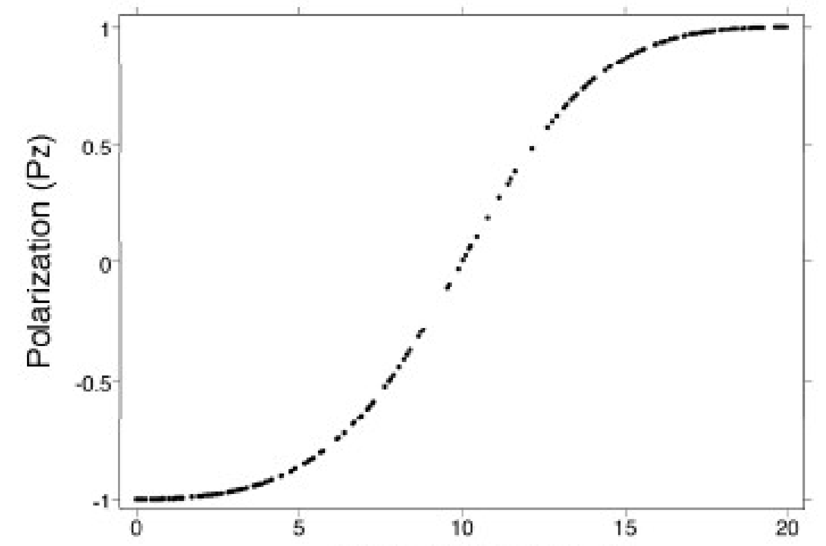
Polarized Positron

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

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

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





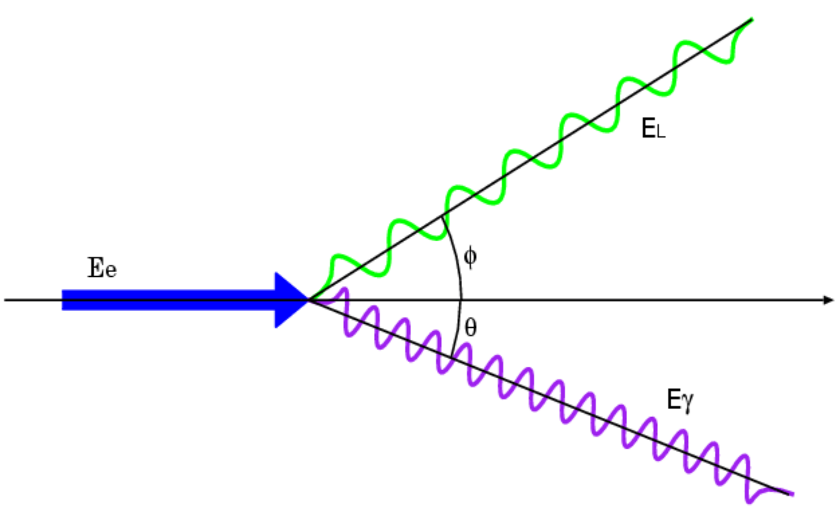
T.Kamitani

Laser Compton(1)

- Inverse Compton scattering between laser photon and electron beam.
- Laser photon (wavelength is in μm order) is scattered by high energy electron and its energy is boosted.
- As 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, $\gamma=2000$.
- $E_\gamma \sim$ 16MeV



Laser Compton (2)

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

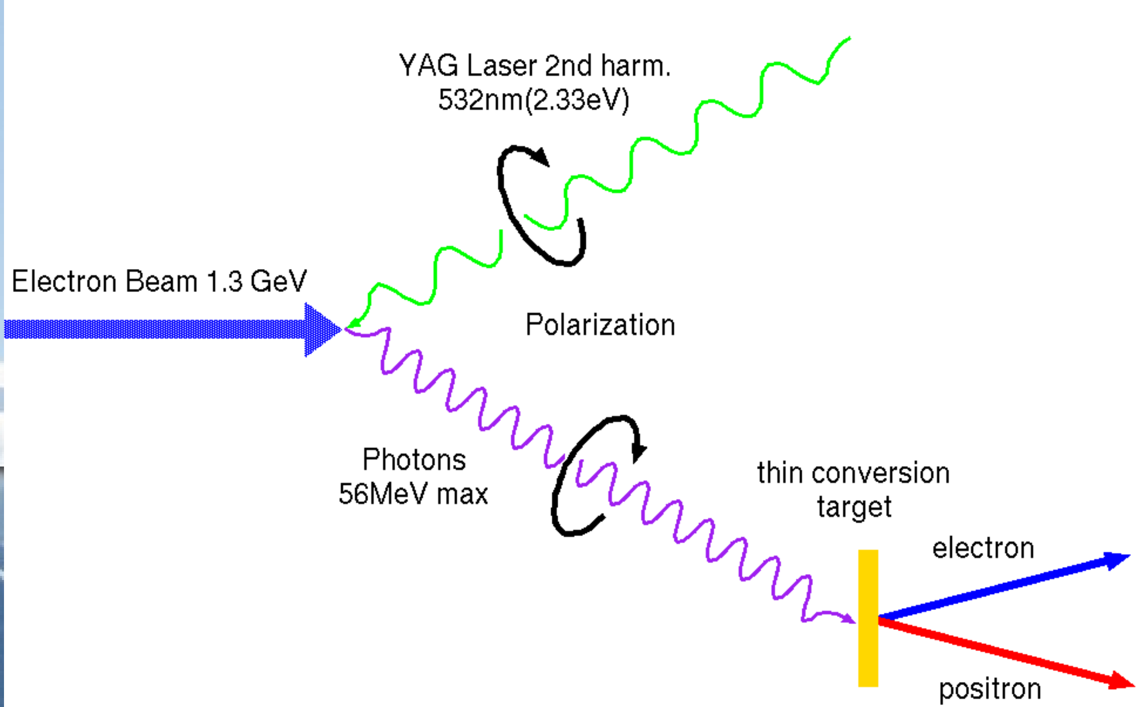
$$E_\gamma \sim 4\gamma^2 \hbar \frac{2\pi c}{\lambda_L} \qquad (3-17)$$

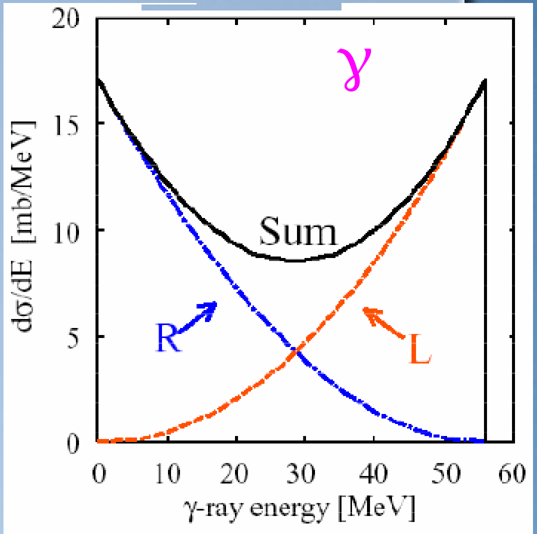
where λ_L is laser wave length.

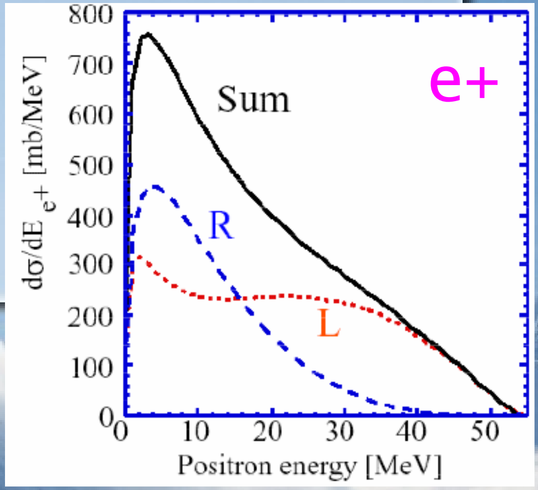
- High energy gamma (several 10s MeV) is obtained with few GeV electron beam.
- Laser focal length is limited to Rayleigh length. It is difficult to make a long “laser undulator”.

Laser Compton (3)

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







Positron Source

Positron Source

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

Positron

Drive Beam

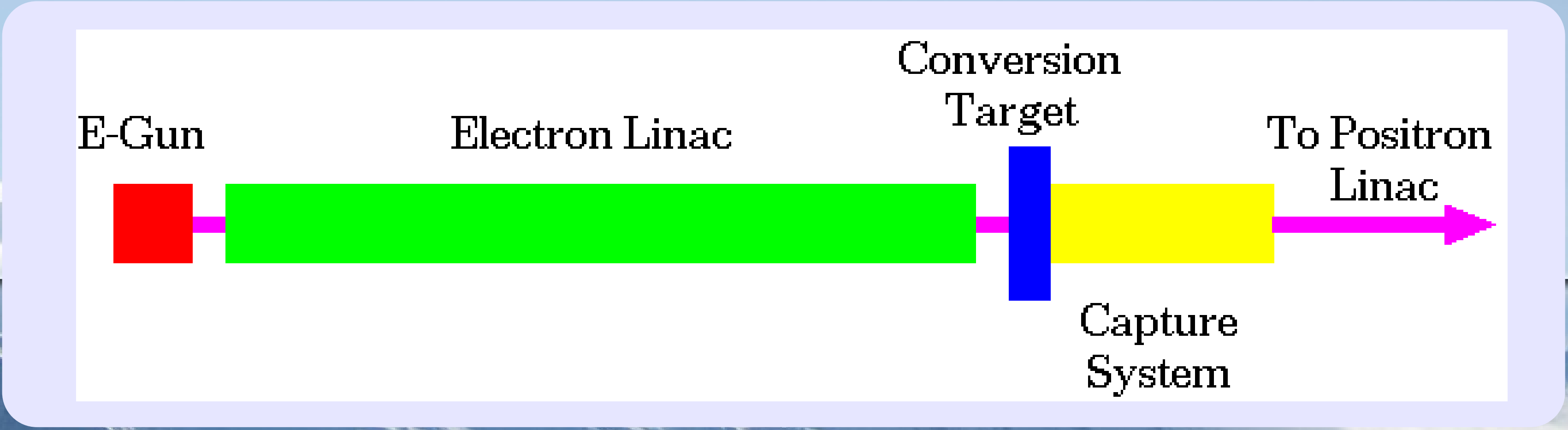
Conversion Target

Matching Device

Capture Accelerator

Electron Driven (1)

- Sub or Several GeVs driver electron beam.
- High Density Material for 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)

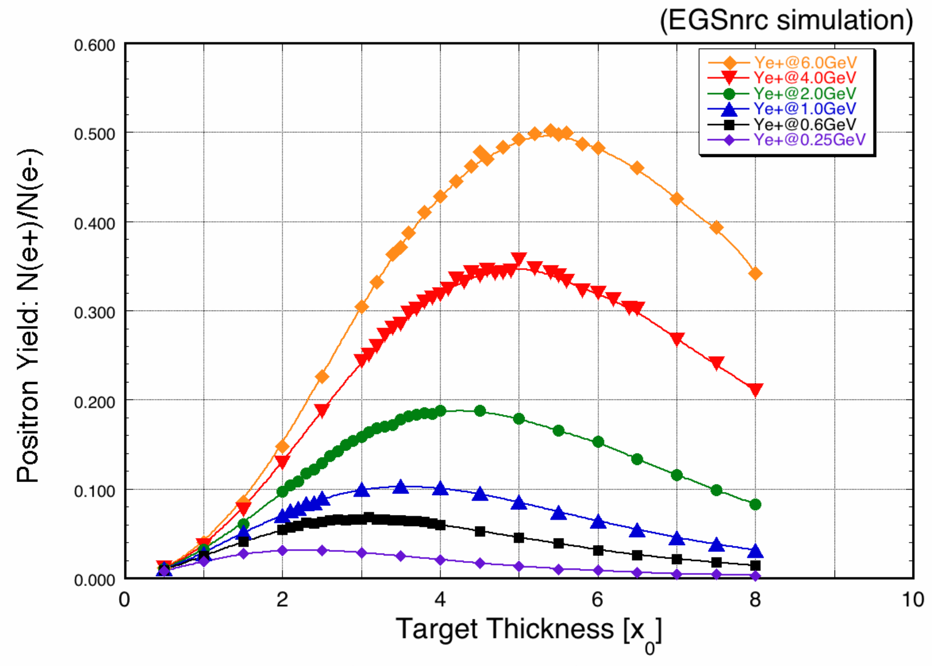
Thickness and material of the target for positron generation is determined by the shower max;

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

Positron yield η and normalized yield η_n are defined as;

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

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



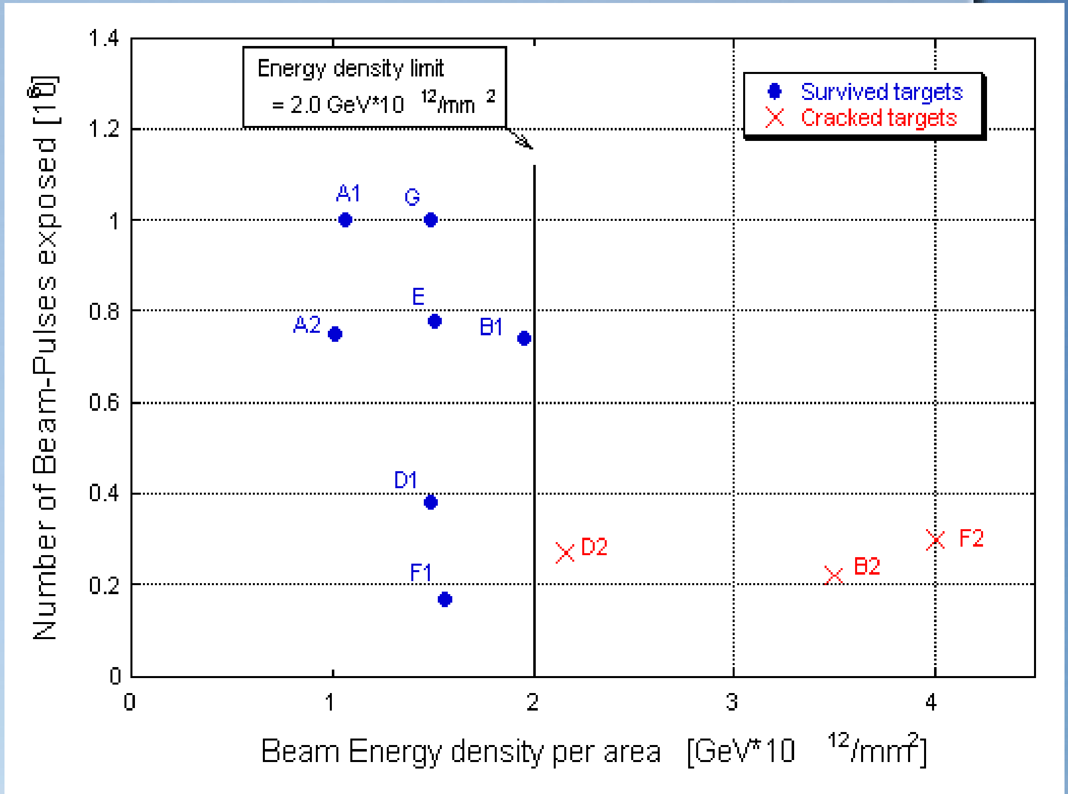
Courtesy of T.Kamitani

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)

- 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

Damage Threshold (2)

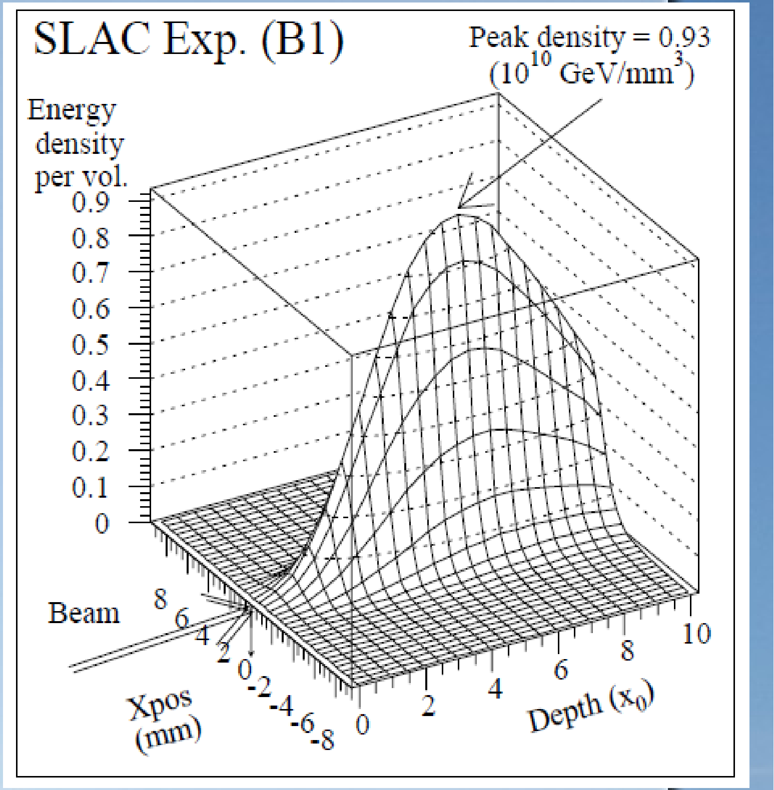
To evaluate the universal damage threshold, the energy deposited density in the SLAC experiment is evaluated as

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

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

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,

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



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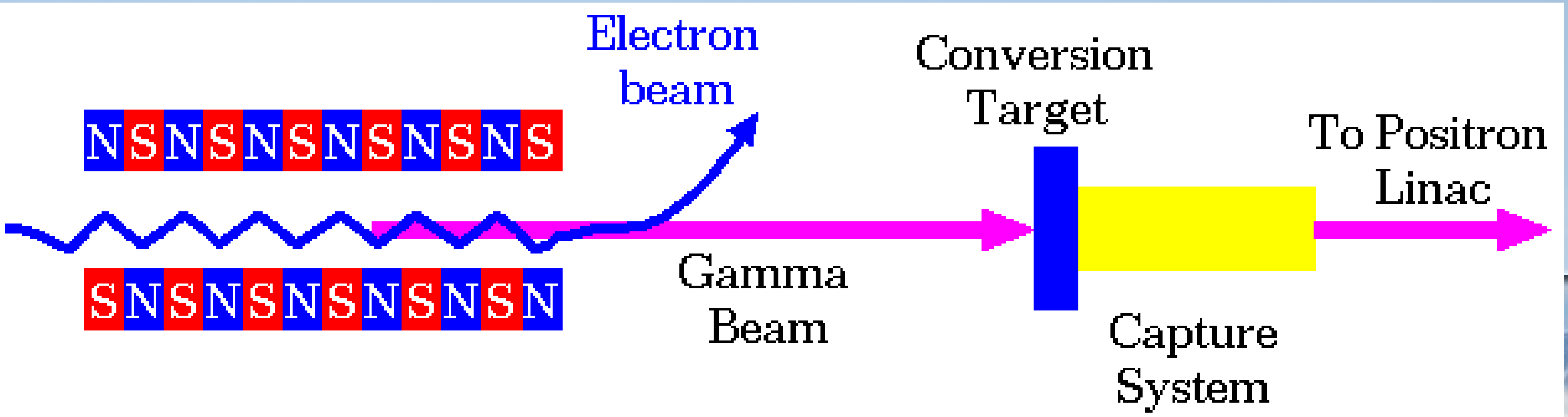
Undulator Scheme (1)

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

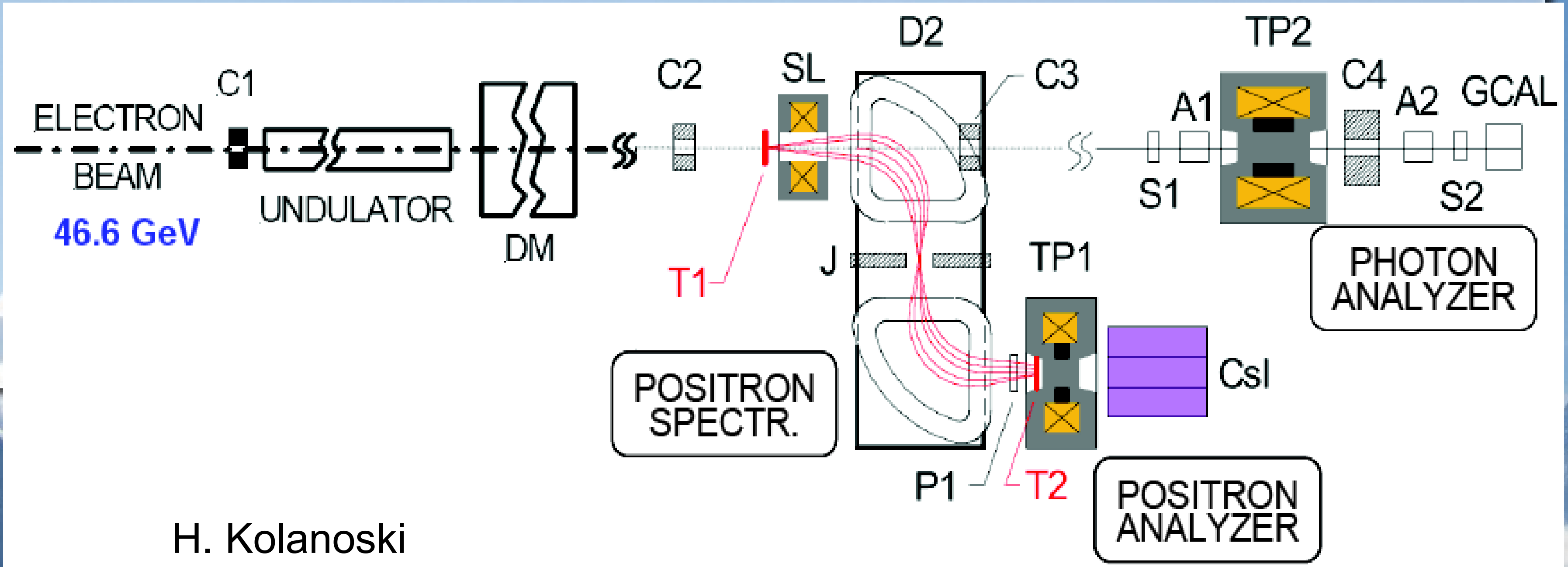


Undulator Scheme (2)

- Constructing a 130 GeV electron linac dedicated to positron generation is not realistic.
- The main electron linac is shared by collision beam and positron generation.
- In low energy operation, the positron yield becomes very low. It could be solved by alternate-pulse operation.
- By employing helical undulator, polarized positron is obtained.

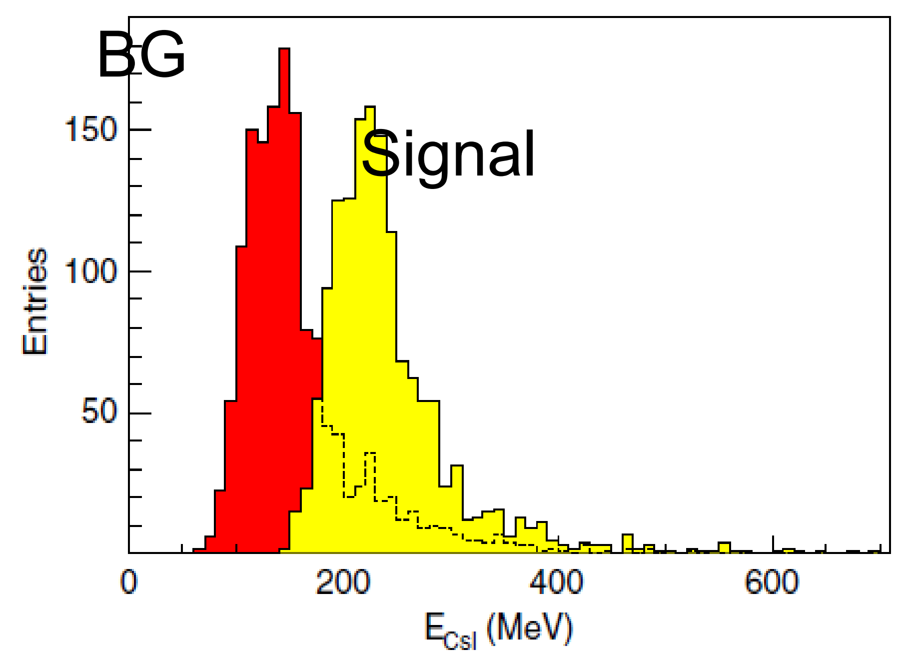
E166 (1)

- 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

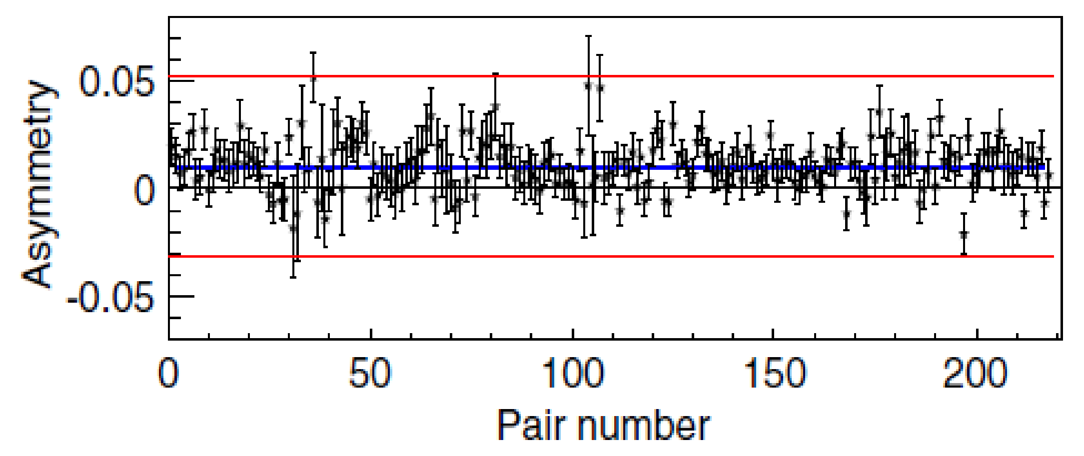
E166 (2)



- The signal is observed from the undulator radiation.
- The asymmetry is calculated with each pair of data with opposite magnetization of the polarimeter for polarization measurement.

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

G. Alexander

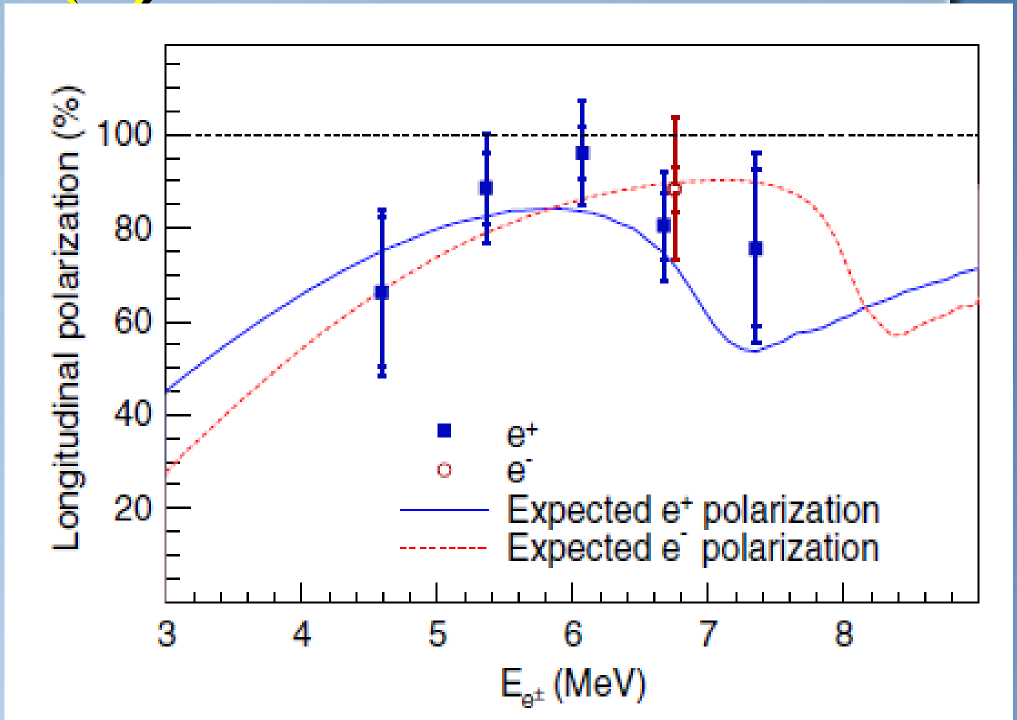


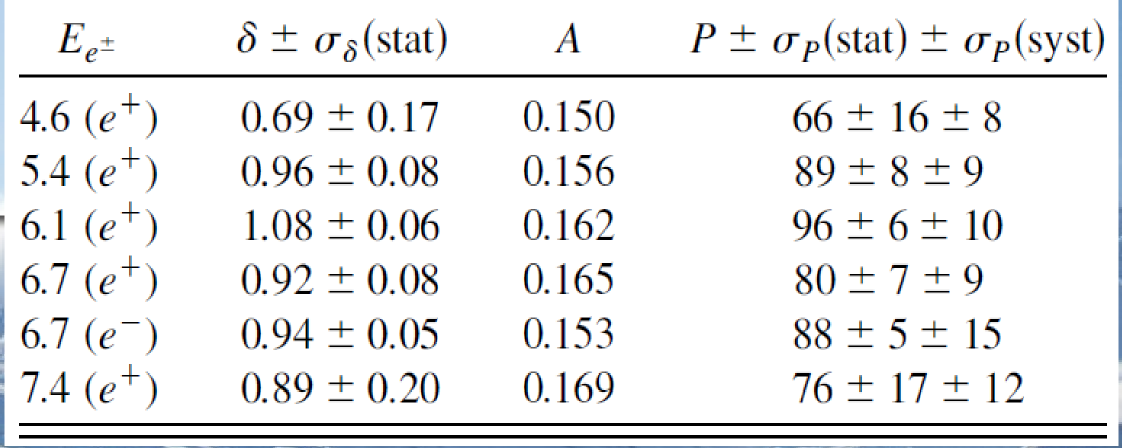
E166 (3)

From the asymmetry of 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.



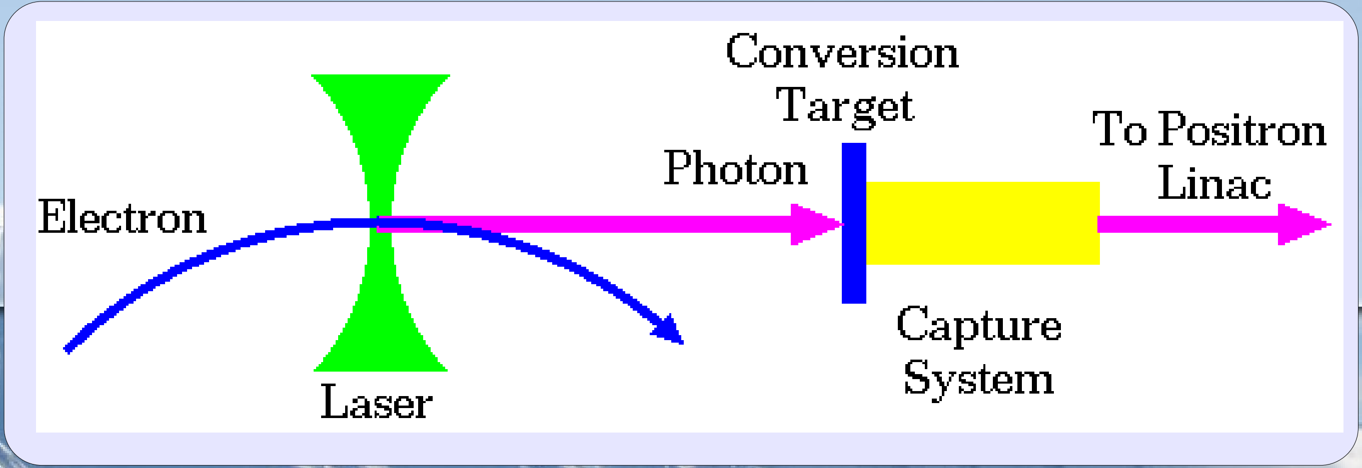


$E_{e^\pm}$	$\delta \pm \sigma_\delta$(stat)	A	$P \pm \sigma_P$(stat) $\pm \sigma_P$(syst)
4.6 (e^+)	0.69 ± 0.17	0.150	66 ± 16 ± 8
5.4 (e^+)	0.96 ± 0.08	0.156	89 ± 8 ± 9
6.1 (e^+)	1.08 ± 0.06	0.162	96 ± 6 ± 10
6.7 (e^+)	0.92 ± 0.08	0.165	80 ± 7 ± 9
6.7 (e^-)	0.94 ± 0.05	0.153	88 ± 5 ± 15
7.4 (e^+)	0.89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

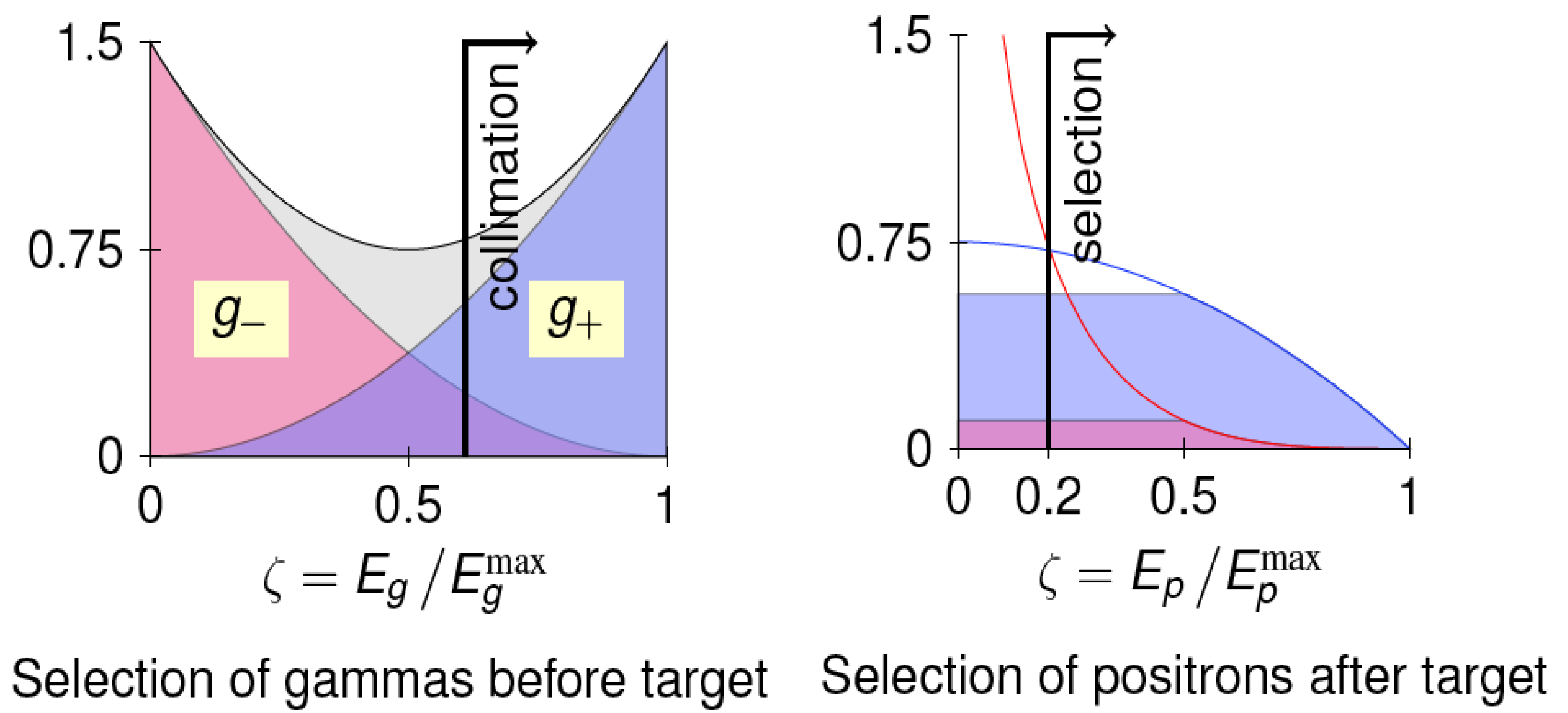
- Positron Polarization.
  - **Higher degree up to 90 %.**
  - **Train by train flipping (5Hz) by laser polarity control.**
- Dedicated e- beam.
  - No concern for e- beam quality degradation.
  - No inter-system dependence.
    - **Simple, easier construction, operation, commissioning, maintenance,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

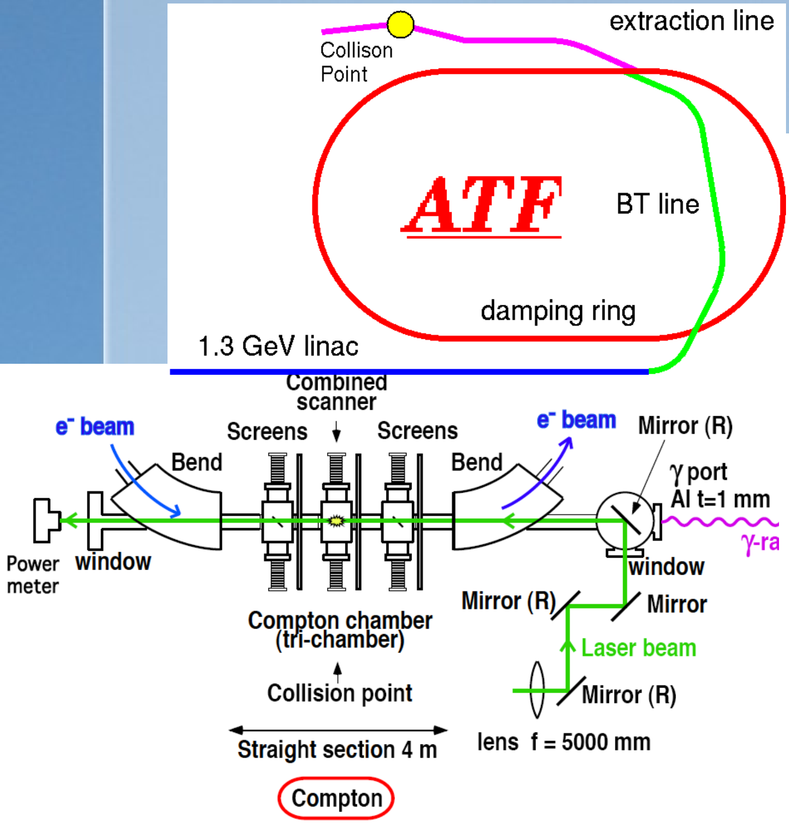
Compton Scheme (3)

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

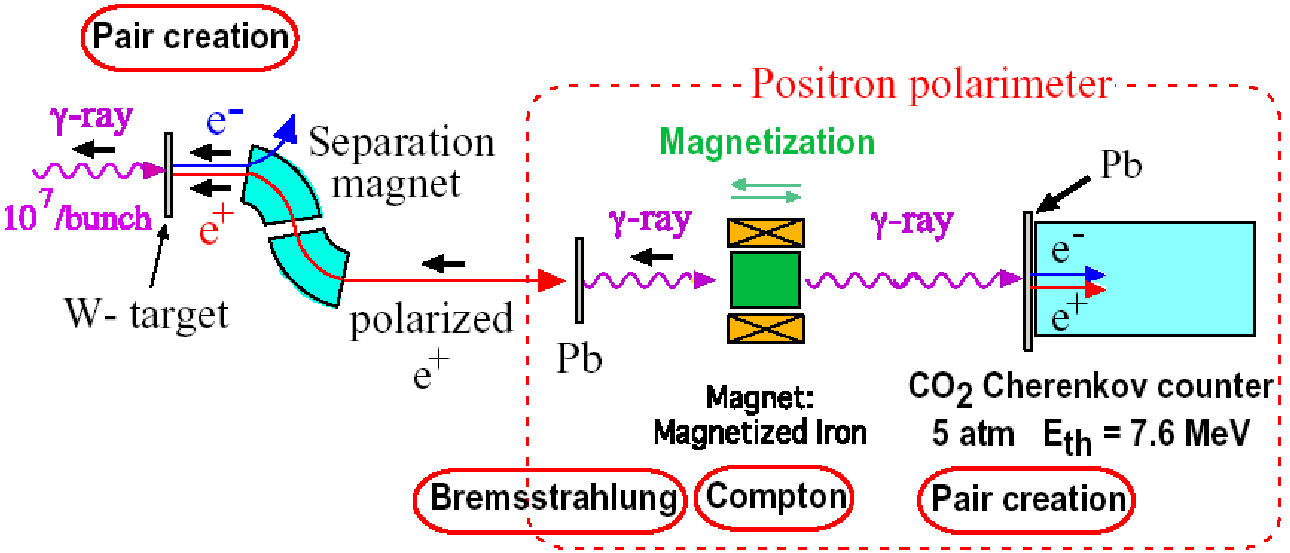


Selection of gammas before target Selection of positrons after target

KEK-ATF experiment



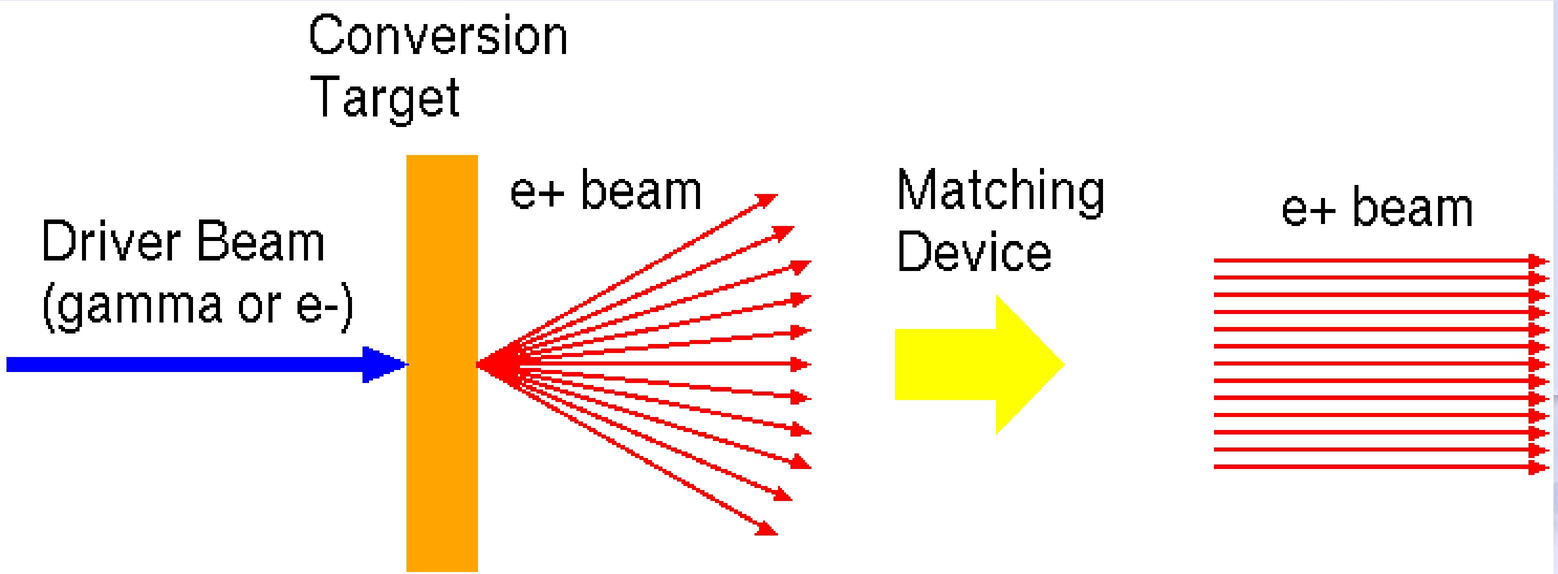
Positron: production, selection, and polarimetry



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

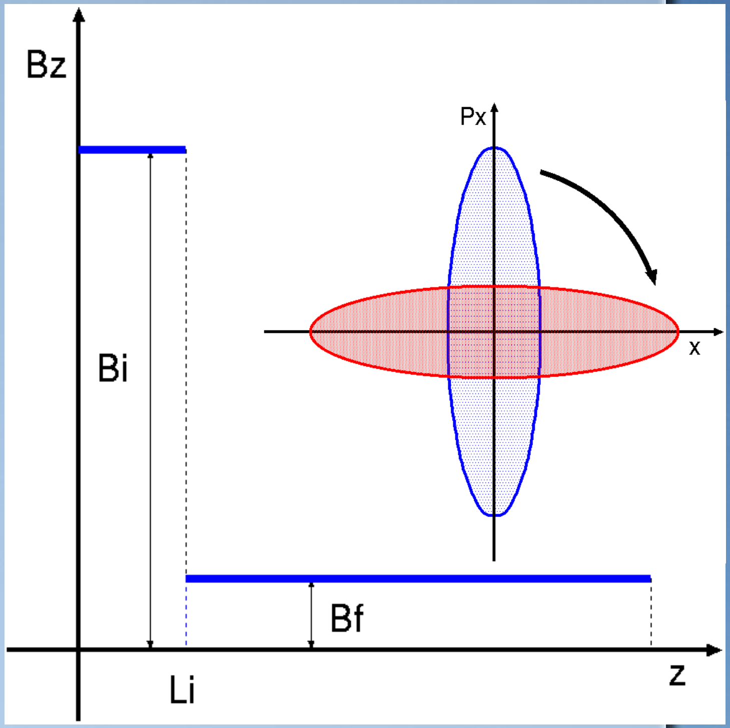
Positron Capture (1)

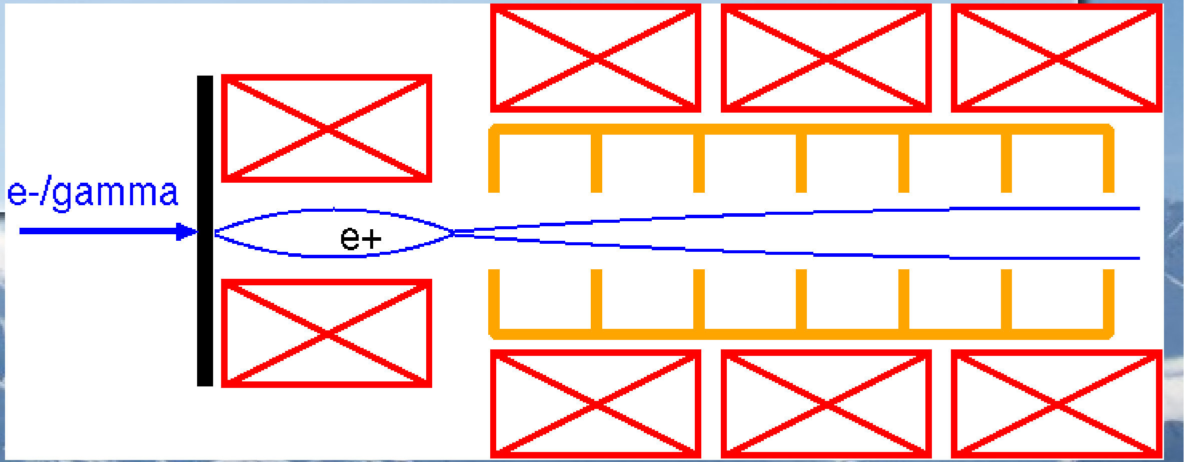
- The generated positrons are distributed in a small spot size and in a large momentum space. To convert it to the parallel beam, capture devices are used
  - QWT (Quarter Wave Transformer)
  - AMD (Adiabatic Matching Device)



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° in the phase space, that is why it is called as Quarter Wave Transformer.





QWT(2)

Positrons are circulated with radius ρ.

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

Time to travel πρ in xy plane,

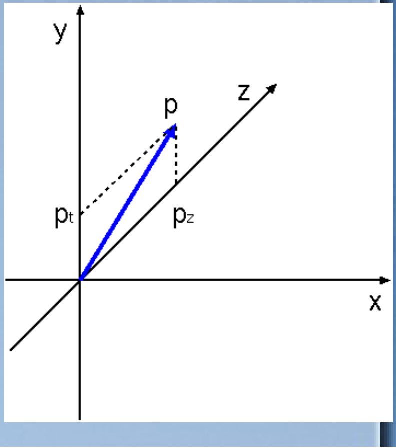
$$t_{xy} = \frac{\gamma m \pi \rho}{p_{t0}} = \frac{\gamma m \pi}{eB_i} \qquad (2-2)$$

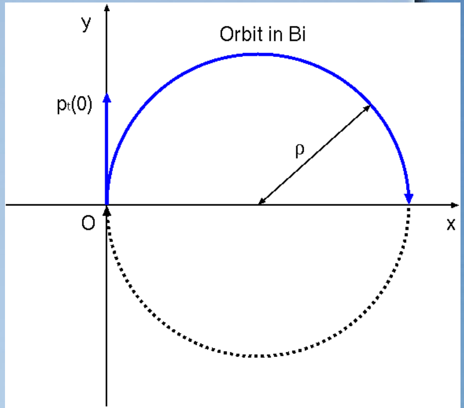
Time to travels L_i

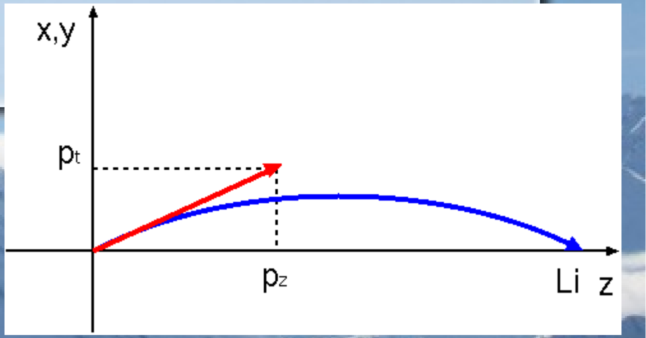
$$t_z = \frac{L_i m \gamma}{p_z} \qquad (2-3)$$

Only positrons satisfying these conditions 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

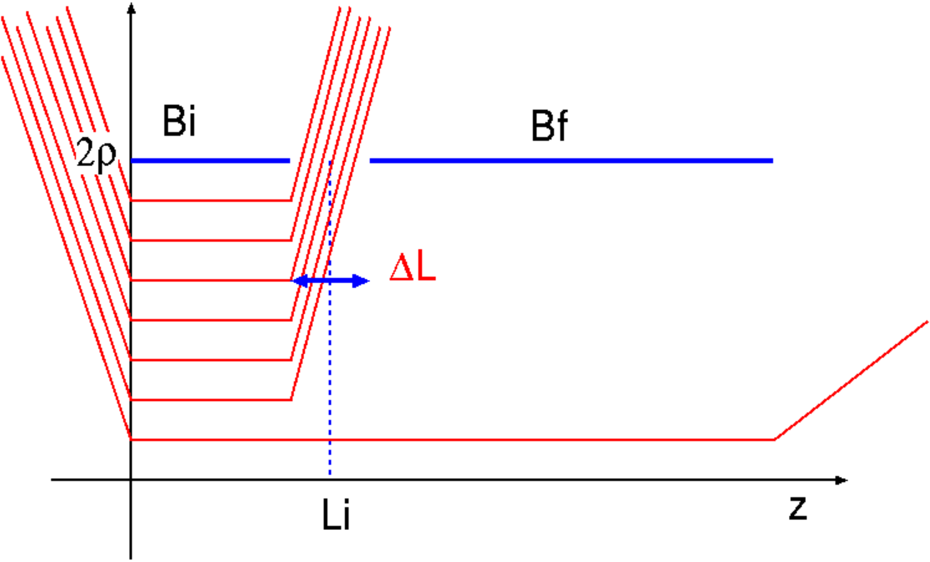
$$\Phi_i = \pi (2\rho)^2 B_i \quad (2-5)$$

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

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

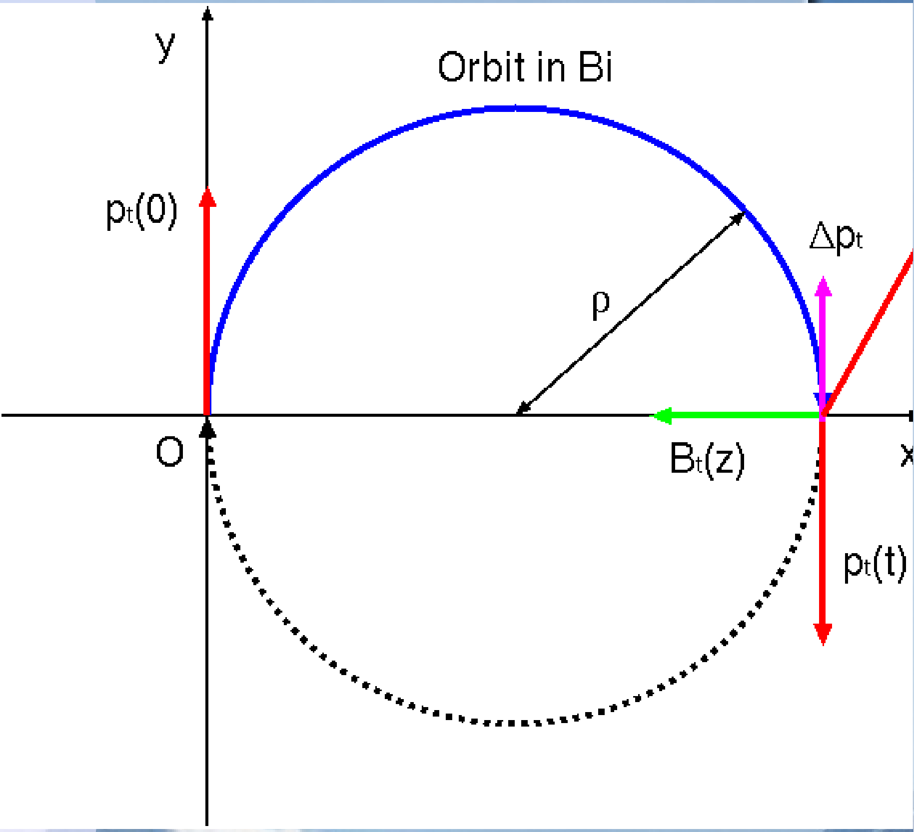
$$=e v_z \int B_t(z)\frac{dz}{v_z}$$

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

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)

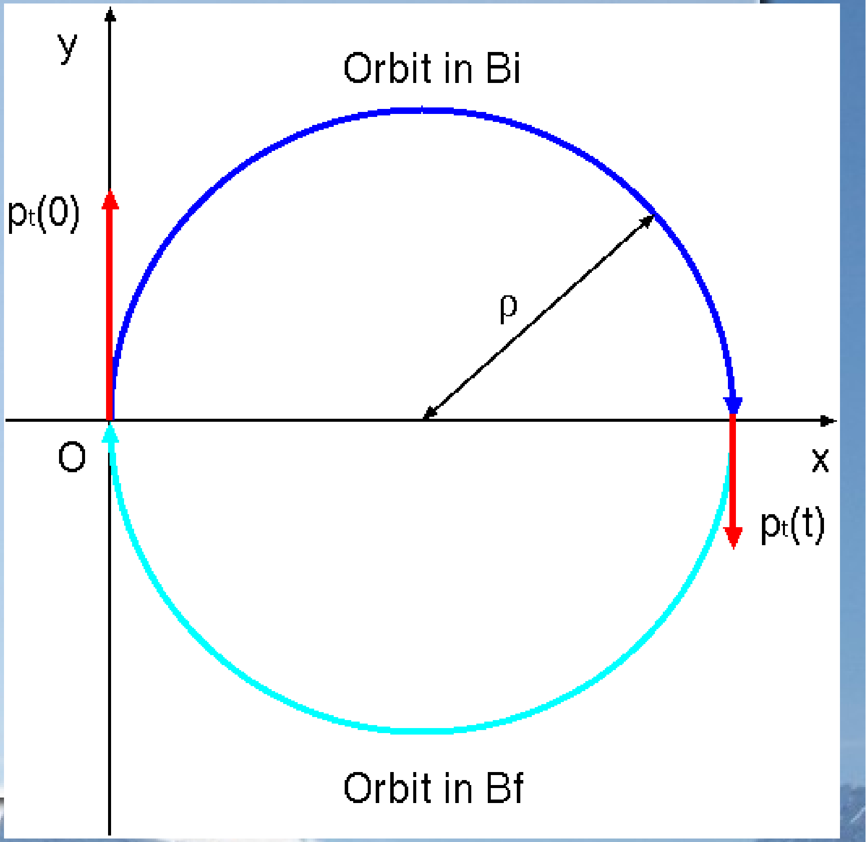
Pt(t) after the kick is

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

Radius of circulating motion of this particle in B_f is

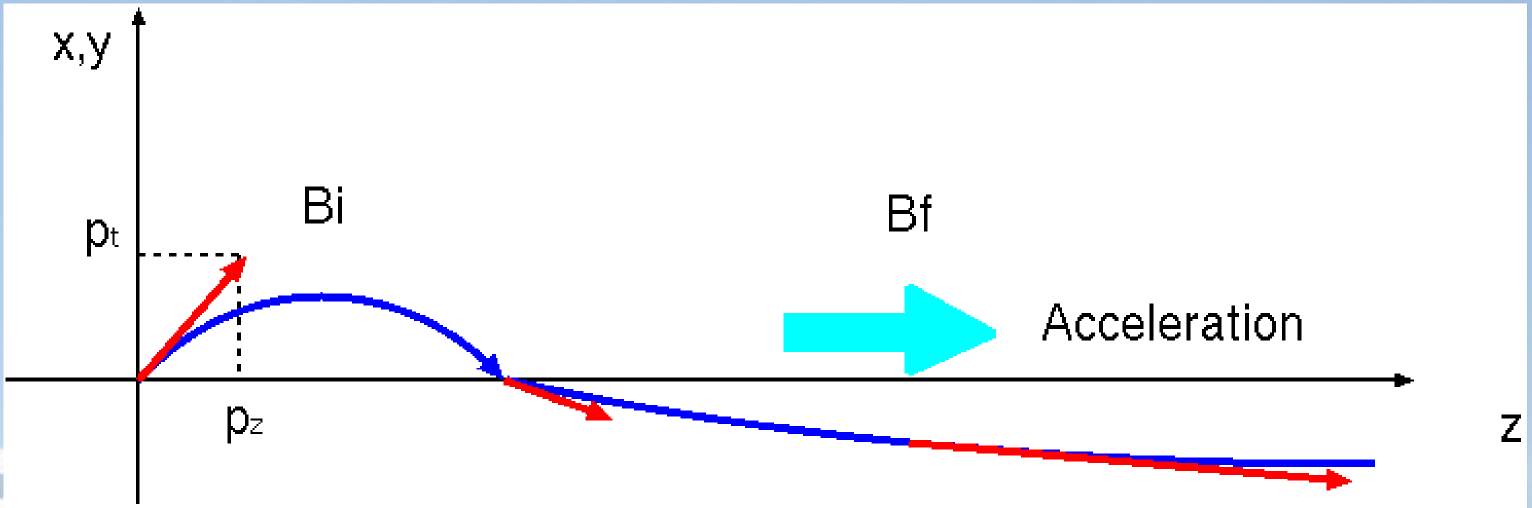
$$\rho_f = \frac{1}{eB_f}\frac{P_{t0}B_f}{B_i} = \frac{p_{t0}}{eB_i} \quad (2-13)$$

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



QWT(6)

- Positrons, which continue the circulating motion in B_f region, is simultaneously accelerated and transverse momentum (x' and y') 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

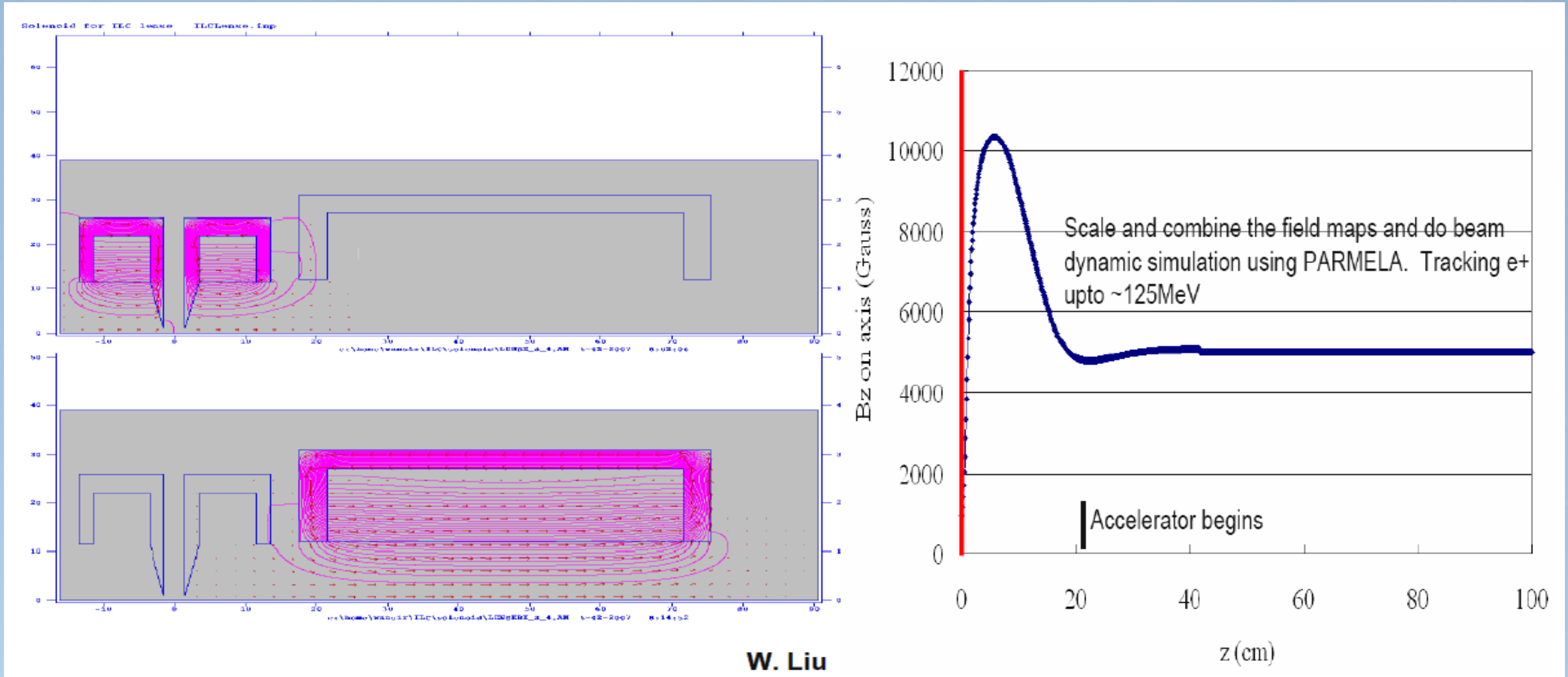
$$\frac{\delta E}{E} \sim \frac{B_f}{B_i} \qquad (2-15)$$

Momentum acceptance

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

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

QWT(8)



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

W. Liu

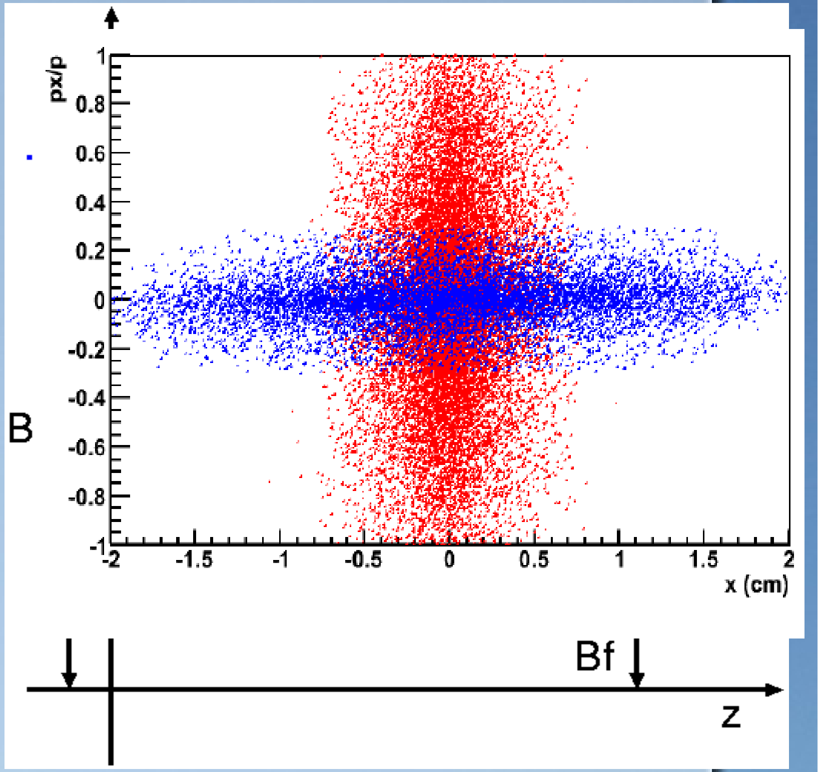
- Initial strong solenoid magnet with bucking to cancel B field on target.
- B_f is 0.5 T.
- NC L-band accelerator is placed in B_f region.

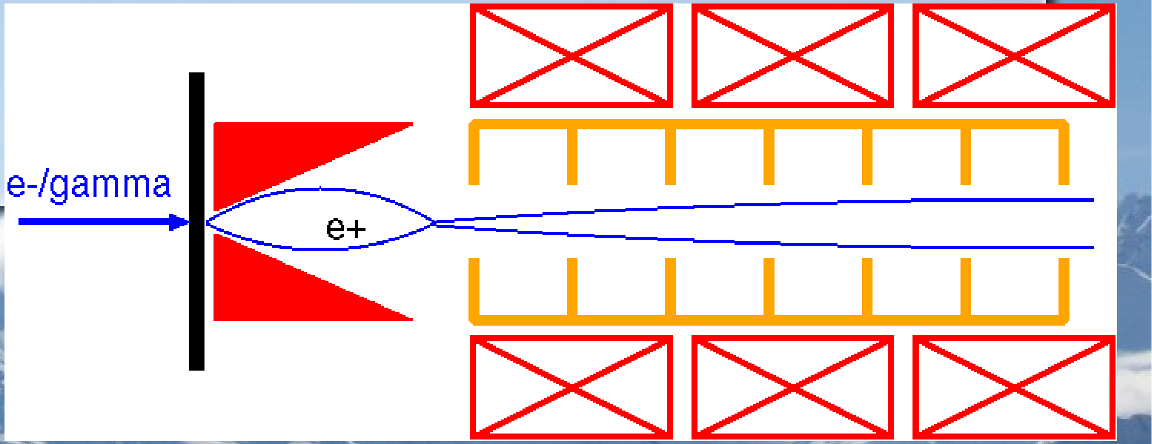
AMD(1)

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

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

AMD has relatively large energy acceptance.





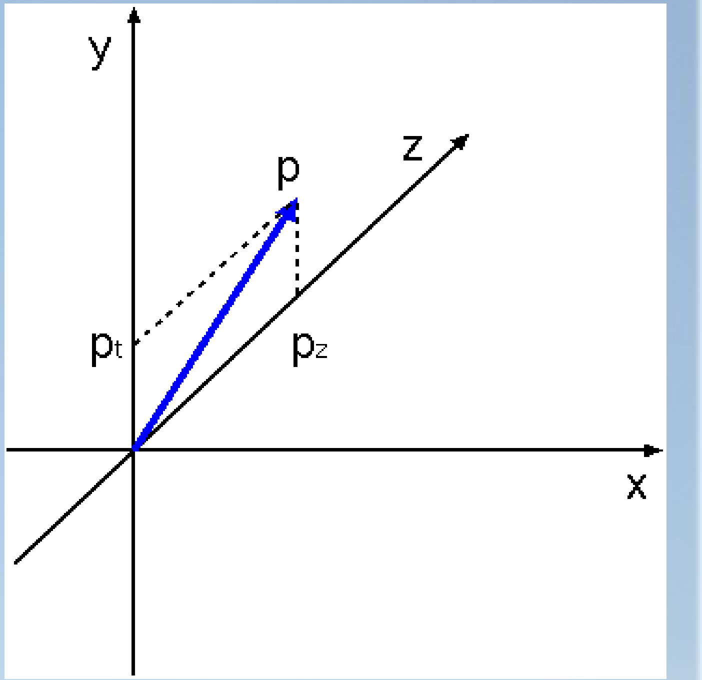
AMD (2)

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 the motion is changed slowly compare to the circulating frequency, adiabatic invariant is constant during the motion.

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



AMD(3)

Due to the adiabatic condition,

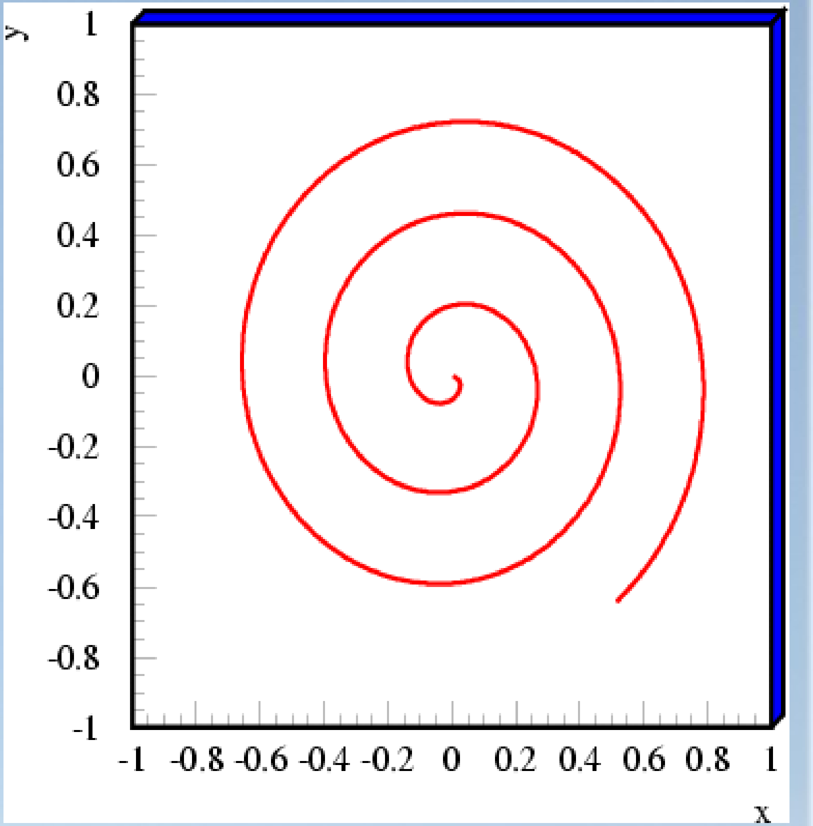
$$\frac{p_t(z)^2}{eB(z)}=\frac{p_{t0}^2}{eB_i} \qquad (2-21)$$

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

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 (step solenoid field variation)

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

The ratio (compensation by AMD)

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

AMD(5)

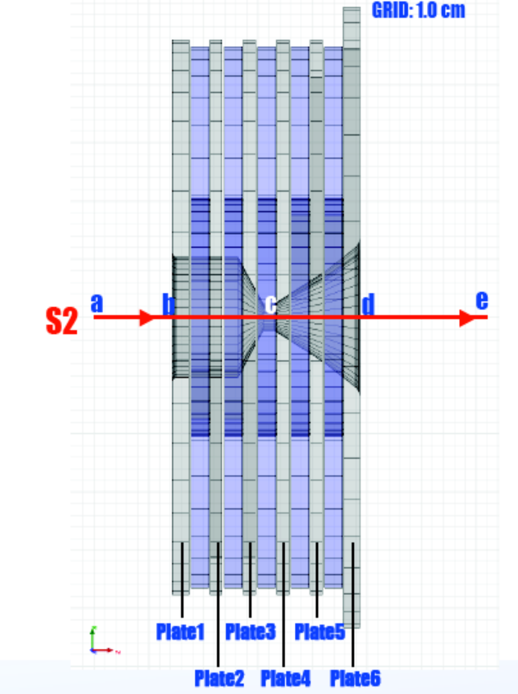
Acceptance on transverse momentum

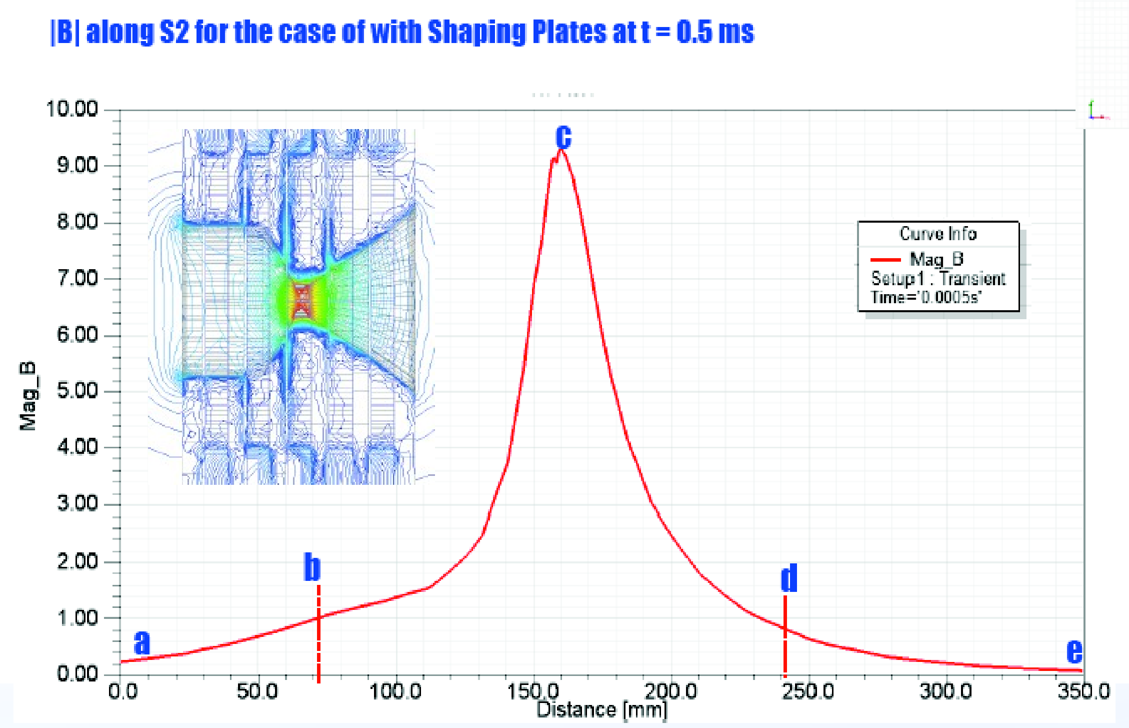
$$p_t < \frac{a}{2} e \sqrt{B_f B_i} \qquad (2-27)$$

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

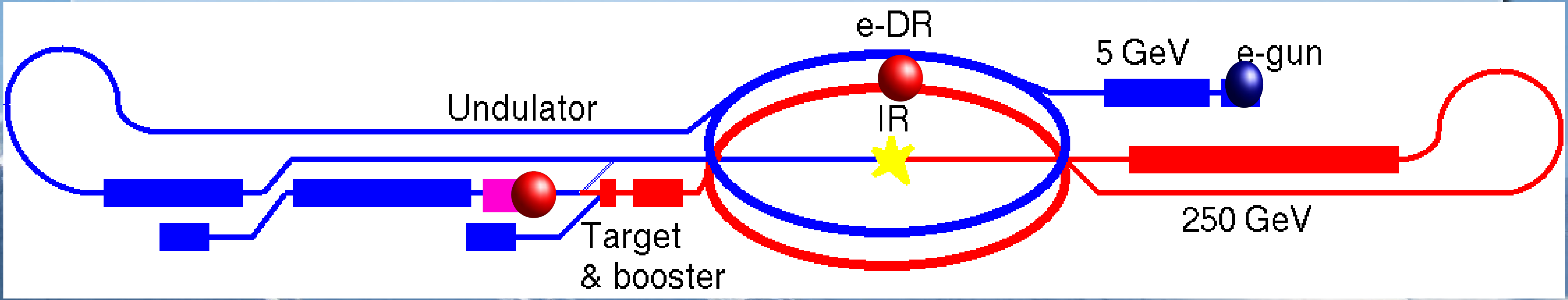
Parameters

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

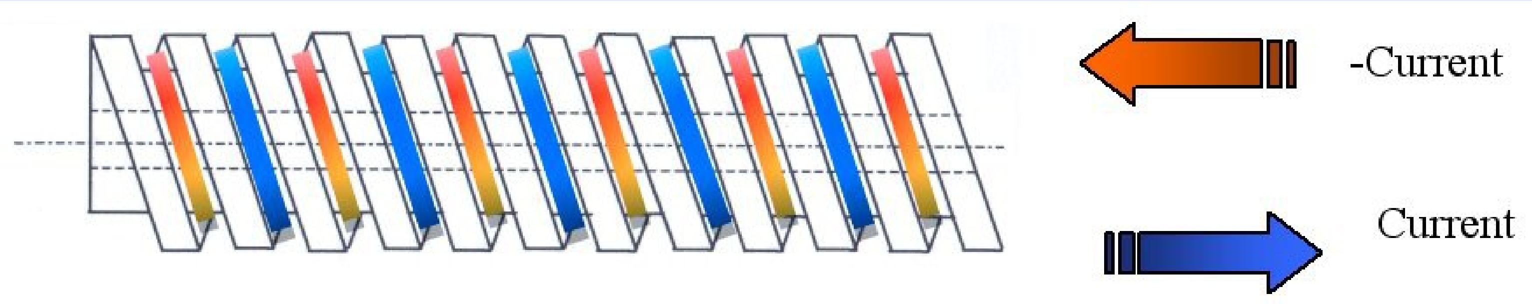
- It is a first undulator based positron soure in the world.
- 250GeV electrons generate gammas.
- Gamma rays are converted to positron.
- A positron source driven by 0.5 GeV electron is a back up for high availability.
- A common 5 GeV positron booster.

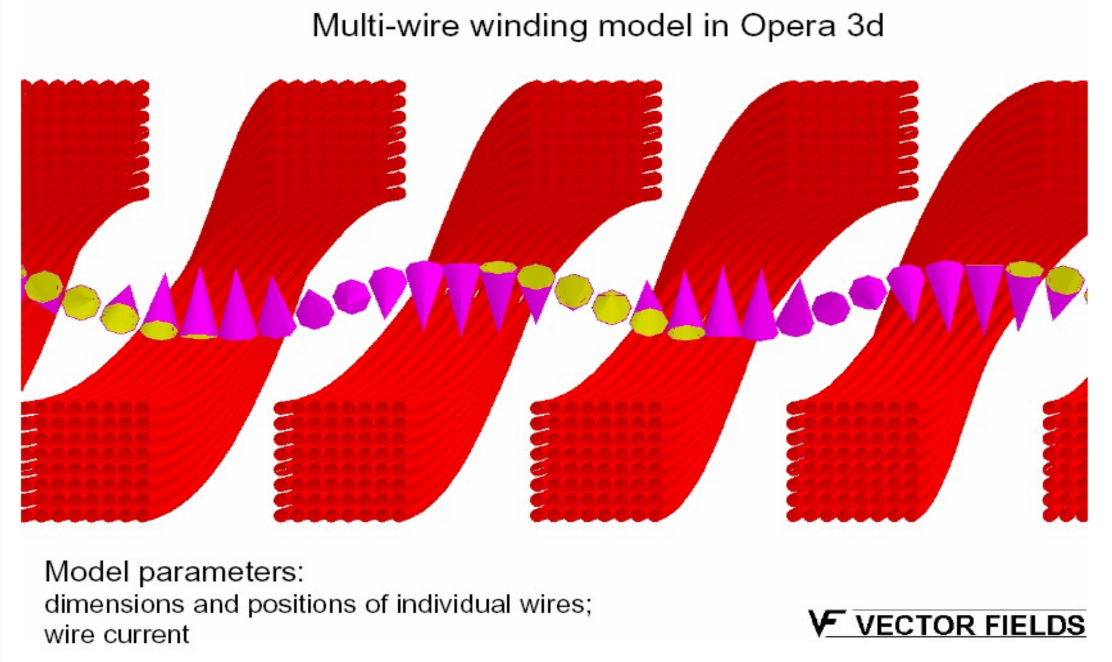


System Specifications

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




Multi-wire winding model in Opera 3d

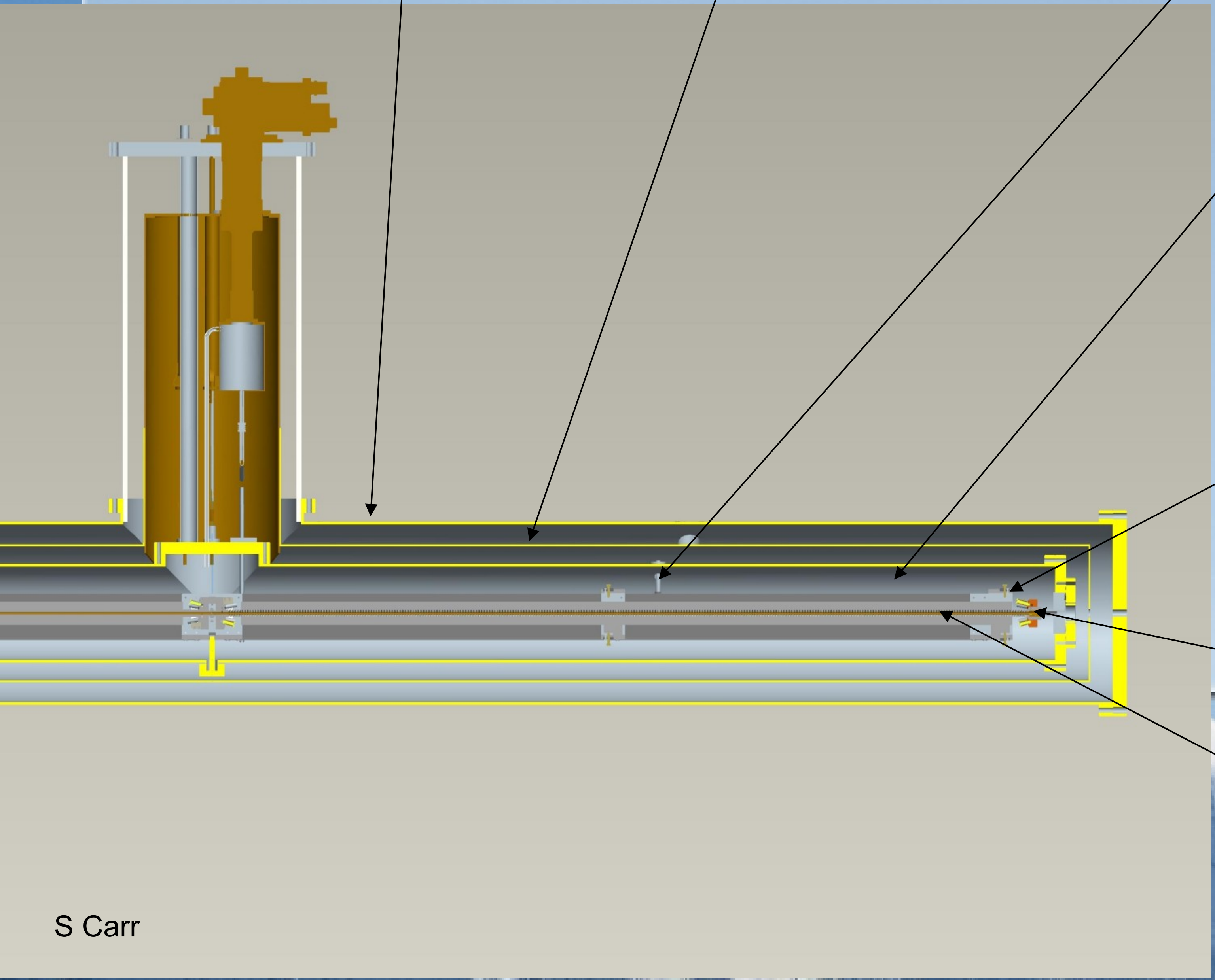
Model parameters:
dimensions and positions of individual wires;
wire current

By Yury Ivanyushenkov

Undulator Specifications

Parameter	Value	Unit
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

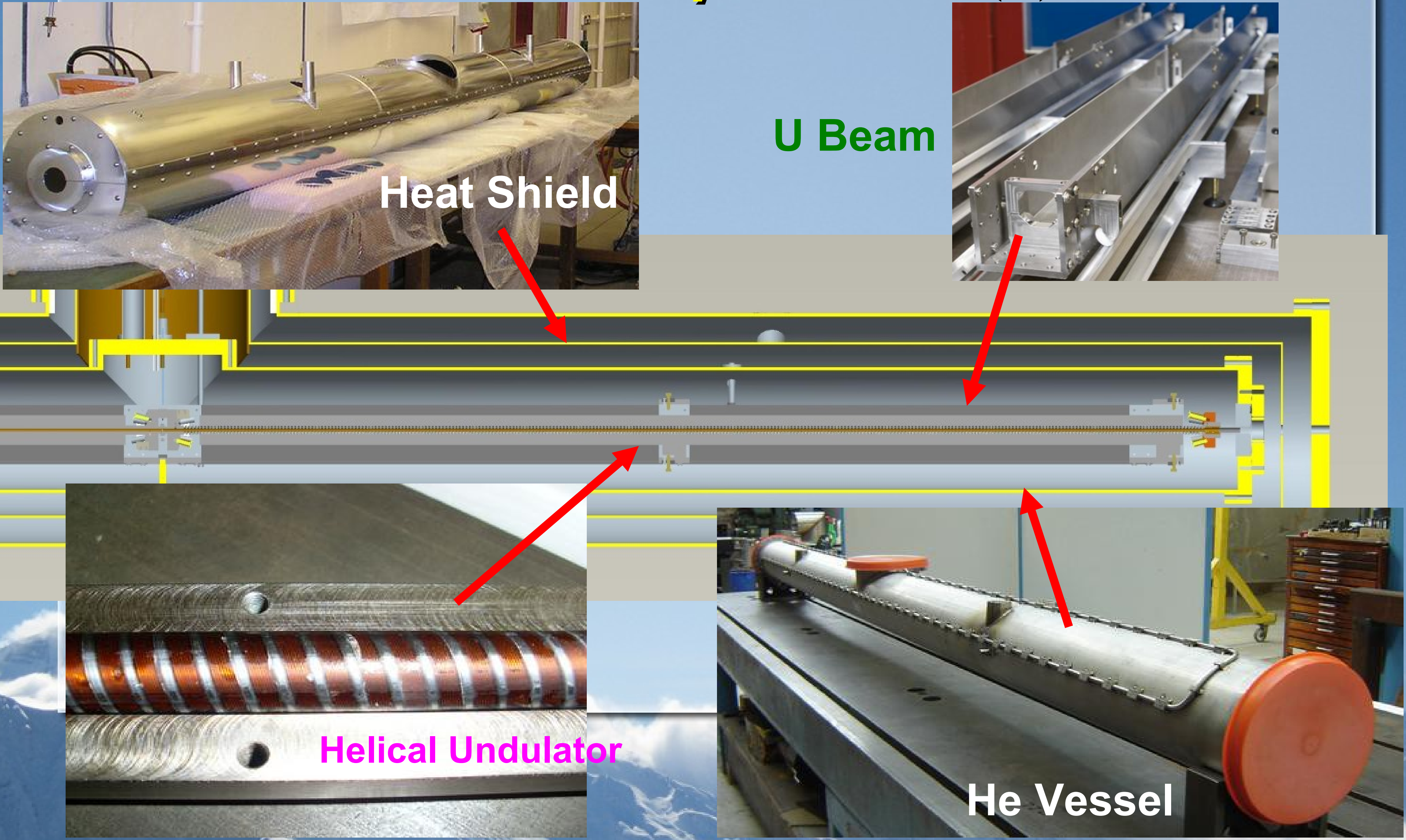
U Beam used to support/align the magnet.

Beam Tube

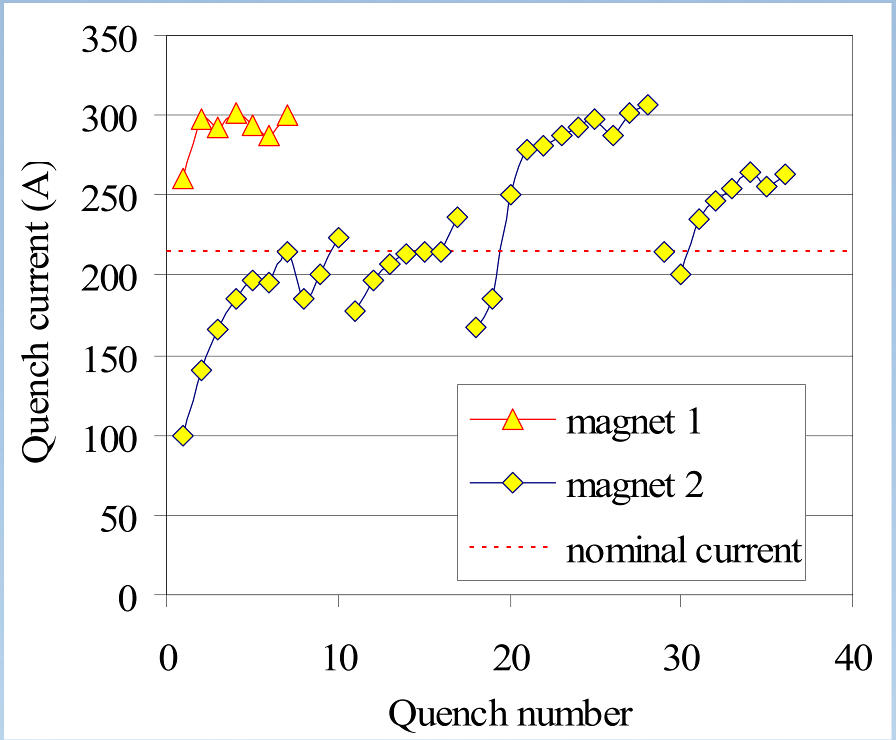
Magnet cooled to 4.2K by liq He in bath.

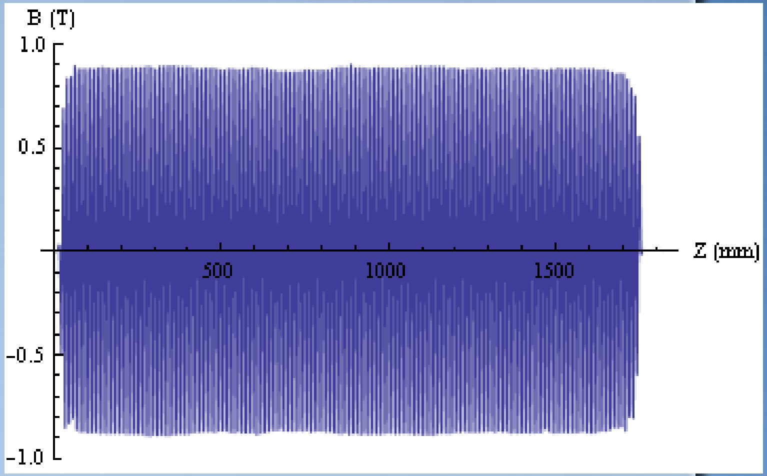
S Carr

Undulator Cryomodule (2)



Undulator: Field test

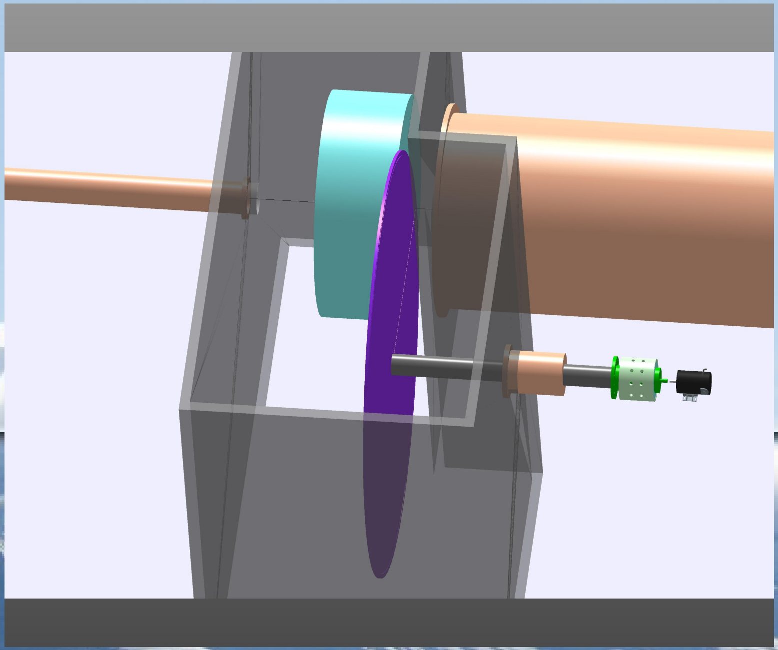


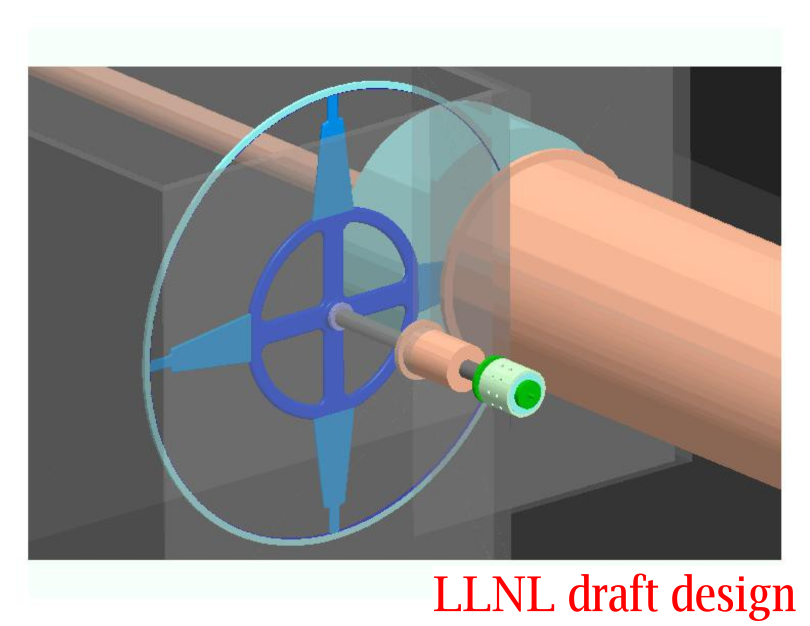


- All two magnets finally satisfied the specification.
- Field profile is measured by hall probe, showing a good quality.

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.
- Vacuum seal is a technical issue.

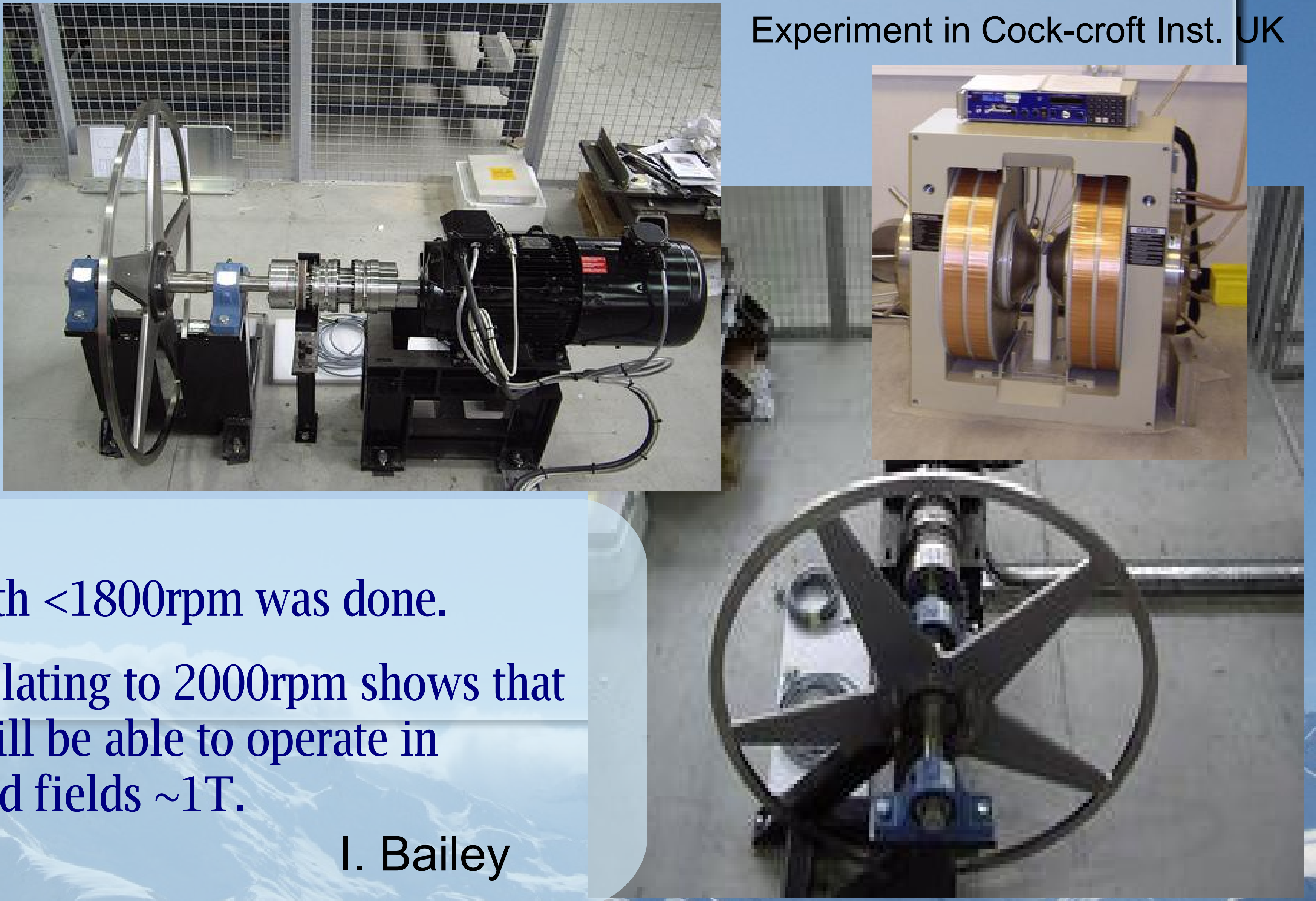




LLNL draft design

Target Prototype

Experiment in Cock-croft Inst. UK

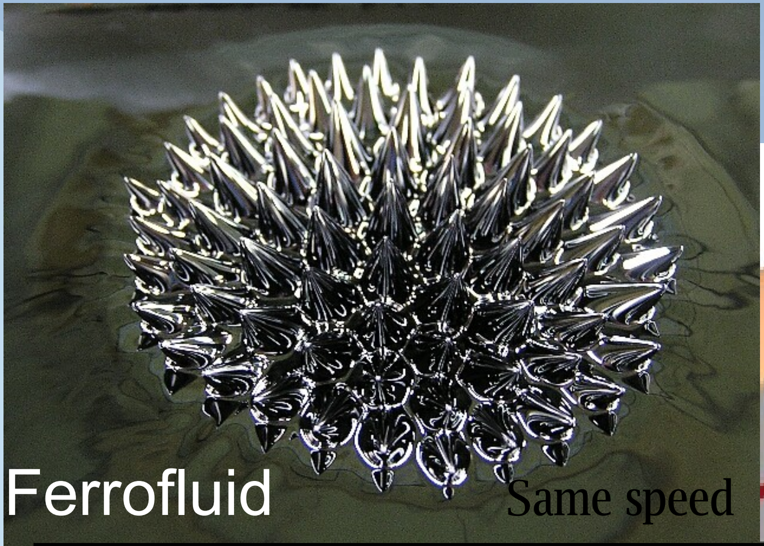


- Test with <1800rpm was done.
- Extrapolating to 2000rpm shows that wheel will be able to operate in immersed fields ~1T.

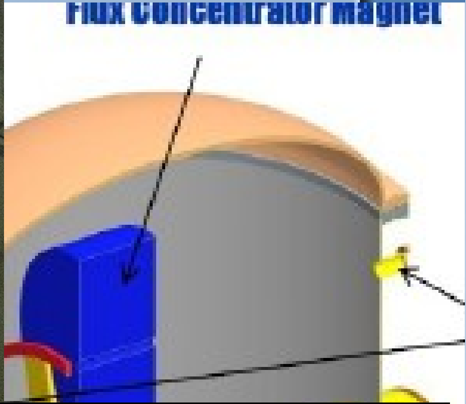
I. Bailey

Target Design

- 15mm Ti-alloy for high thermal conductivity.
- 100m/s tangential speed to suppress thermal depostion.
- The rim wheel shape to prevent heat load and mechanical force by eddy current.
- The target should be fastly rotated in a vacuum. Need technical R&D , especially fo vacuum seal.



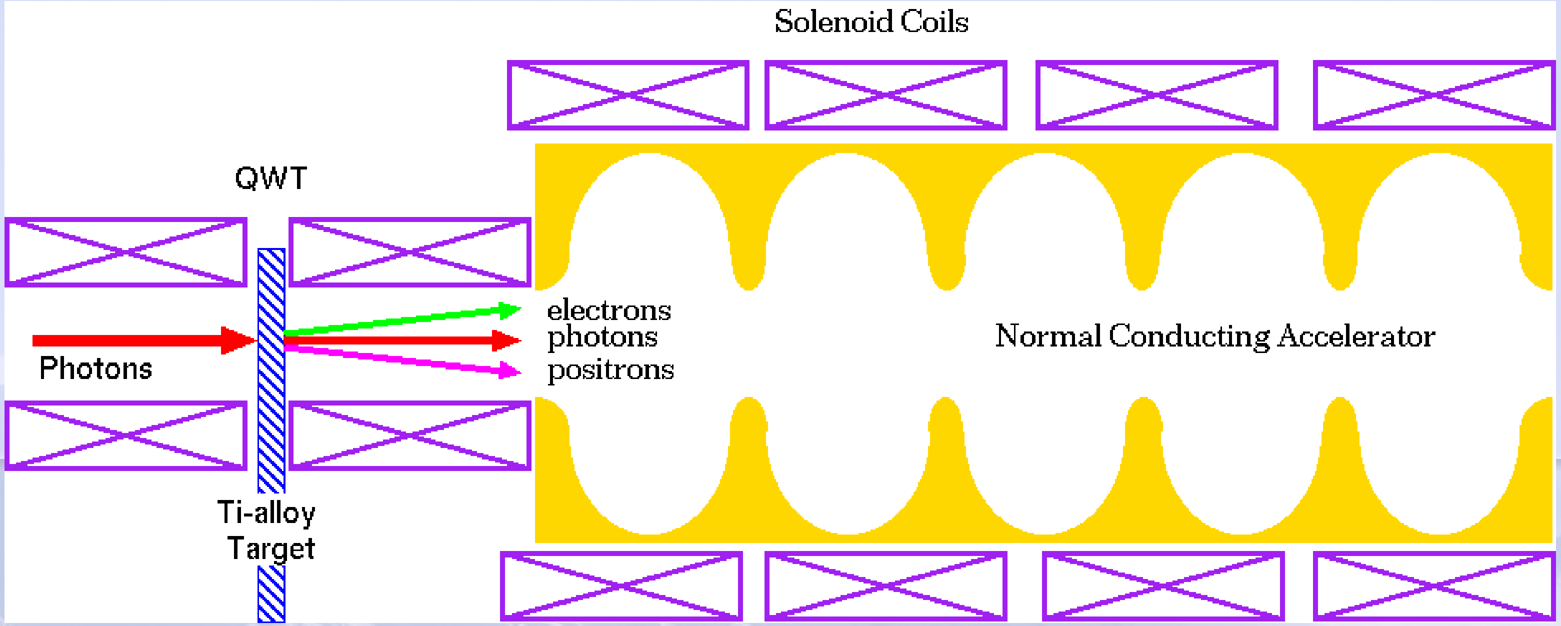
Same speed



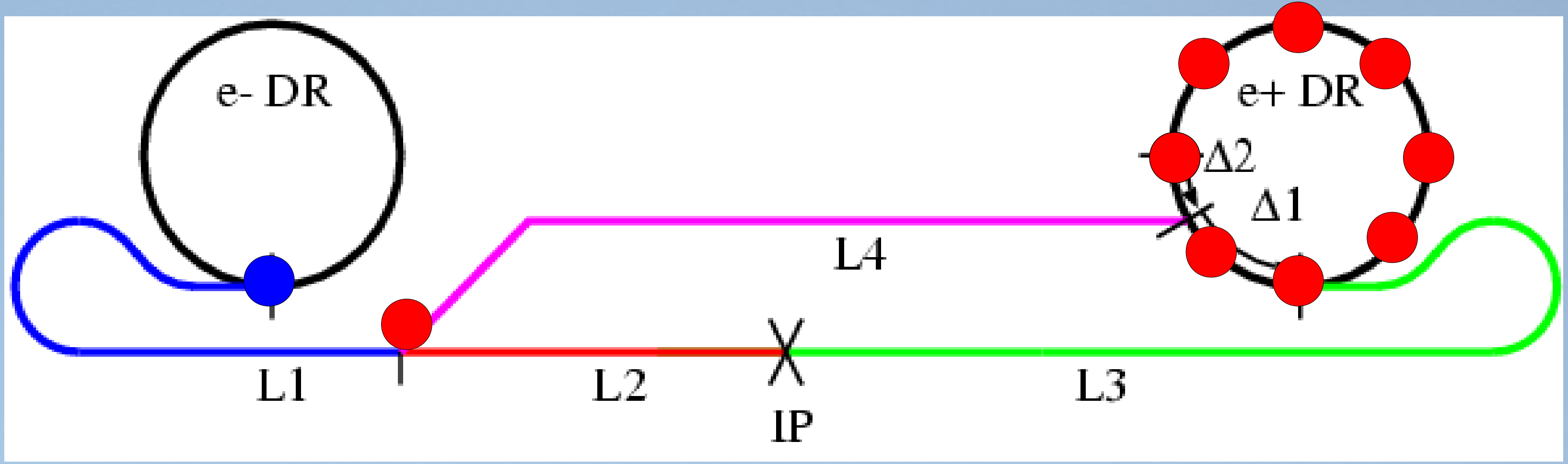
JR East

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



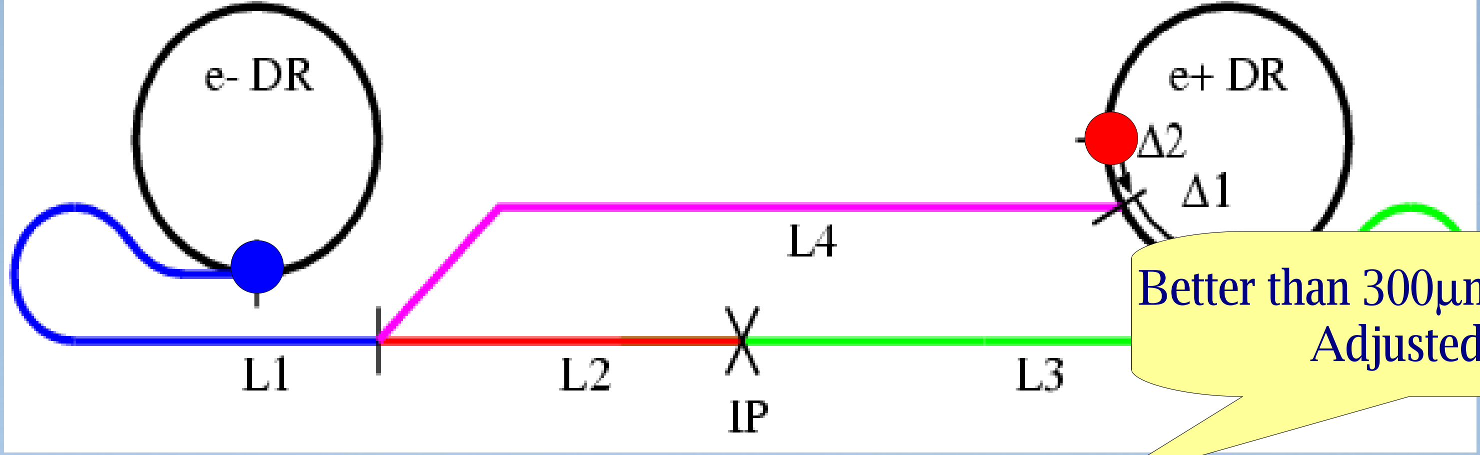
$$For\ collision: L_1+L_2=\Delta_1+\Delta_2+L_{3,}$$

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

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

- Positron beam i
- The generated p e 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.

Pathlength condtion:
Self-reproduction + collission



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

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

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

Physical path length{Li | i=1,4}
has to be adjusted.

Better than RF bucket height (5mm)
Adusted by other than Δ2.

Pathlength Condition Adjustment

- Collision condition has to be adjusted with even better than the bunch length (300μm). It is less than 0.1ps by assuming 30μm accuracy. It is not so easy, but it can be adjusted by timing between the electron and positron linacs.
- Accuracy for self-reproduction condition is 5mm, but it has to be adjusted "physically".

Installation accuracy

- GPS determines position in a common system with high accuracy, e.g. path fromCERN to Gran Sasso is determined as 700km ± 3cm.
- GPS can not be used in tunnel or underground.
- In OPERA experiment, distance from the tunnel entrance to OPERA detector was measured with survey meter. The accuracy was 10.5km±20cm.
- The accuracy in 15km ILC tunnel could be 30cm, worse than 5mm.

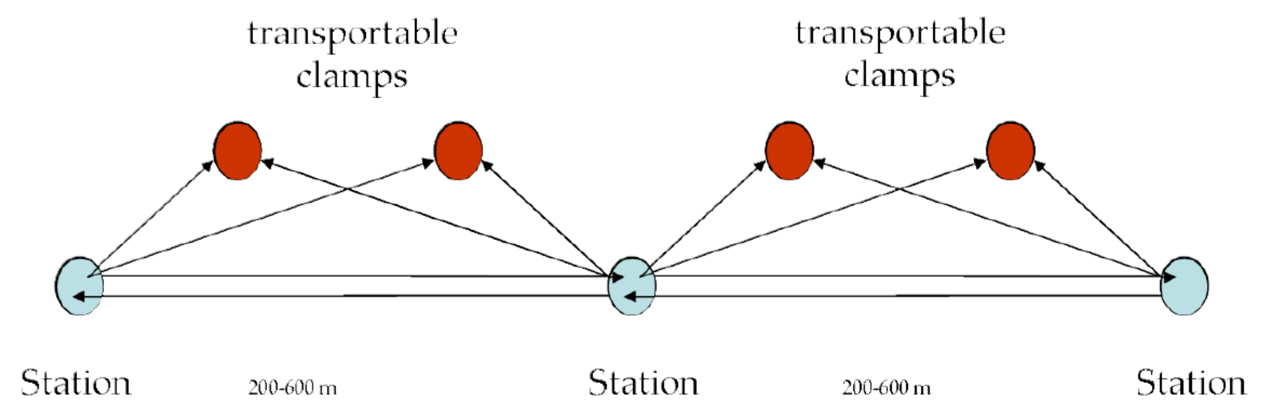
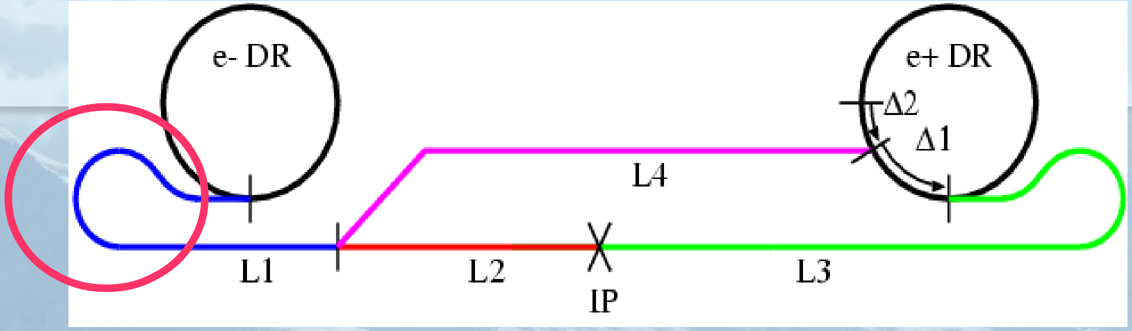


Figure 2: The traverse surveying pattern

OPERA Public Note132 v3

Pathlength Adjustment

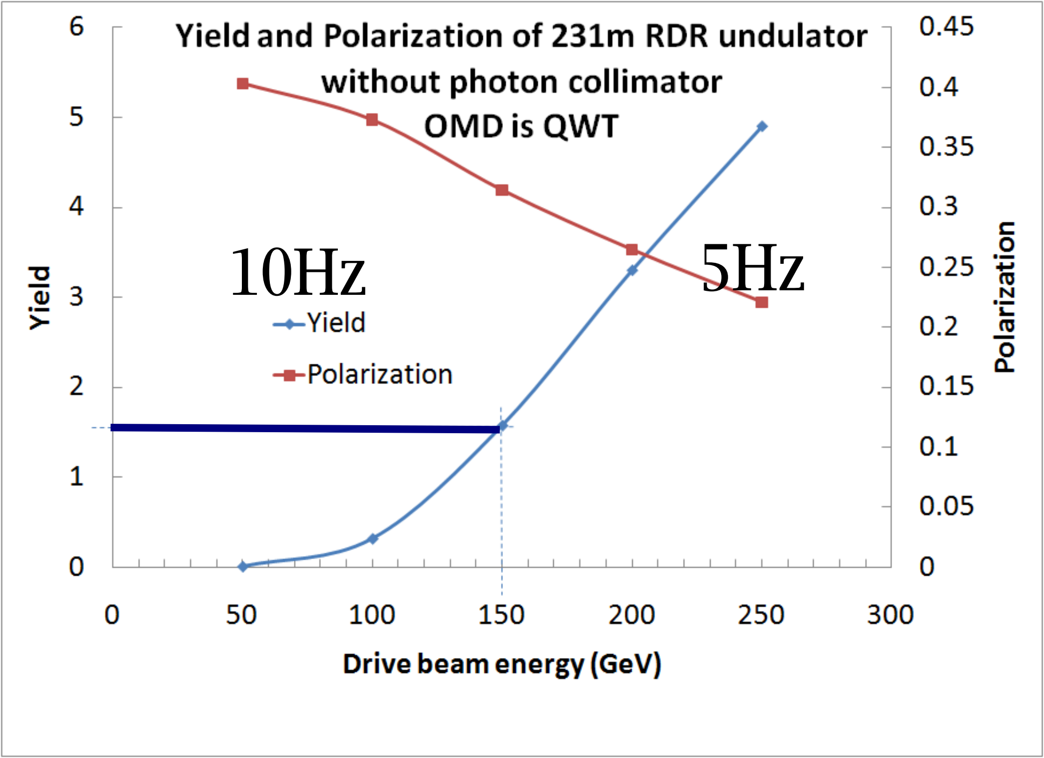
- Accuracy after installation:15km±30cm, is worse than the requirement.
- To adjust 30cm by 50m chicane orbit with 1m shift, the total length could be 1500m. It is unrealistic.
- DR circumference C_{DR} can be adjusted by RF frequency with extremely good accuracy. In early comissioning, the adjustment length can be estimated by varying C_{DR}.
- The physical pathlength is adjusted according to the estimation.
- Small adjustment mechanism, e.g. orbit in turn around, is necessary.



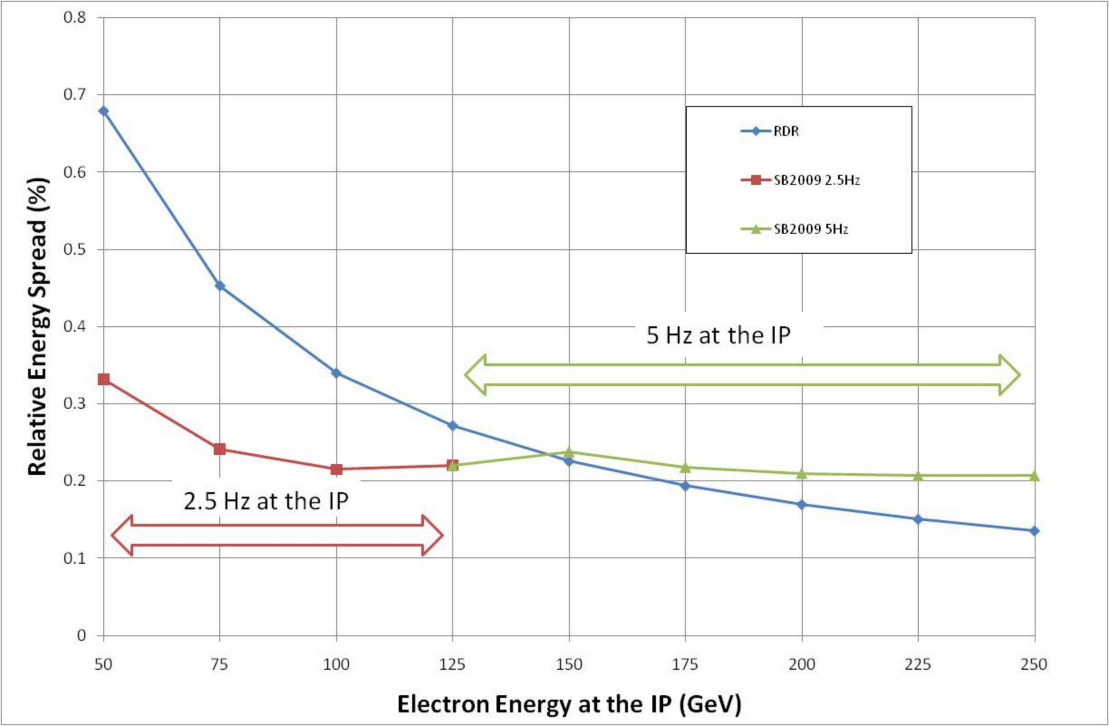
$$L_1+L_4=\Delta_2+nC_{DR},$$

Positron Yield

- Drive energy for undulator is same as the collision energy.
- Positron yield at the low energy becomes less because of the low gamma energy and almost zero at less than 100 GeV.
- The electron beam dedicated for the positron generatin is accelerated alternately with the beam for collision.
- Electron and positron linacs are operated in 10 and 5 Hz, respectively.



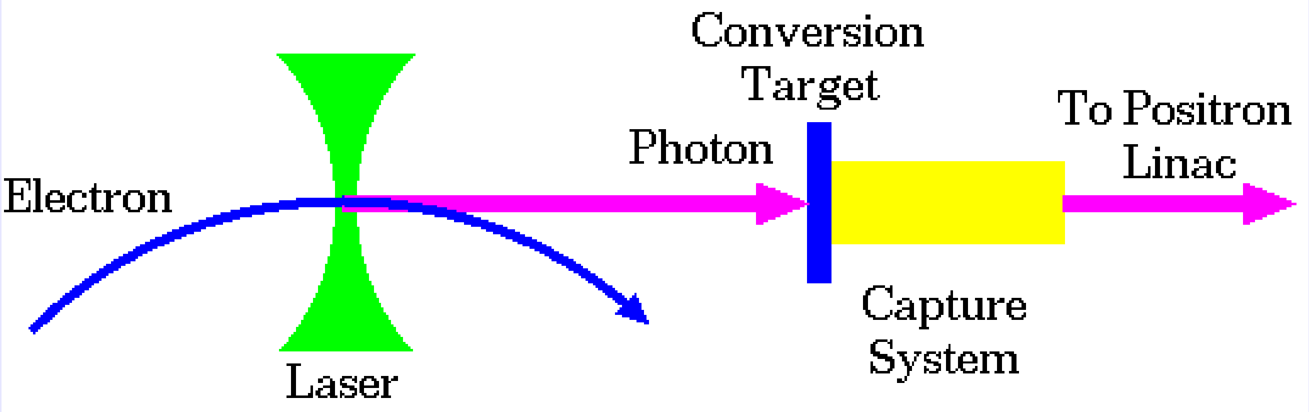
Electron energy spread



- The energy spread is increased by the undulator radiation.
- It is 0.15% at 250GeV.
- No enhancement by the undulator in 10 Hz operation.

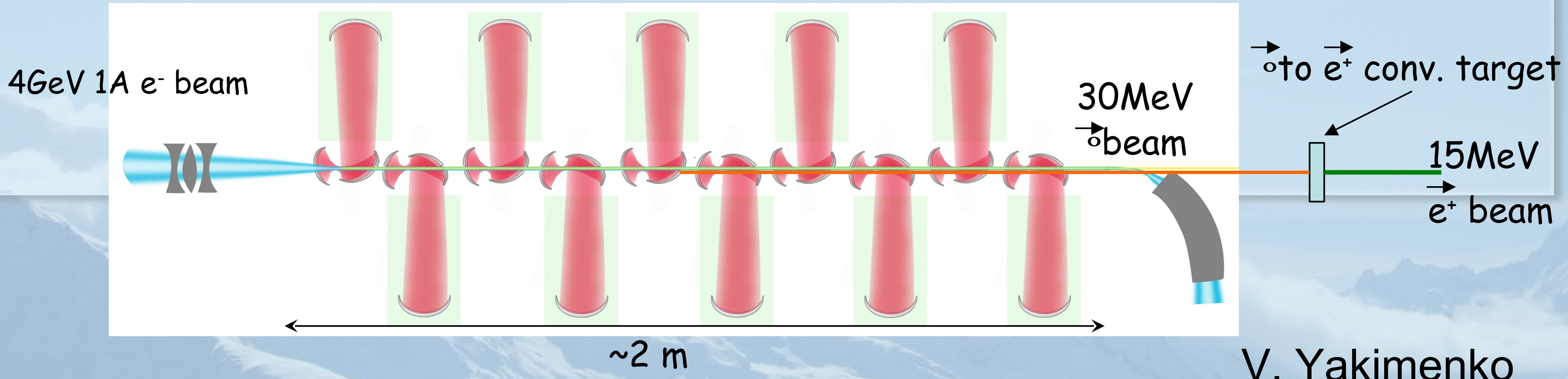
Laser Compton Scheme

- 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

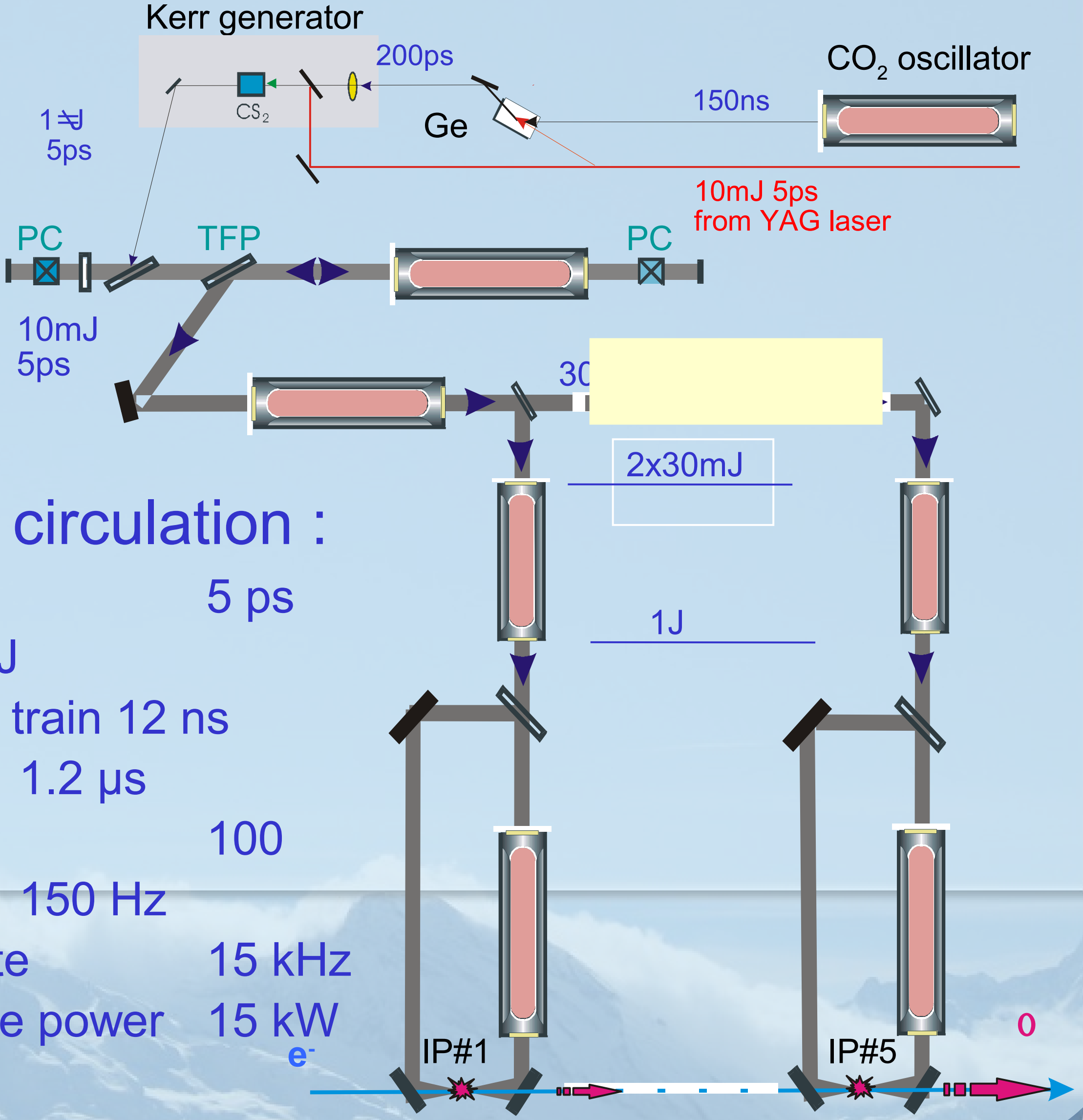
- Polarized gamma-ray beam is generated in the Compton back scattering inside optical cavity of CO_2 laser beam and 4 GeV e-beam produced by linac.
- Laser system relies on the commercially available lasers but need R&D for high repetition operation.
- Ring cavity with laser amplifier realizes the $C0_2$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



V. Yakimenko

Linac Laser Compton (2)

Linac Laser Compton scheme is designed with CO2 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 power	15 kW

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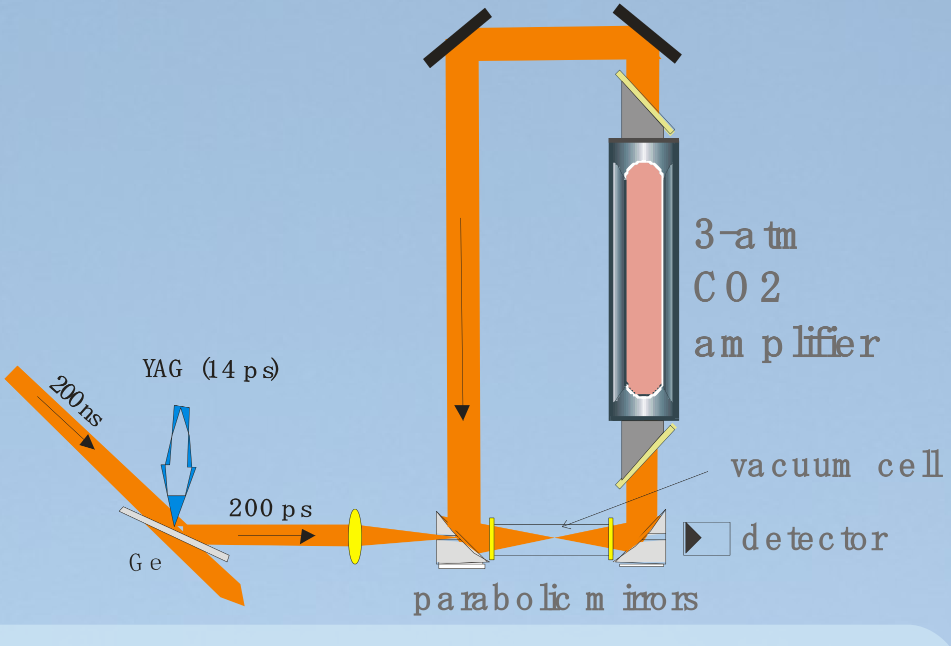
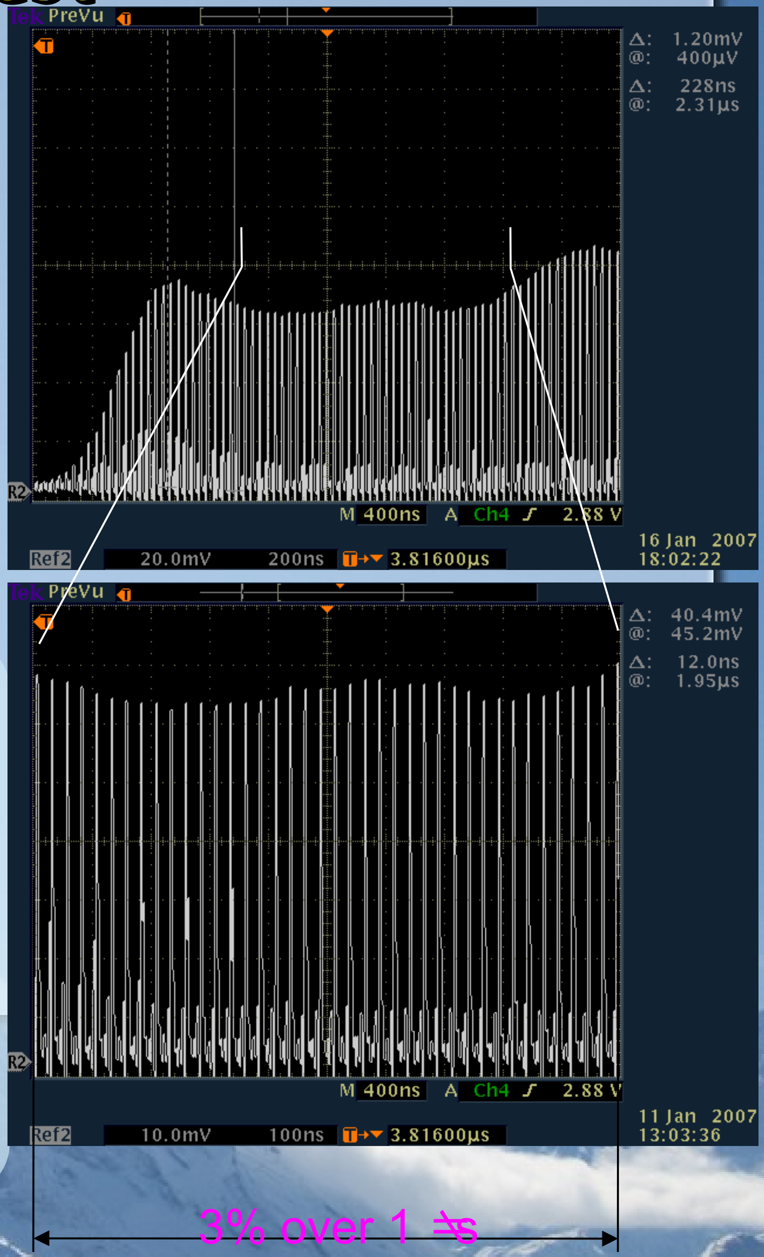
CO2 Laser Test





Observations:

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

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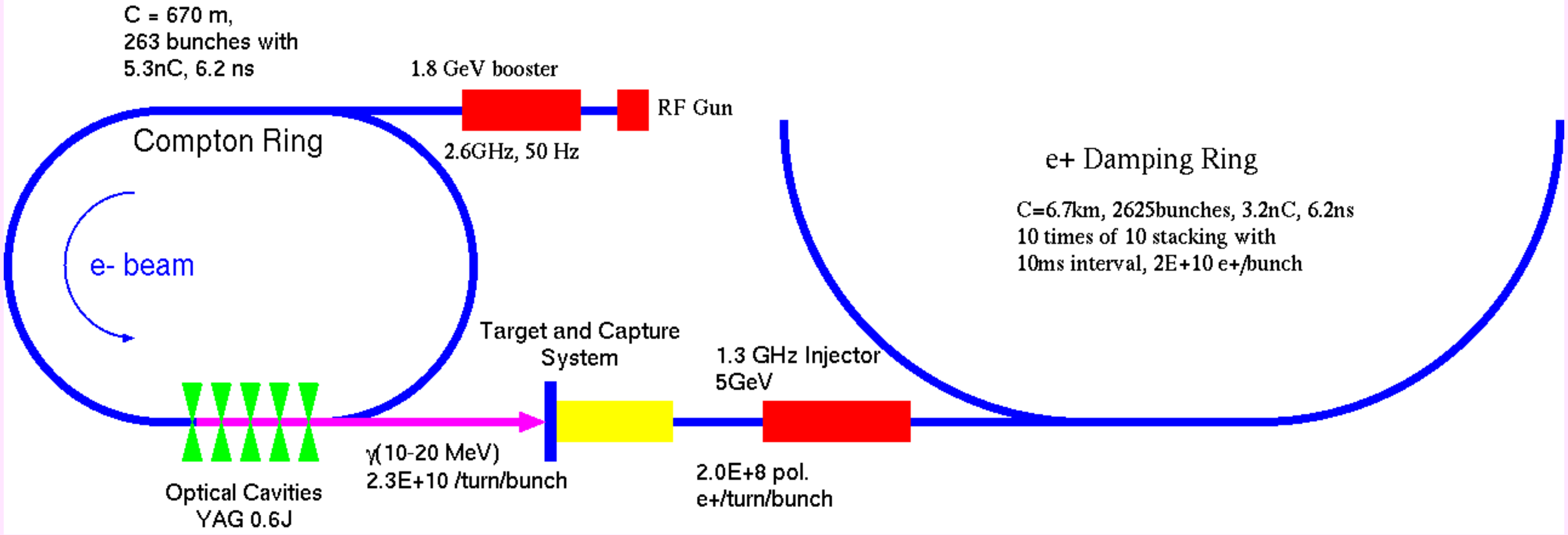
V. Yakimenko, I. Pogorelsky

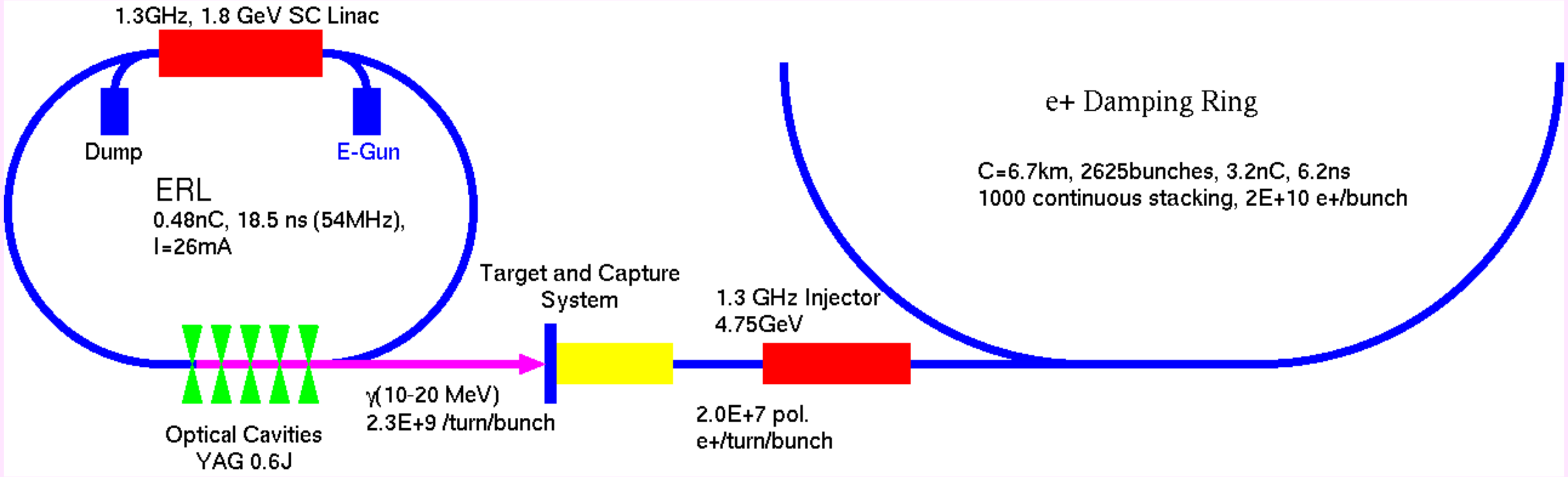
Compton Ring

- A storage ring for electron driver:5.3nC, 6.2ns, 1ps, 1.8GeV.
- 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.

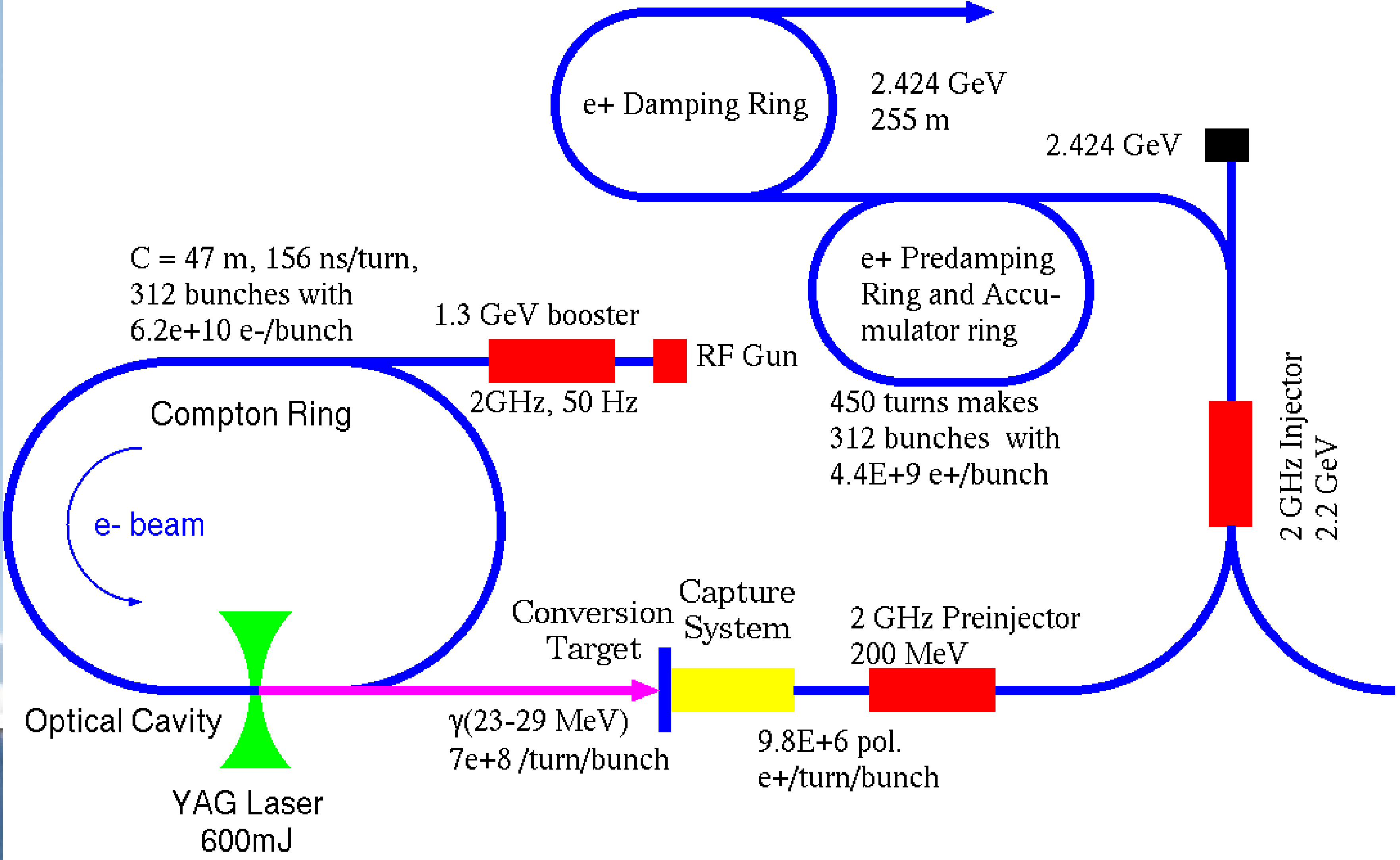


ERL

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

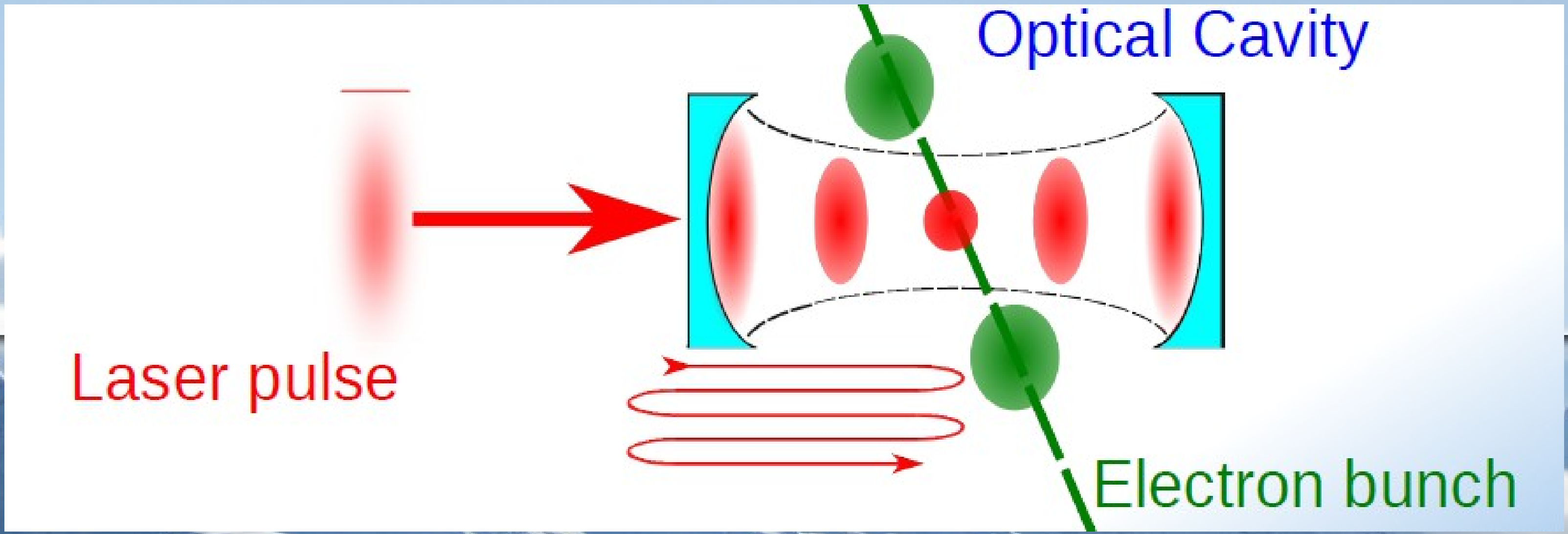


Pulse Stacking Cavity

- 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.

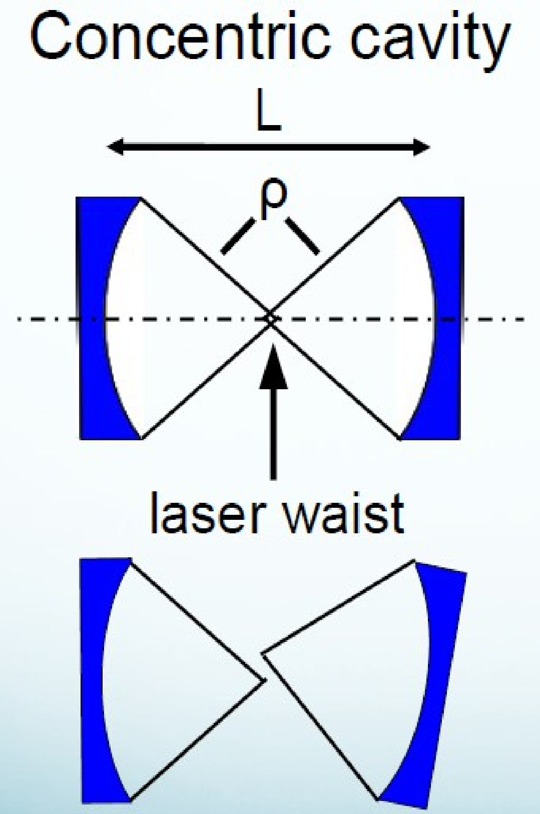
$$L_{cav} = nL_{rep}$$

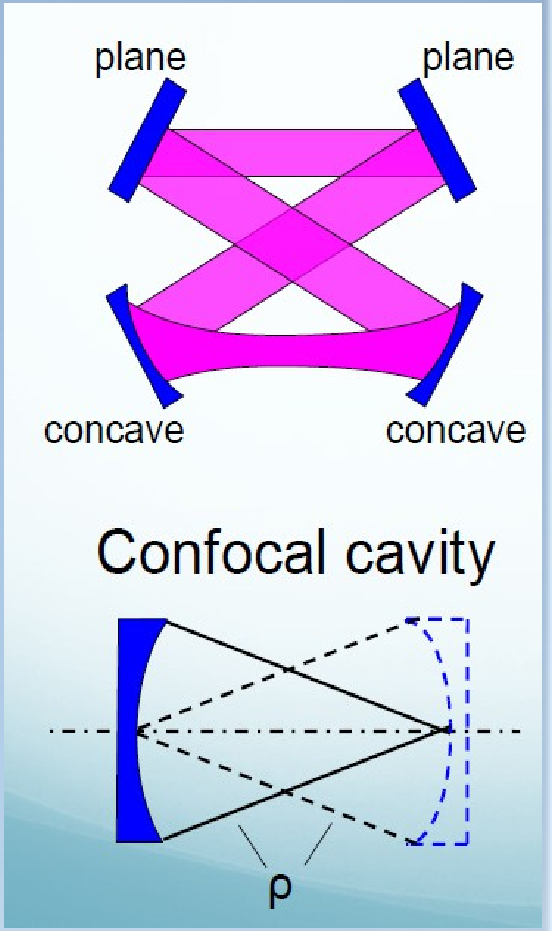
$$L_{cav} = m\frac{\lambda}{2}$$



How many mirrors? (1)

- 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.

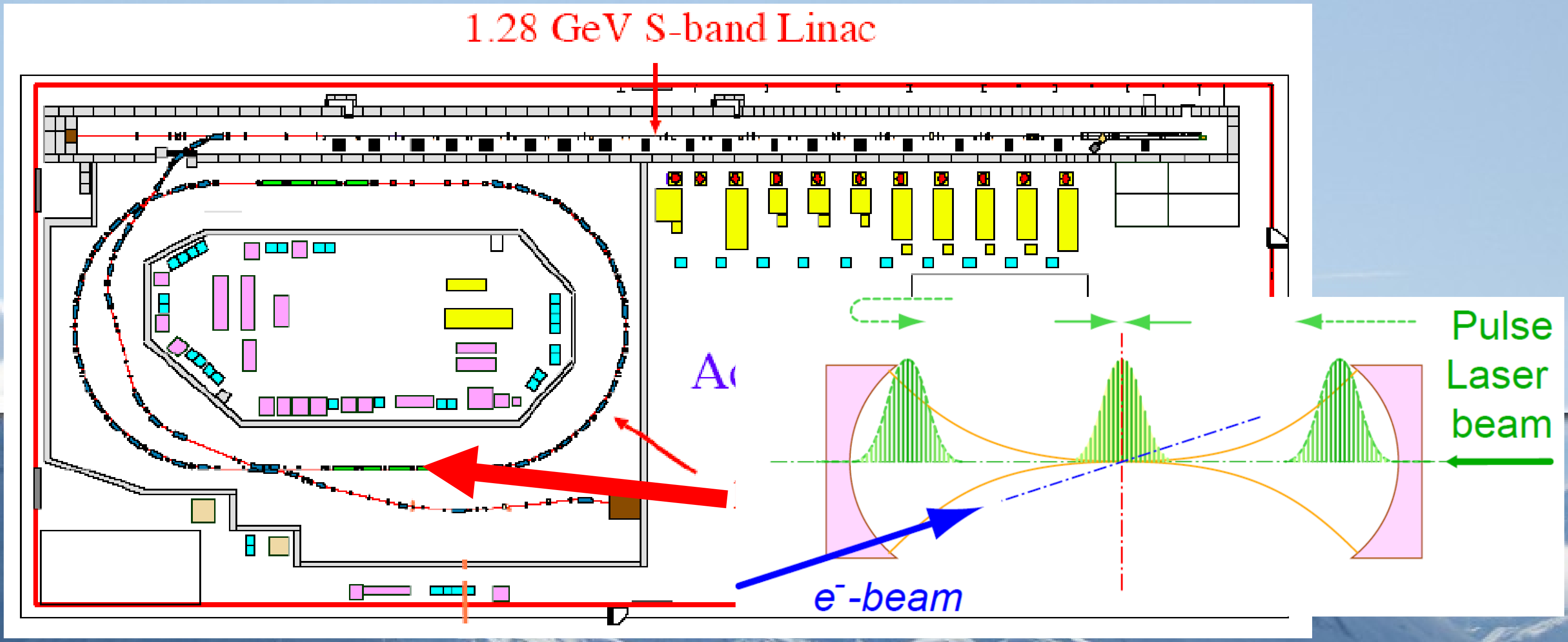




KEK-ATF experiment (1)

Hiroshima-Waseda-KEK

- 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.
- $2\sigma=60\mu m$.
- Laser-Compton collision with stored electron beam.



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.

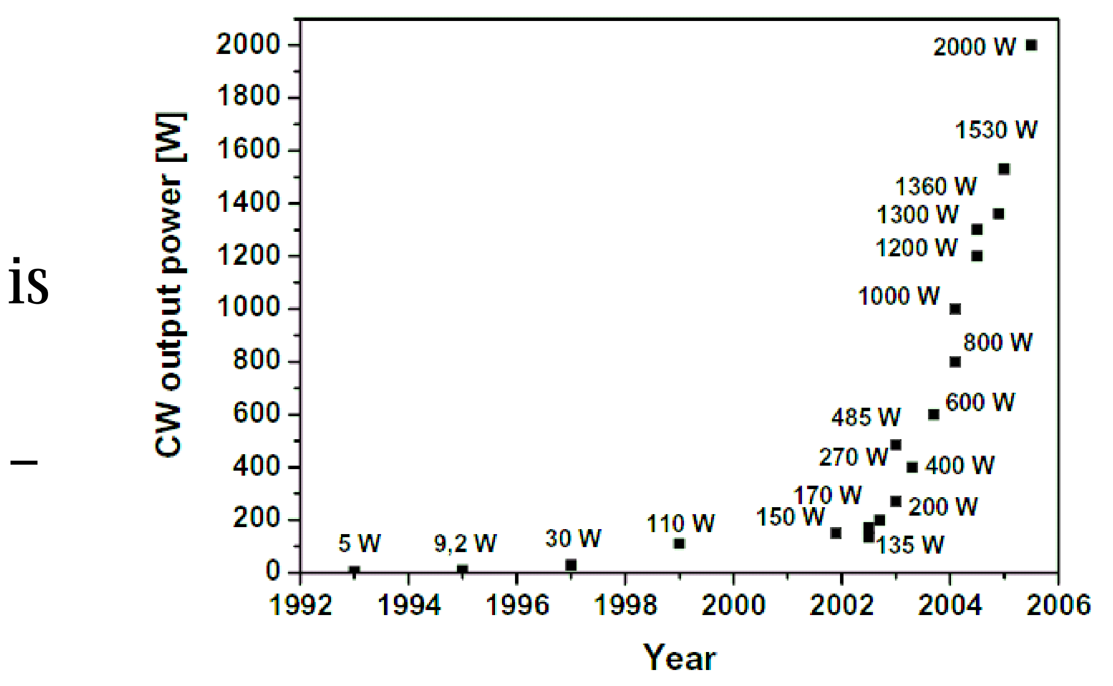
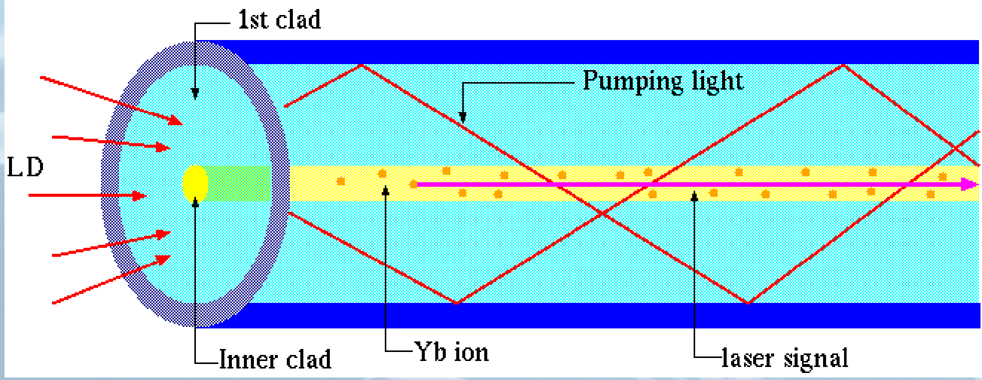


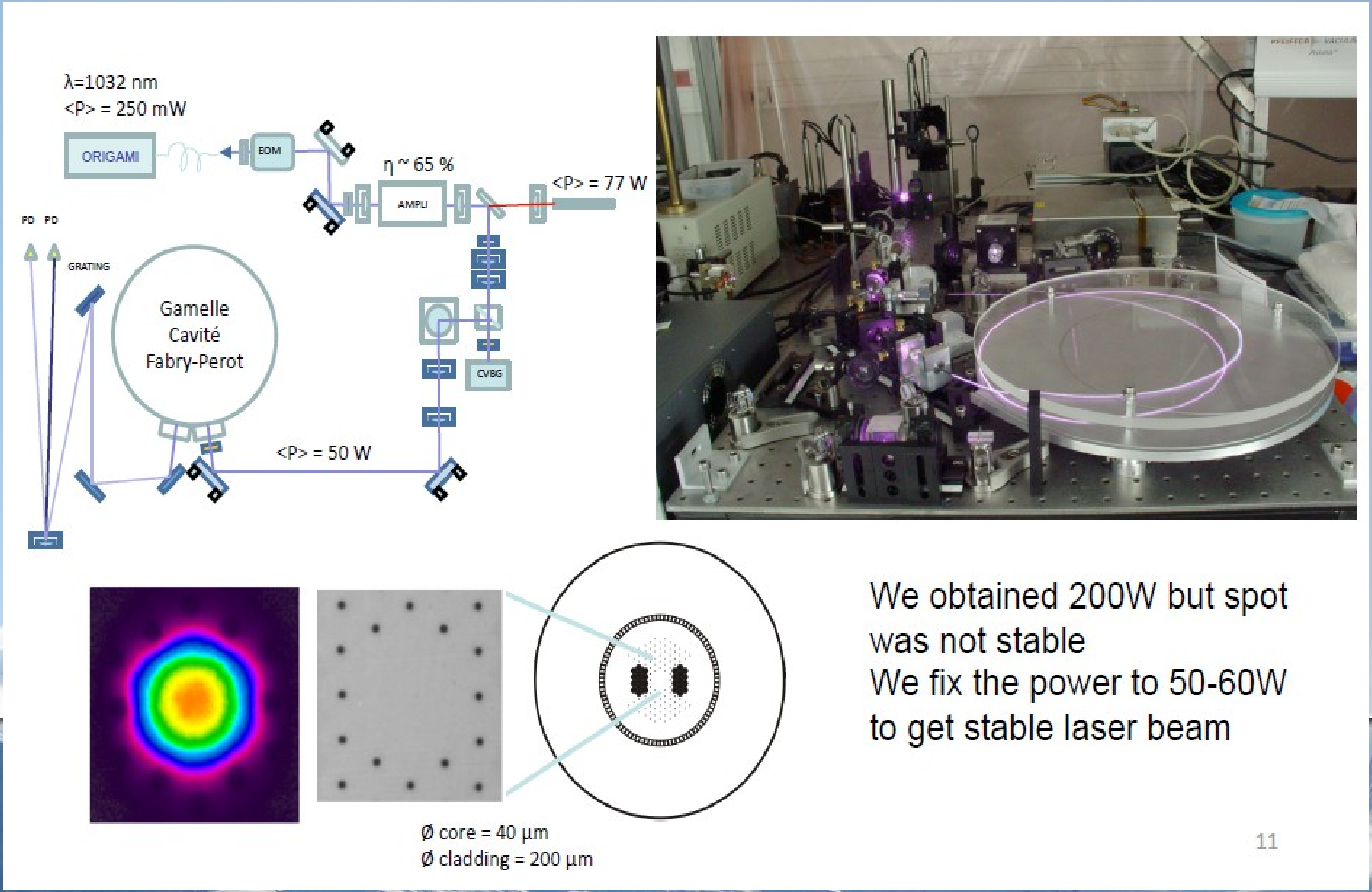
Fig. 4: Power evolution of cw double-clad fiber lasers with diffraction-limited beam quality over the last decade

J. Limpert



By M. Hanna

Fibre Laser (2)

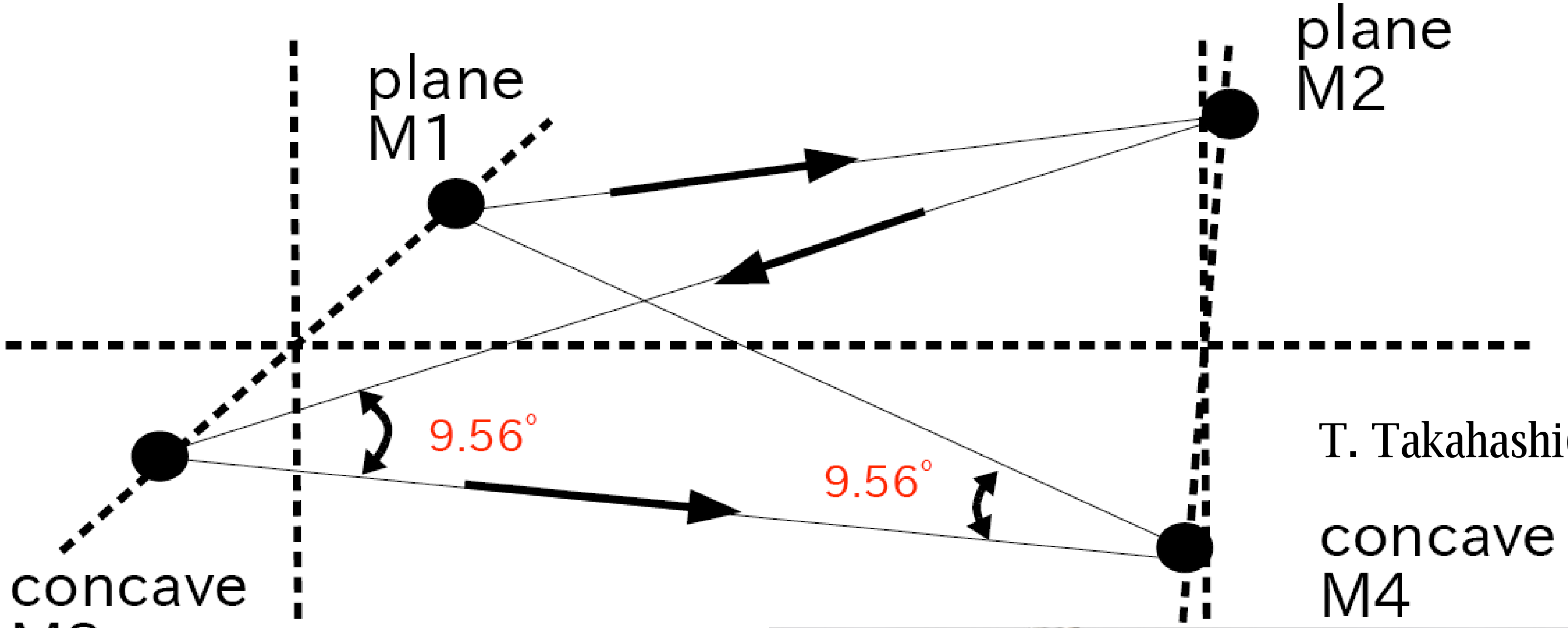


Ø core = 40 µm
Ø cladding = 200 µm

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

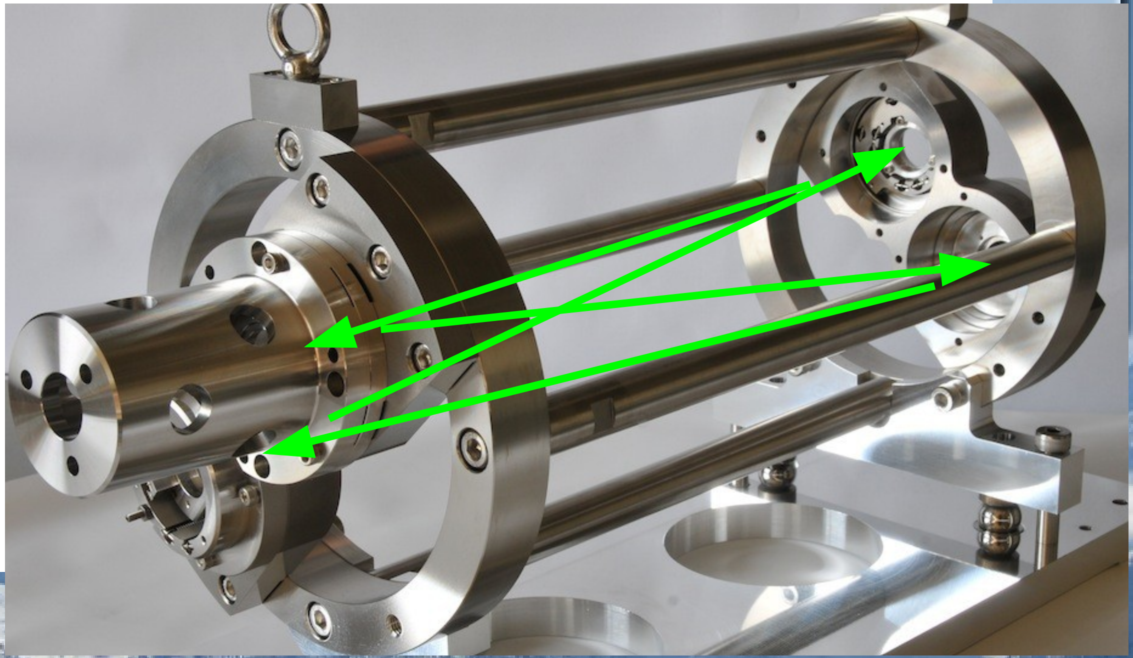
11

New 4 mirror cavity



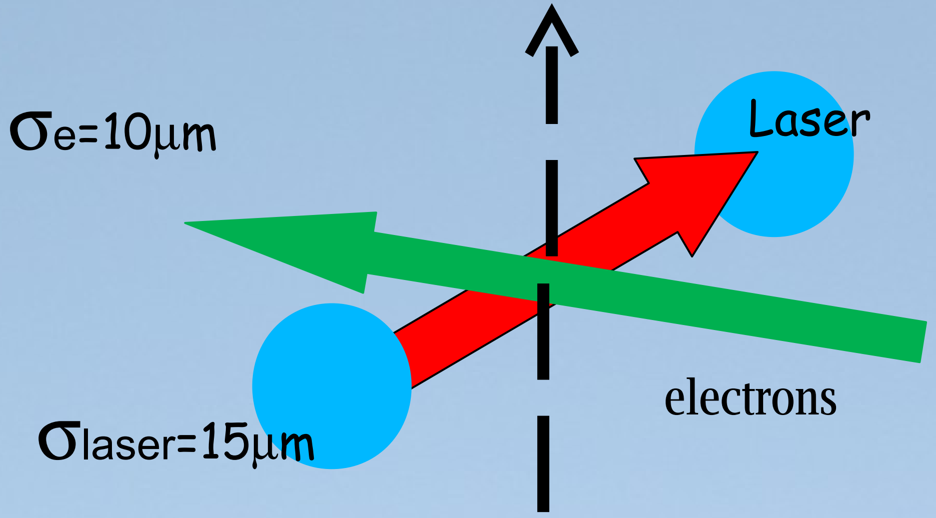
T. Takahashi(Posipol2012)

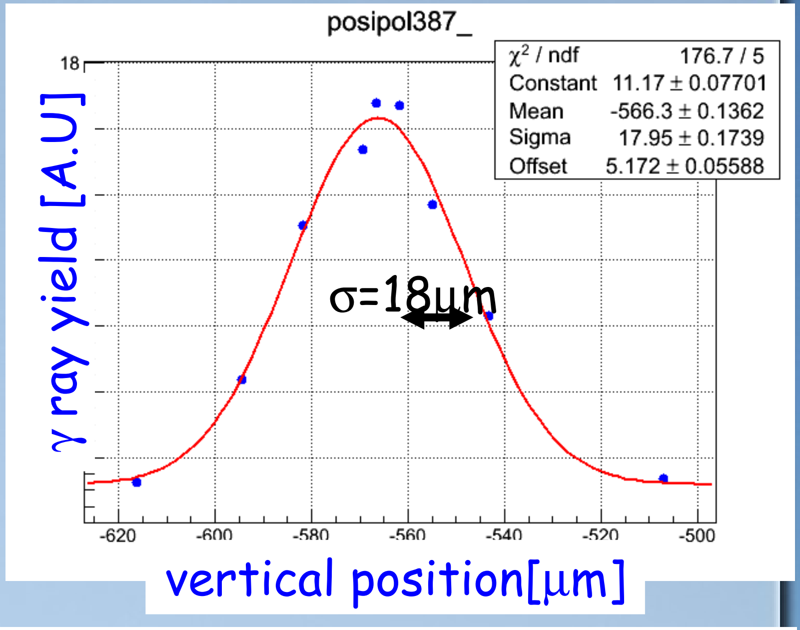
L1=M1-M2=420mm
L2=M2-M3=420mm
L3=M3-M4=420mm
L4=M4-M1=420mm

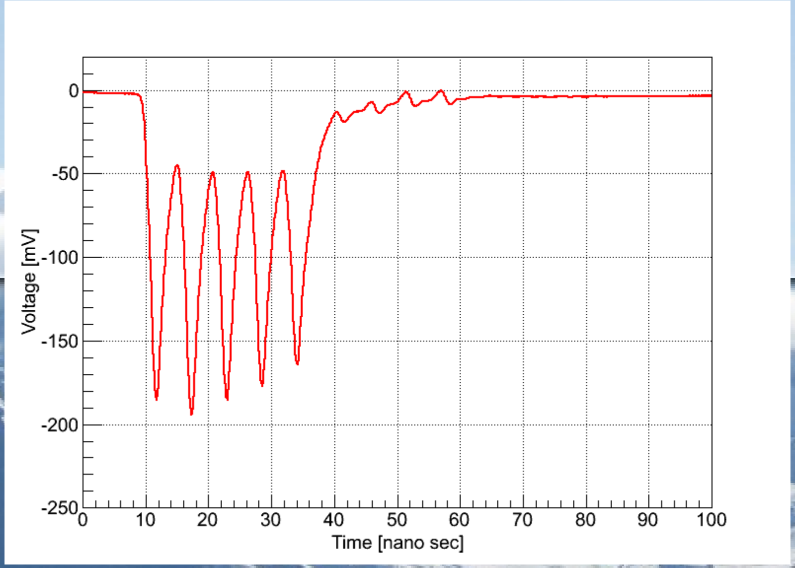


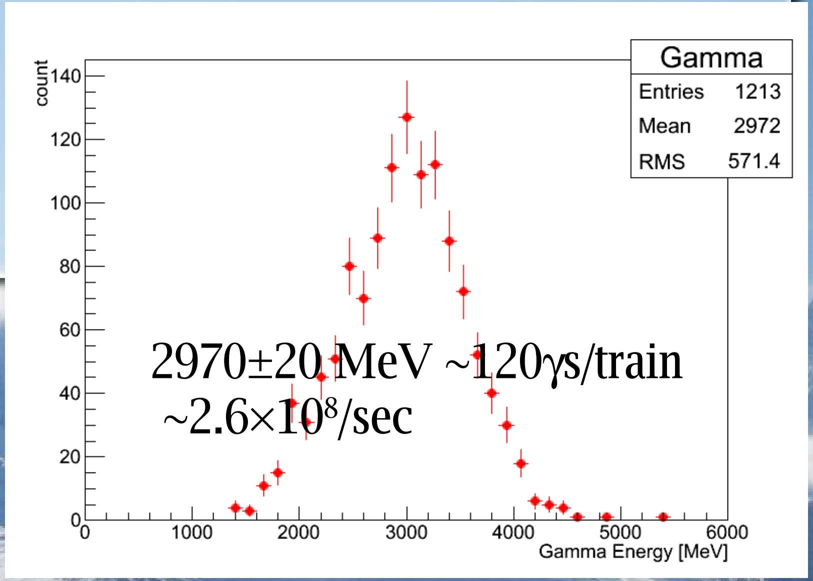
γ ray Generation at ATF

T. Takahashi(Posipol2012)



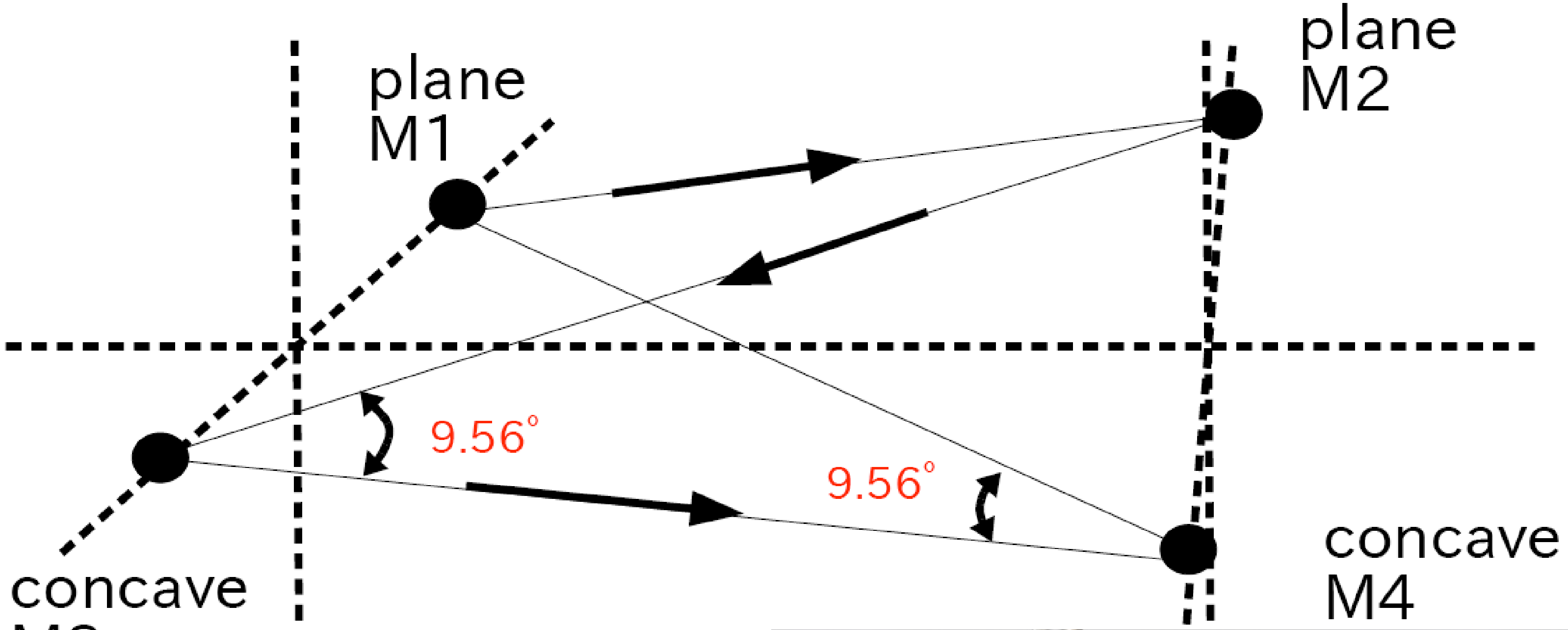




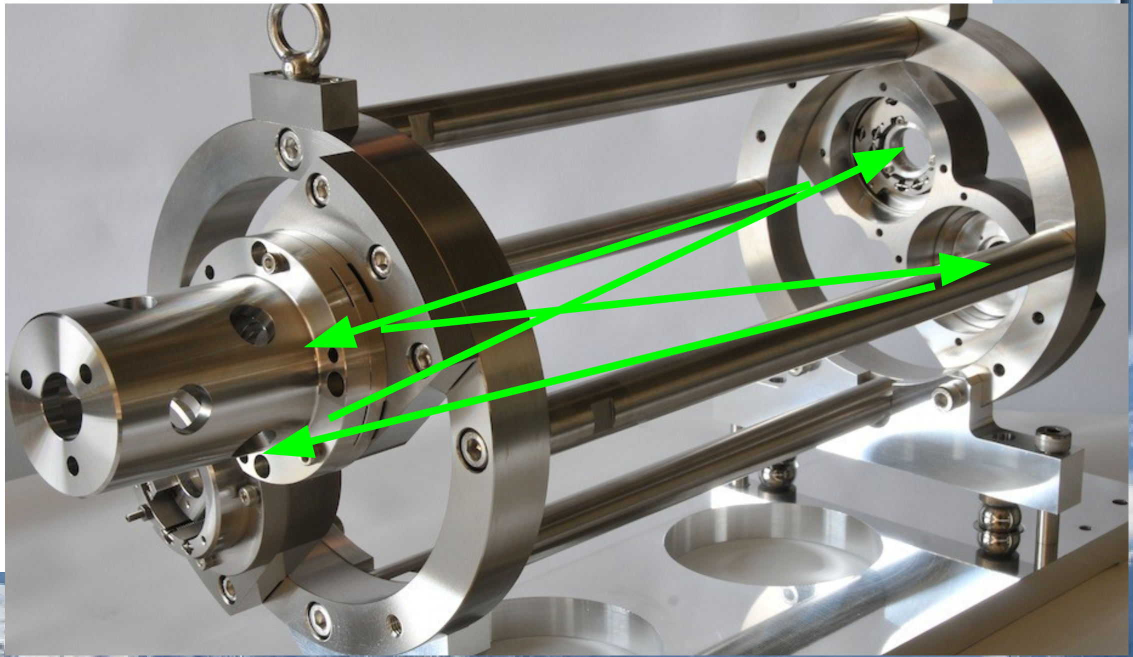


2970±20 MeV ~120γs/train
~2.6×10^8/sec

New 4 mirror cavity

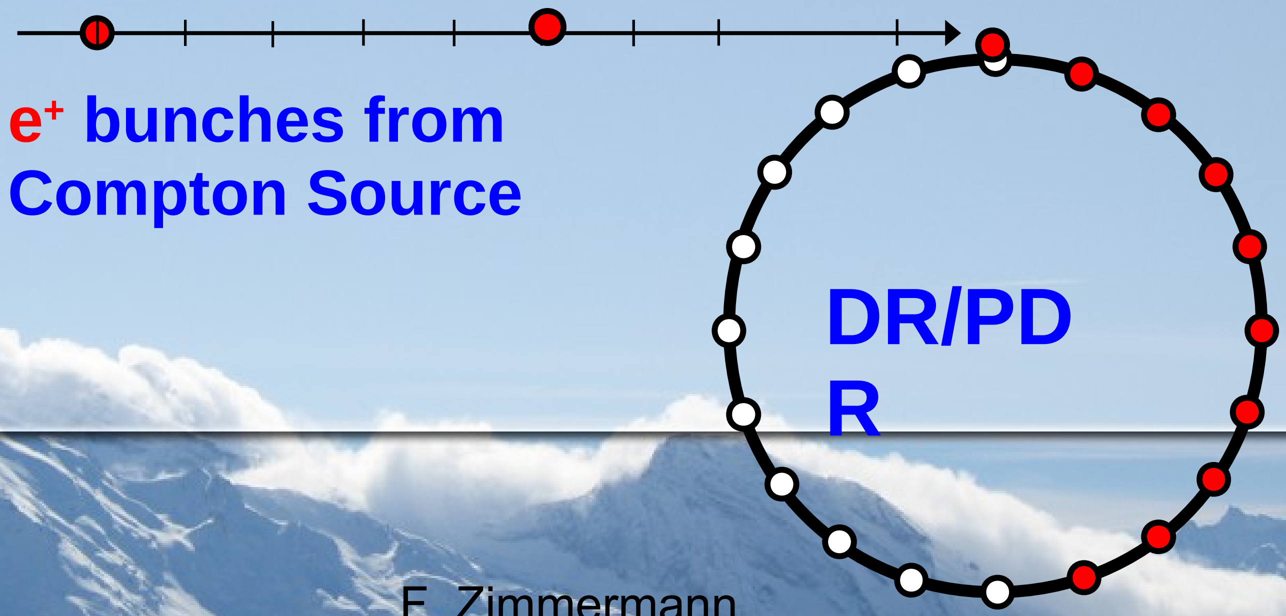


L1=M1-M2=420mm
L2=M2-M3=420mm
L3=M3-M4=420mm
L4=M4-M1=420mm



Positron Stacking (1)

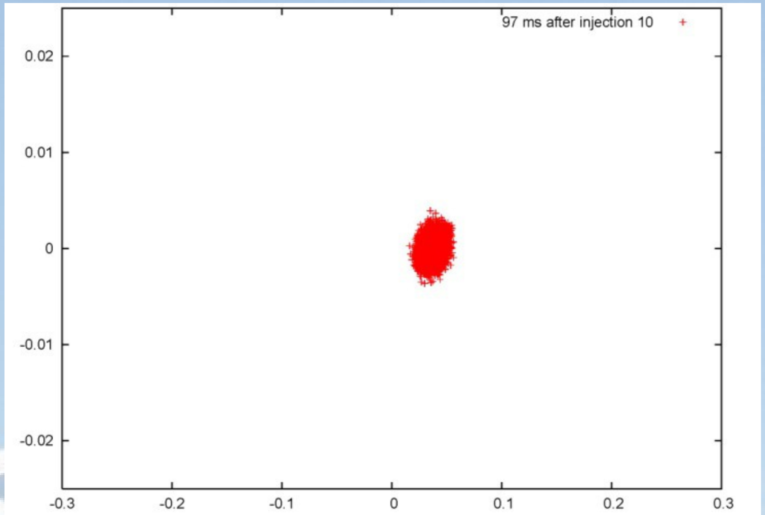
- Except linac scheme, # of positron by a single collision is not sufficient.
- We need accumulate positrons from many collisions to achieve the required bunch intensity for ILC and CLIC.
- Positron stacking: many positron bunches are injected to a same bucket in DR/PDR.



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.



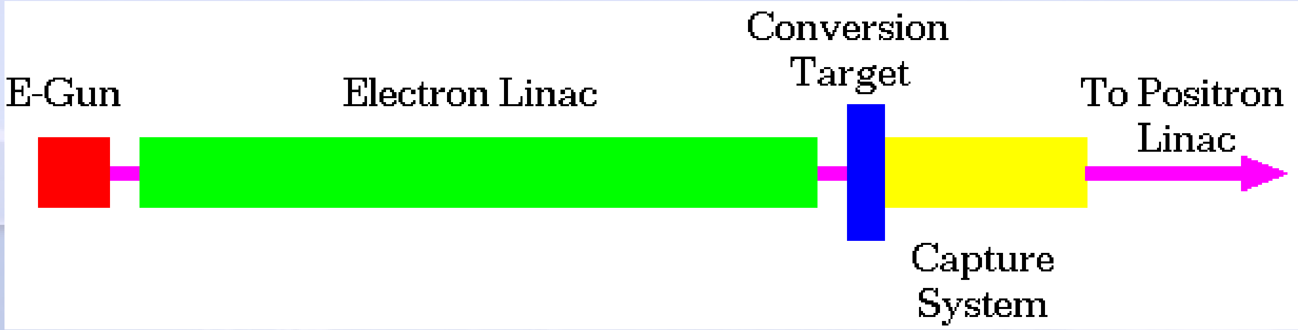
z_{off}=0.045 m,
δ_{min}=5.7x10^{-3},
δ_{step}=0.175x10^{-3}/turn

F. Zimmermann

Electron Driven Scheme (1)

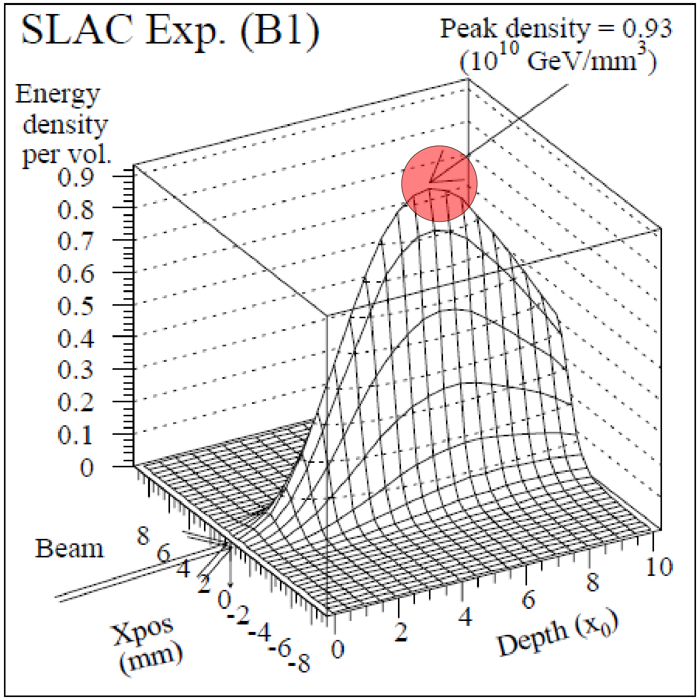
- Electron driven is the only scheme, which is ever been operated, but possible target damage is an issue.
- Only unpolarized positron.
- Several ideas on target
  - Rotating metal target,
  - Liquid metal,
  - Crystalline.

NC Linac



Electron Driven Scheme (2)

- Several GeV drive electron beam for positron generation.
- W-Re rotating target.
- Applying the ILC beam format (369ns, 3.2nC, 1ms), the target shoud be rotated with 400m/s tangential speed to avoid target damage. No way?



4 times faster than SHINKANSEN wheel

JR East

Electron Driven Scheme (3)

Why is it so diffucult?

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

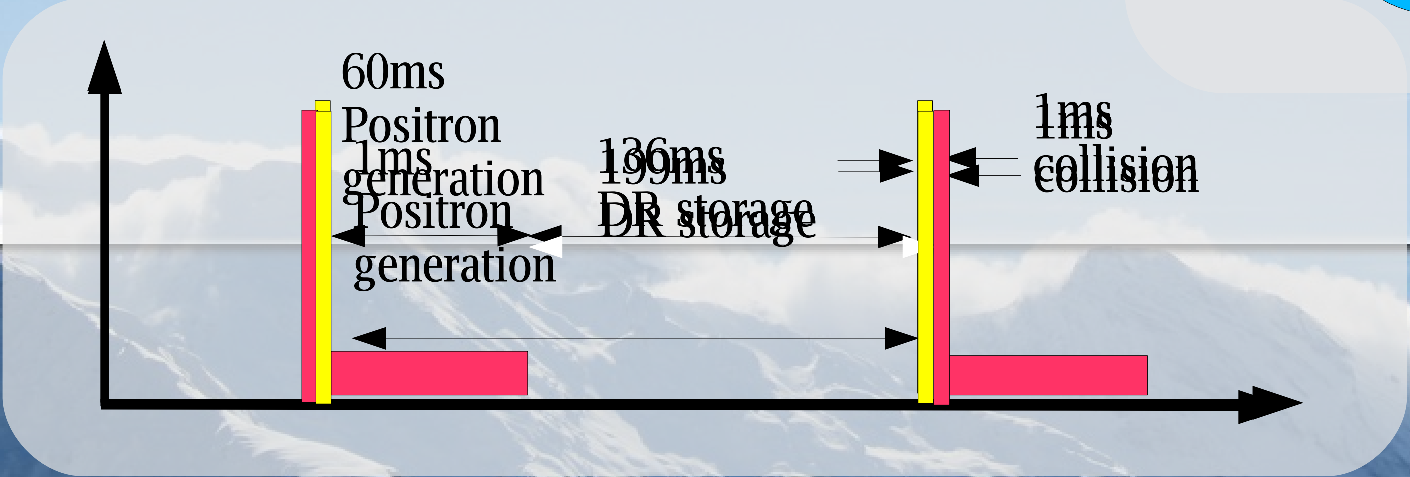
- ILC has to produce 50 times positron comparing to SLC.
- But the issue is not the number of positron per pulse or second.
- PEDD can be compensated by longer pulse length with a slow rotating target.

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

#of bunch

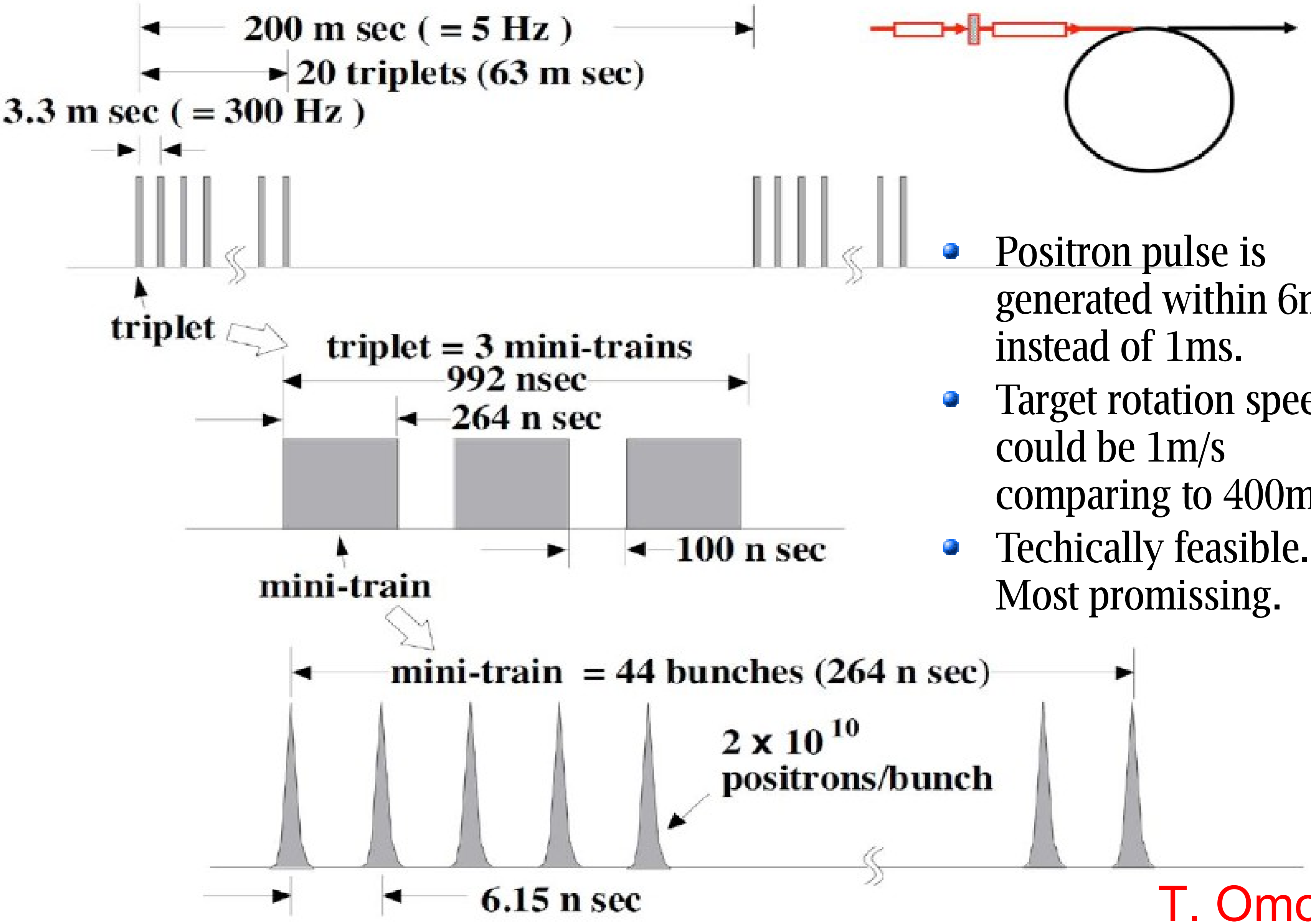
speed

Pulse duration



Electron Driven Scheme (4)

300Hz Generation



- Positron pulse is generated within 6ms instead of 1ms.
- Target rotation speed could be 1m/s comparing to 400m/s.
- Techically feasible. Most promissing.

T. Omori

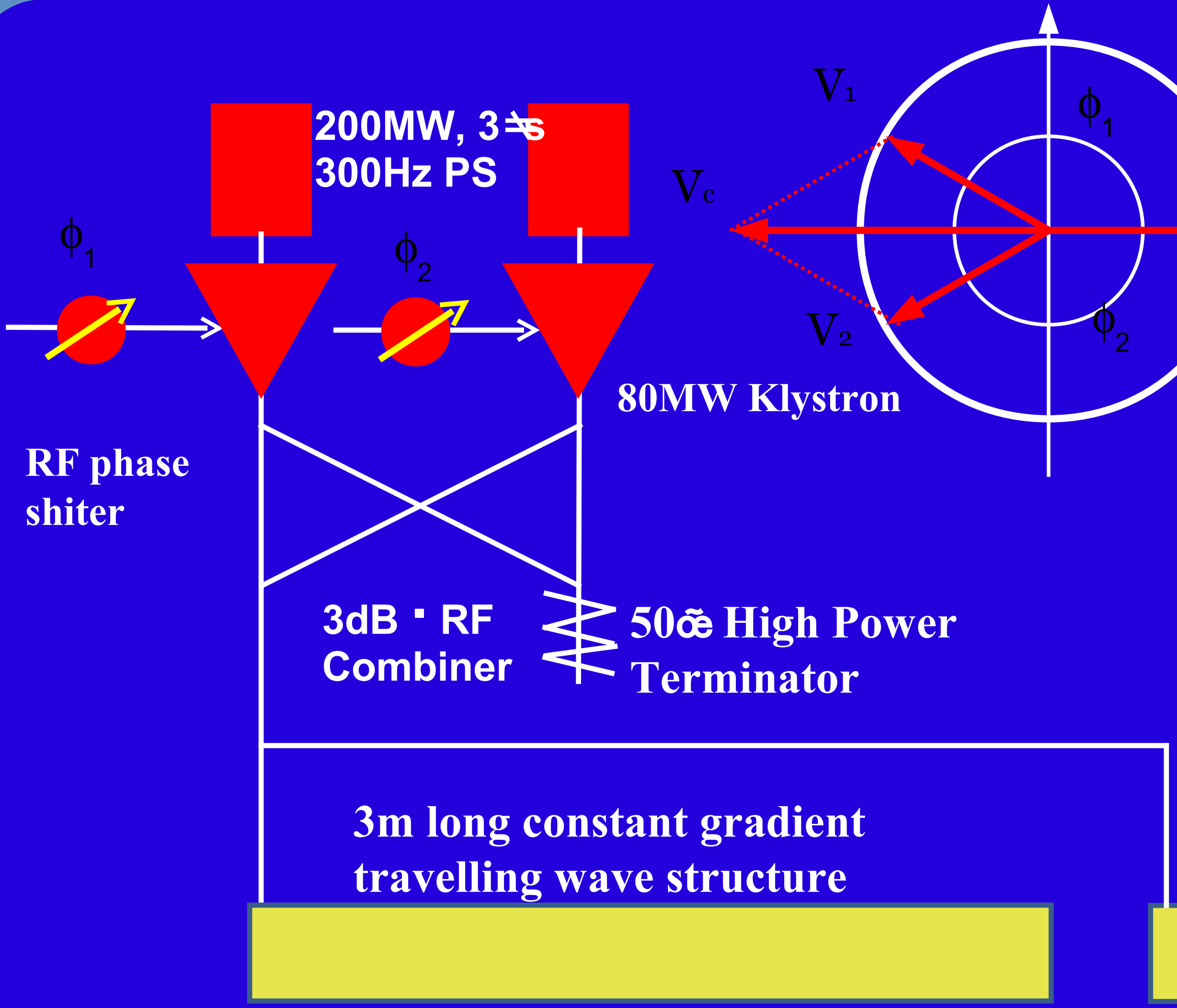
Electron Driven Scheme (5)

Issues on 300Hz Generation

- The pulse structure in the positron generation is totally different from that in ML. Is it acceptable?
  - Yes. The pulse structure is changeable at DR. Injection and extraction pattern are independently controlable.
- ILC SC linac can not operate in 300 Hz. How does she make it?
  - Normal conducting Linac which can be operable in 300 Hz is employed for electron driver and positron booster.
- The multi-bunch acceleration with the heavy beam loading could be diffcult.
  - The energy spread is compensated by FF phase control.

300Hz scheme

Multi-bunch beam acceleration



200MW, 3≒s
300Hz PS

80MW Klystron

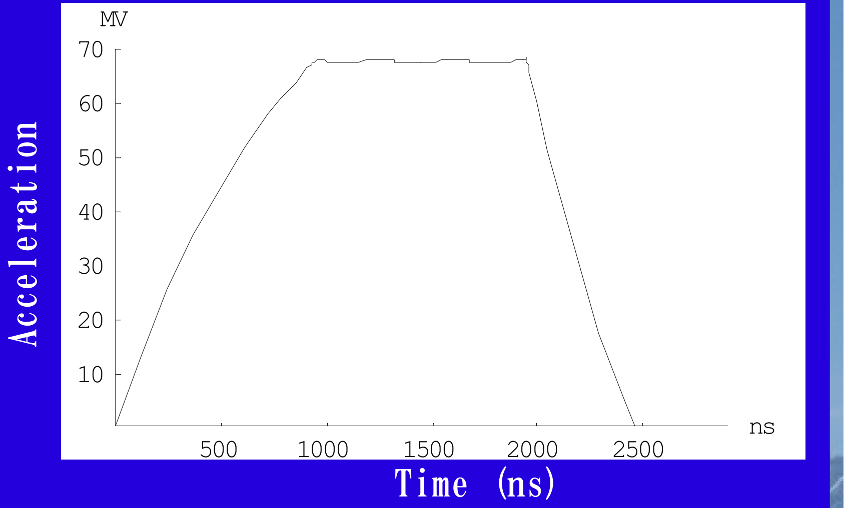
RF phase
shiter

3dB・RF
Combiner

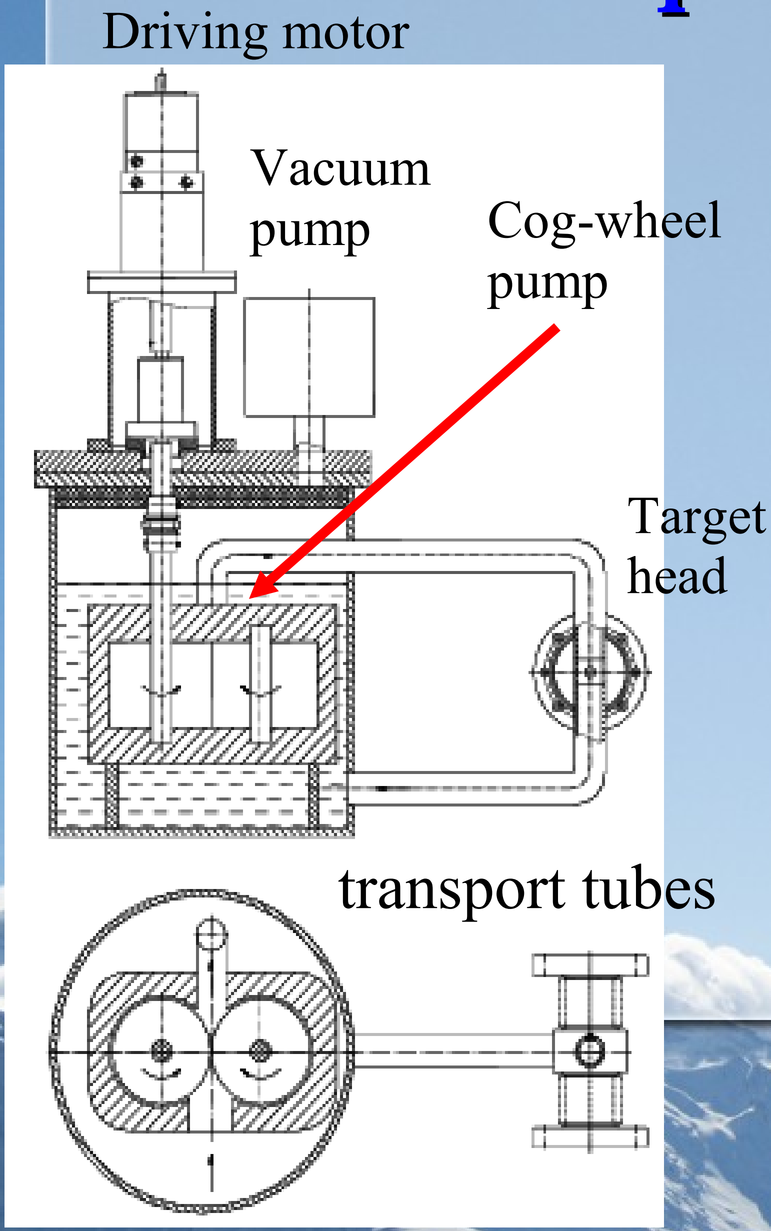
50œ High Power
Terminator

3m long constant gradient
travelling wave structure

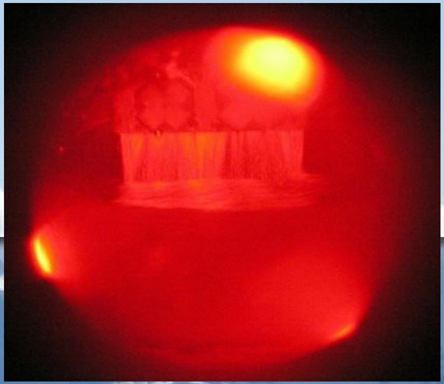
- Amplitude is fastly controlled by phase shifter.
- FF controll make the flat acceleration.



Liquid Pb target (1)



- Liq. Pb target system avoid fear for target damage.
- A prototype in BINP has been operated 20000h without any troubles.
- Possible damage on isolation window to vacuum.
- Pb boiling (2200K) gives another limit.

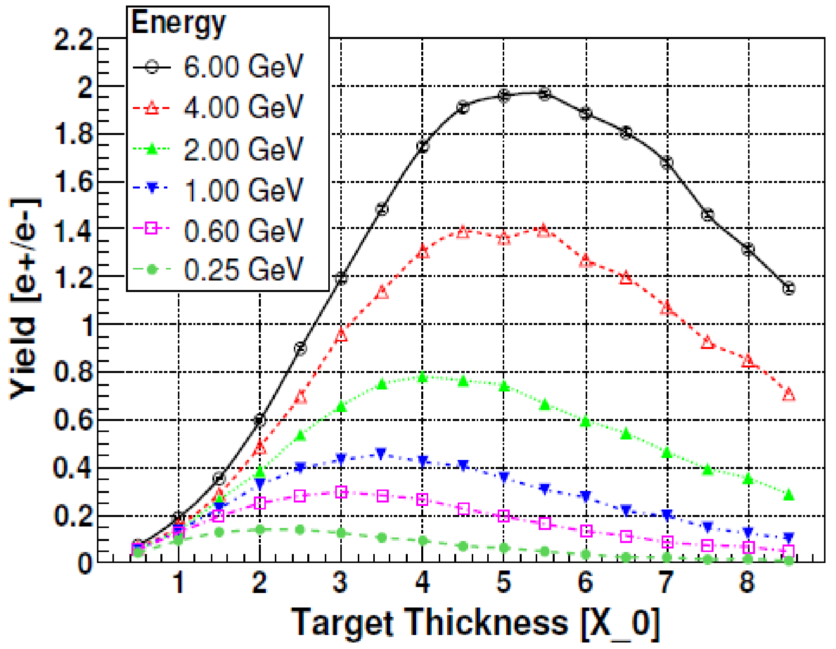


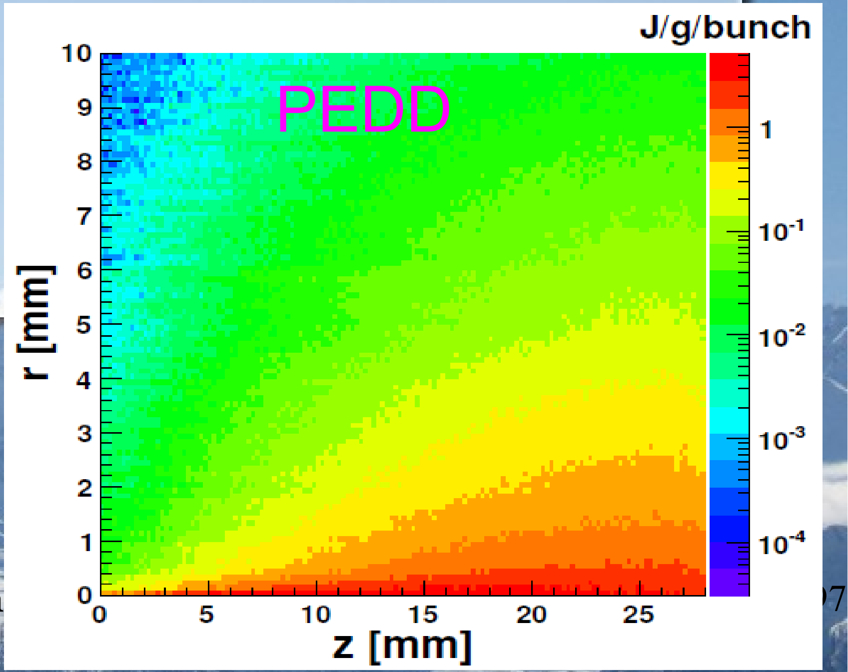
Pb 90% Sn 10%, 300˚C, in vacuum

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.

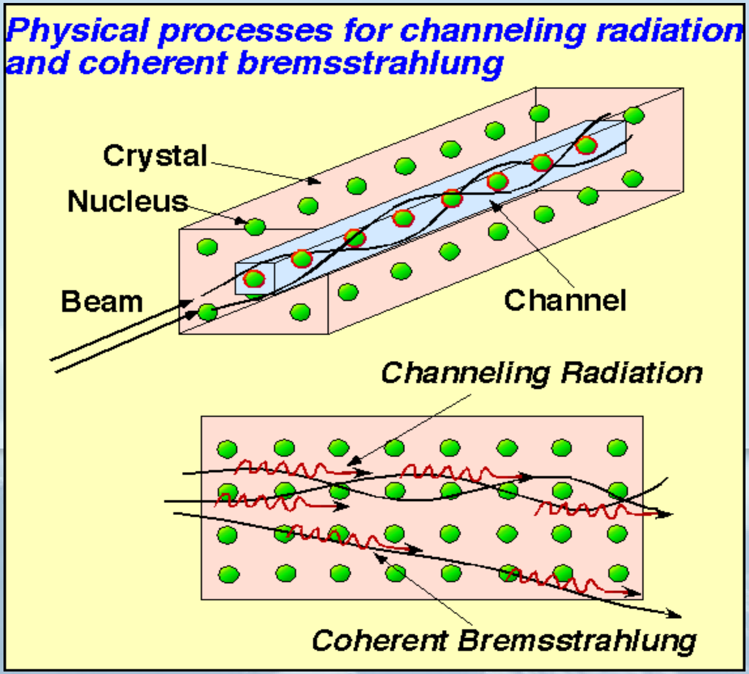
A. Ushkov, Posipol2010

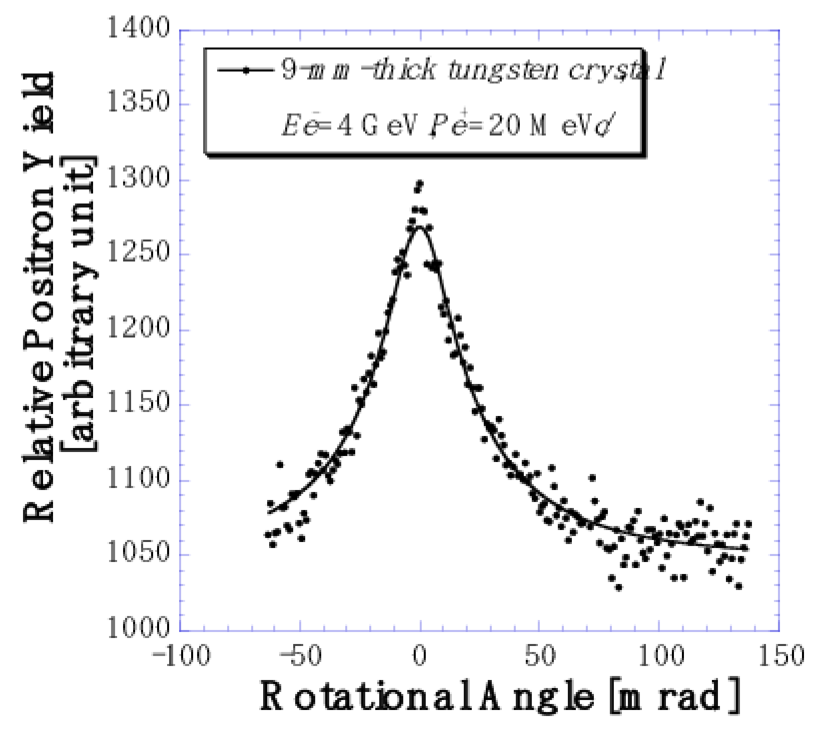




Crystalline Target (1)

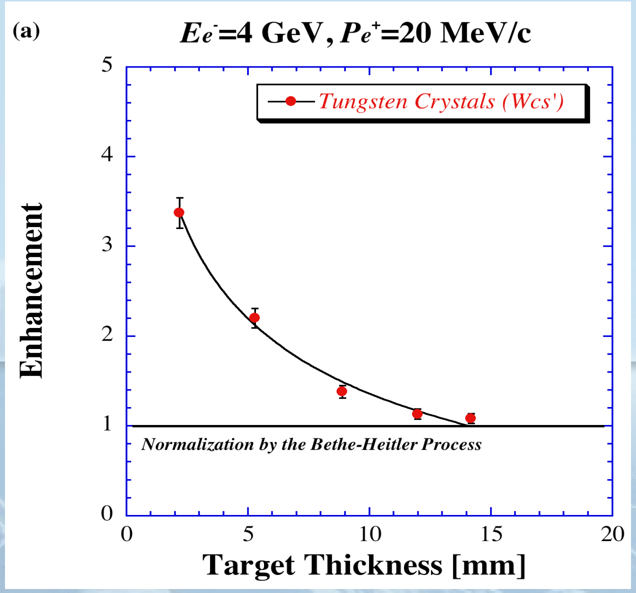
- Gamma radiation by e- beam in a crystalline W target along the crystal axis is enhanced by channeling and coherent bremsstrahlung.
- Less beam power for an equivalent e+ yield.
- A clear enhancement on the positron generation with the crystalline W target is experimentally confirmed at KEKB injector.

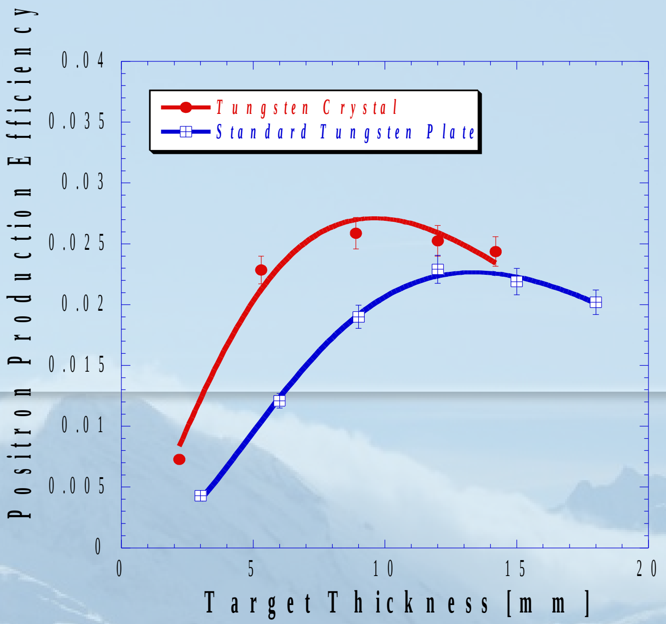

Physical processes for channeling radiation and coherent bremsstrahlung



Crystalline Target (2)

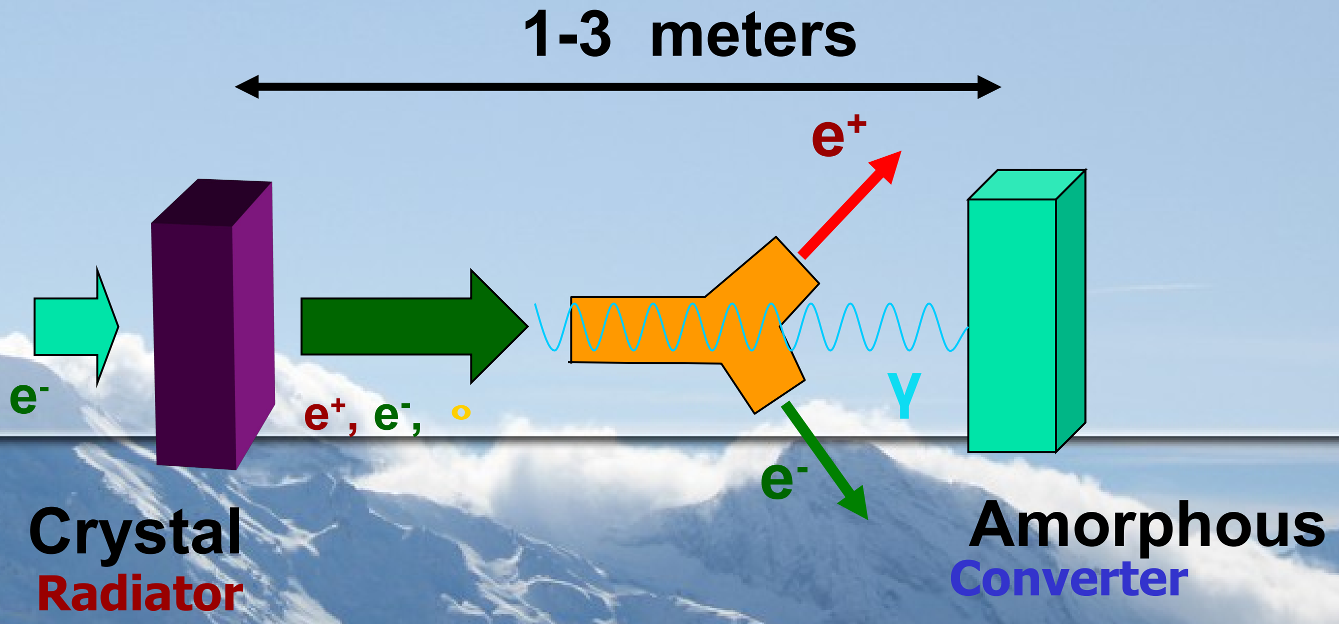
- Positron yield by the crystalline target is enhanced by ~30% with thinner (~9mm) target thickness.
- The heat load becomes almost half compare to the amorphous target.
- The heat load normalized to the generated positron flux is 40% of that by amorphous target. It relaxes the technical limitation very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

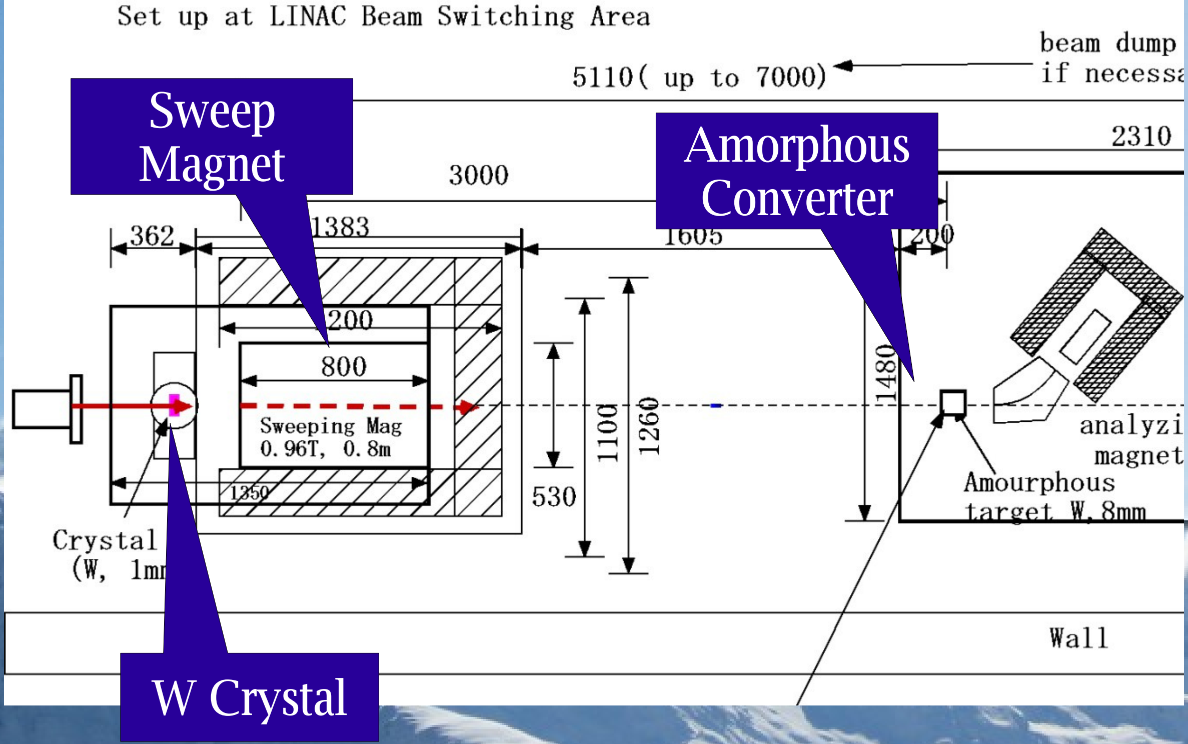


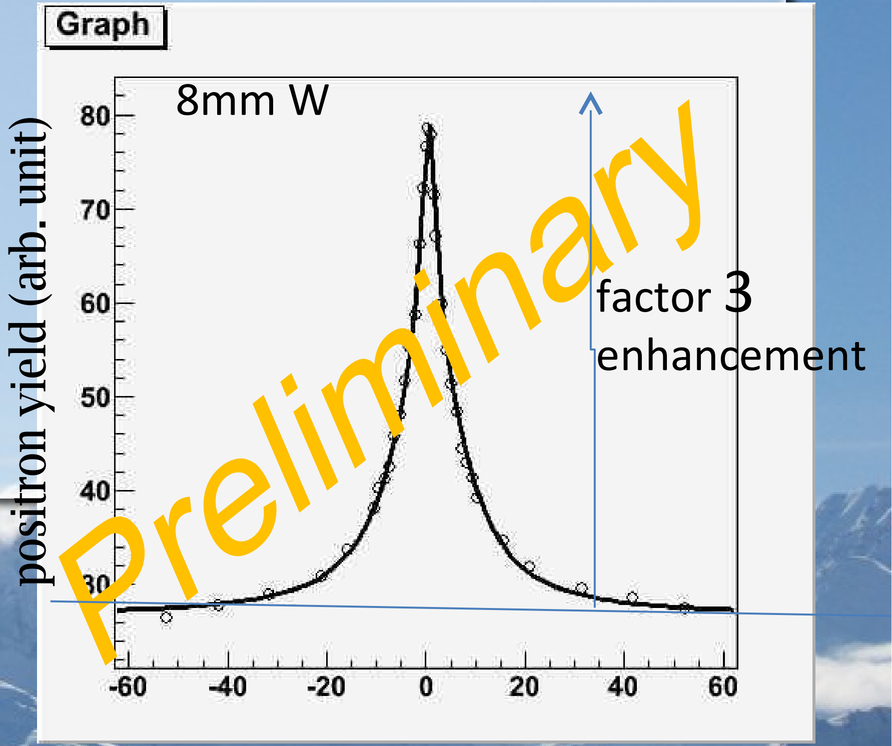
R. Chehab

Crystalline Target(4)

- Experiment at KEKB/PF Linac.
- Crystalline W for radiator and amorphous W for converter.
- Factor 3 enhancement was observed.
- Thermal load reduction by sweeping will be analyzed.

T. Takahashi





Comparison

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

Summary

- Fundamentals of positron generation are explained .
- 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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