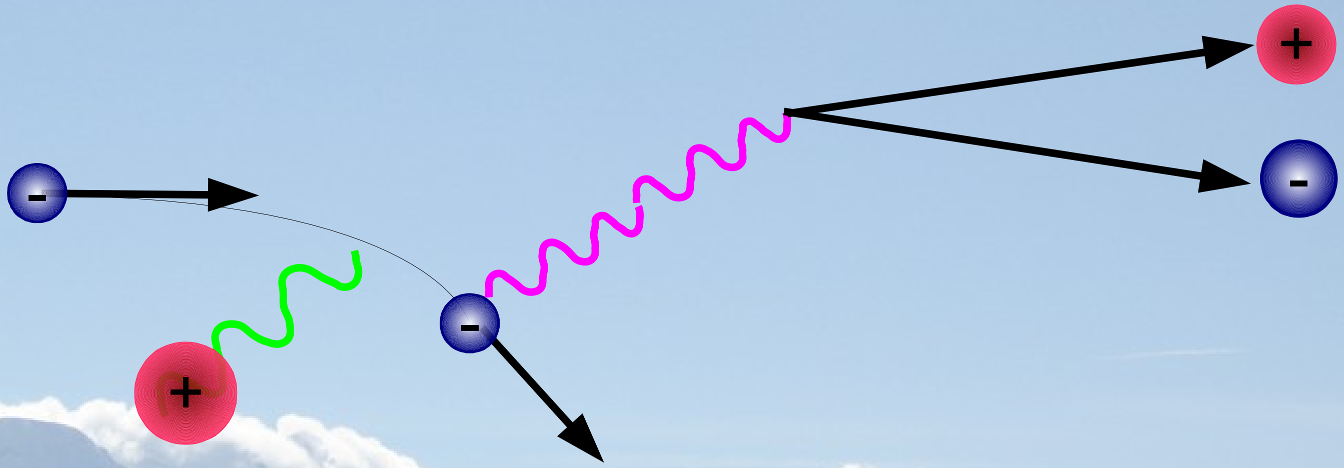
Positron Source for Linear Colliders

KURIKI Masao (Hiroshima/KEK)

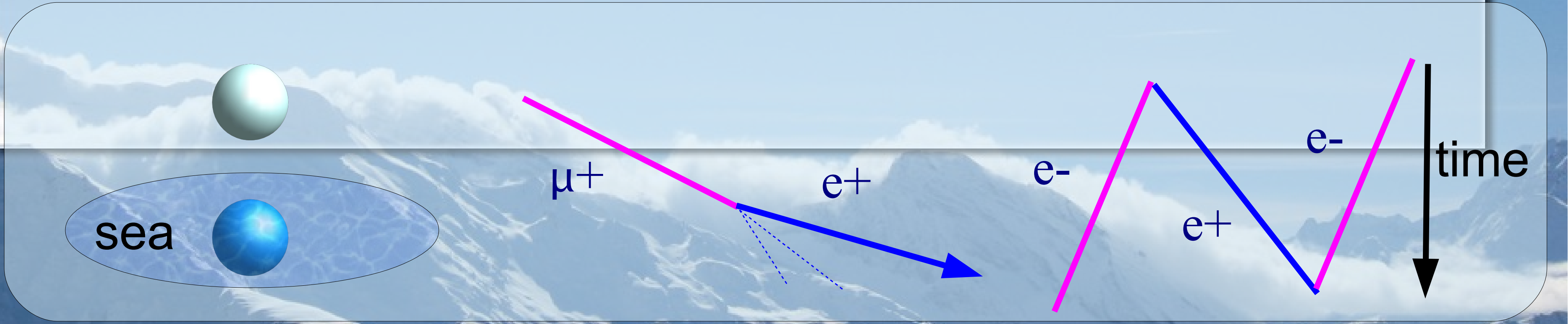


Contents

Introduction

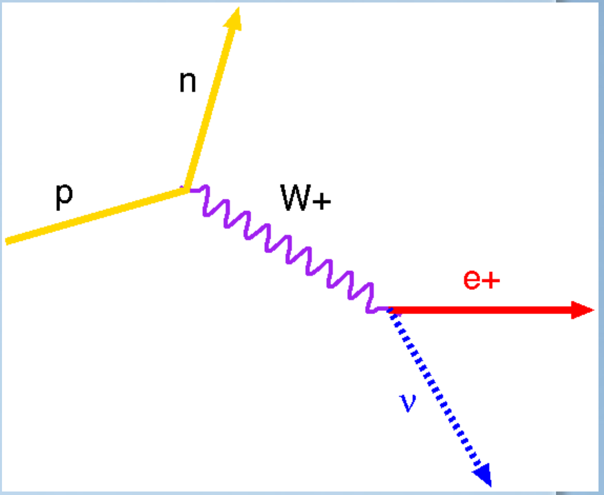
What is Positron?

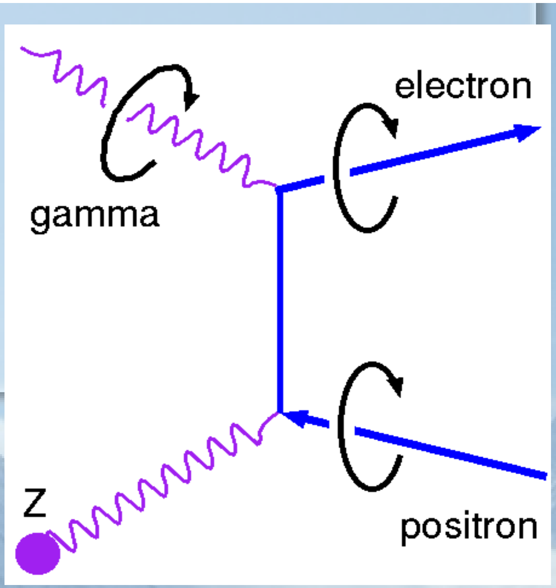
- 1928: Dirac equation suggested electrons with negative energy. Hole hypothesis: "vacuum" is filled with this negative energy electrons to prohibit Klein's paradox. "hole" in the sea of this electrons, acts as positrons.
- 1932:Anderson discovered positrons in cosmic rays with cloud chamber.
- In the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



Positron Production (1)

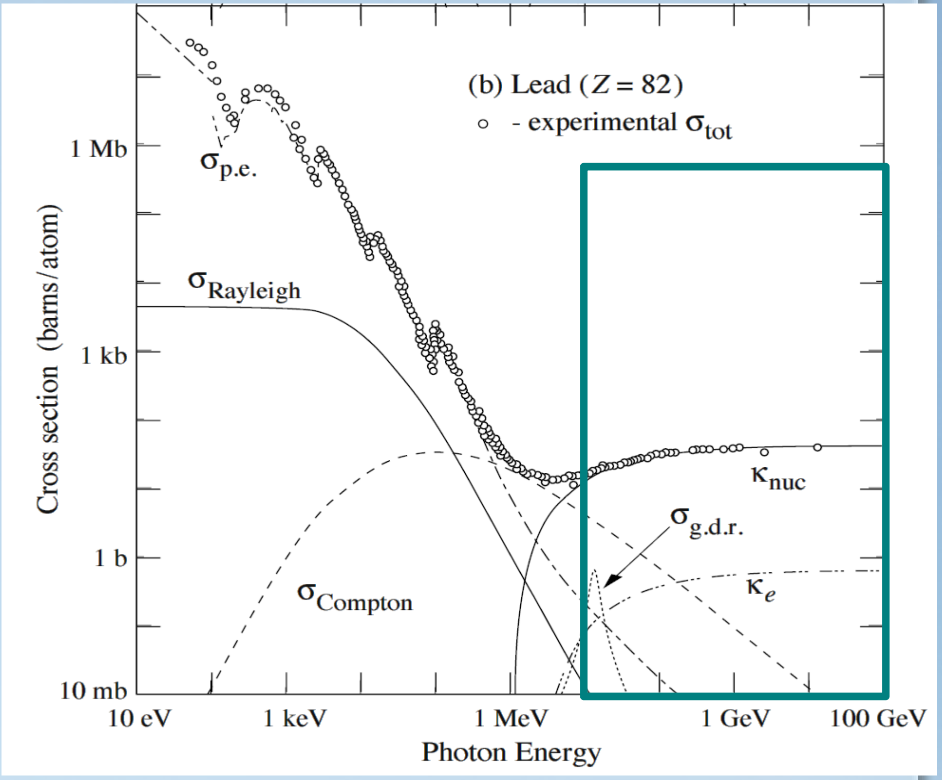
- There is only few positrons in nature.
- Two ways to produce positrons :
  - Create radio-active elements, which beta + decays; p ->n e+ neutrino.
  - Pair-creation ; gamma -> e+ e-
- All of the positron beam sources with a time structure, employ the pair-creation process.





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. Very effective.
  - Undulator radition: Synchrotron Radiation. Need very long undulator with very high energy electron.
  - Inverse Compton scattering : Laser and electron ineraction. Need very high densiy laser field.

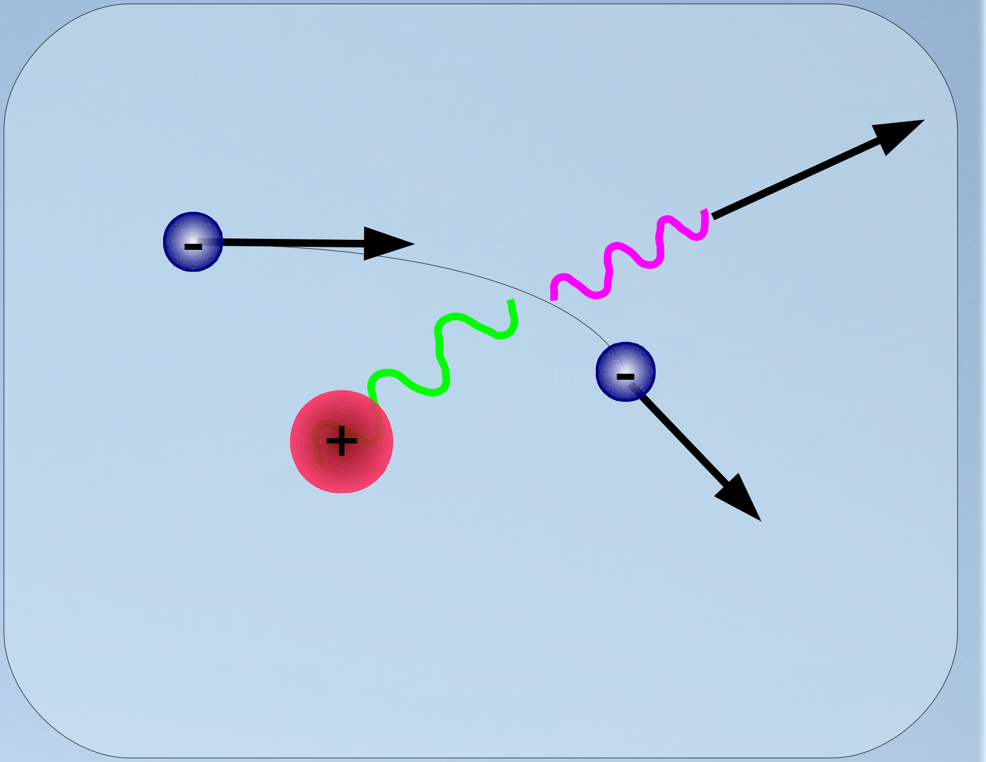
Positron Generation

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

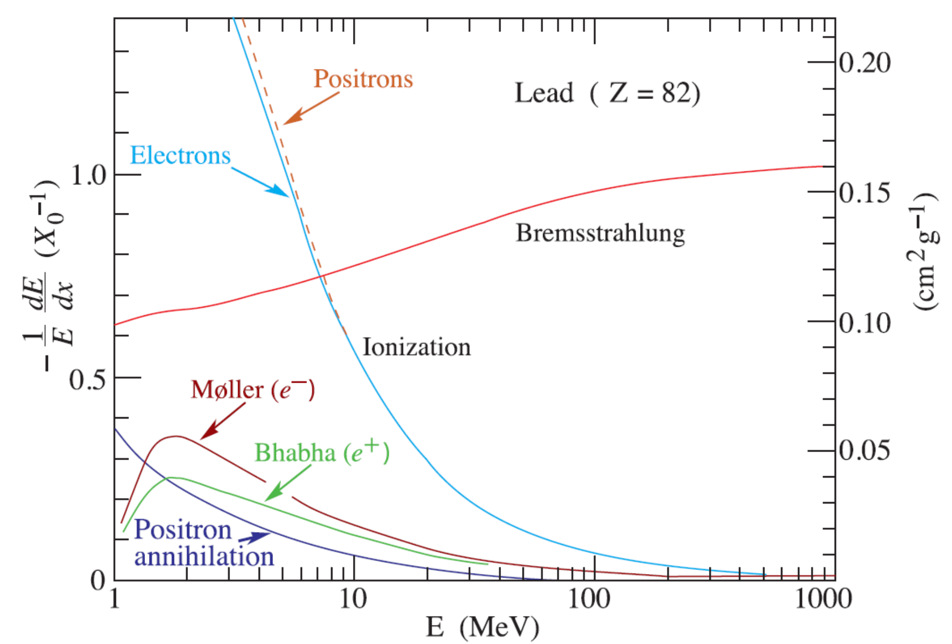
Bremsstrahlung (1)

- 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, Brems-strahlung is not dominant.



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

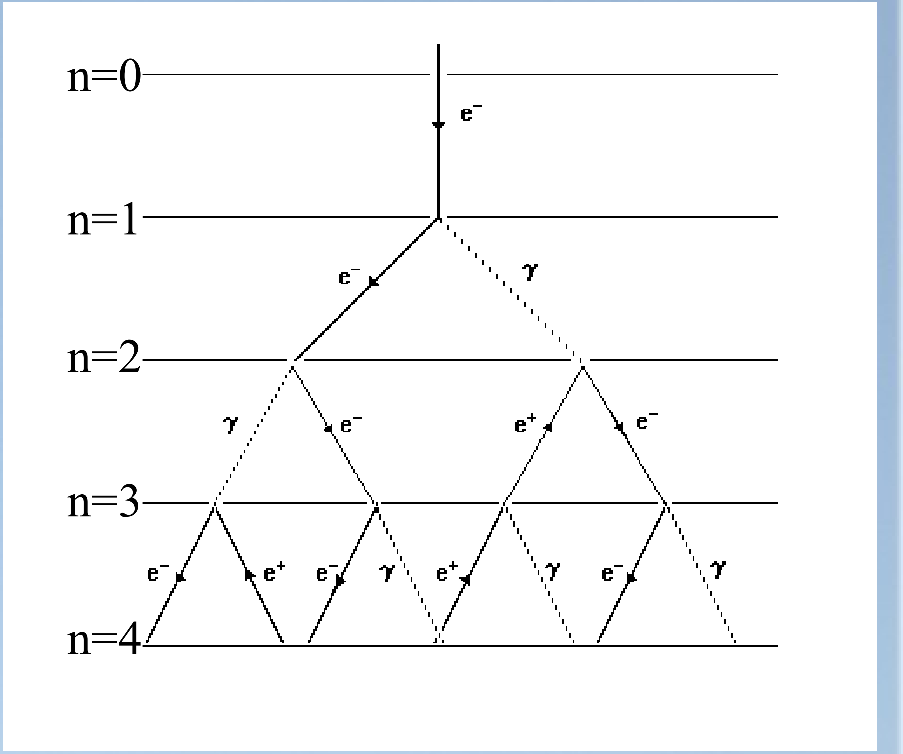
Radiation length X_0: $$\frac{dE}{dx} = -\frac{E}{X_0}$$

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

This process is continued up to;

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

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

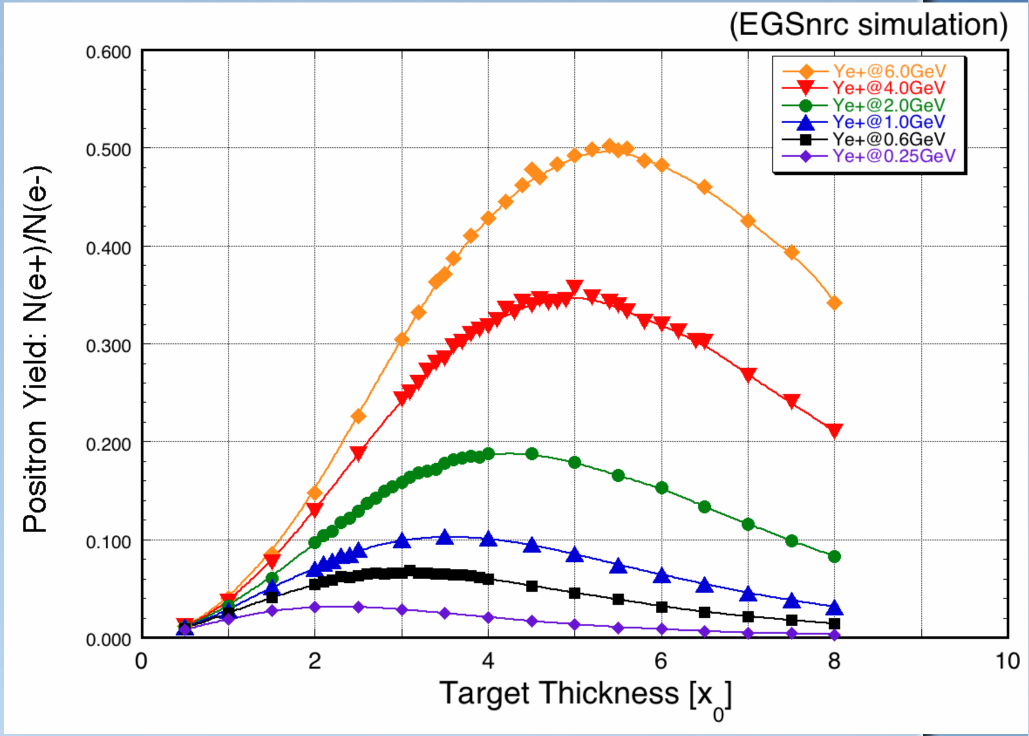


Cascde Shower (2)

- 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.

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

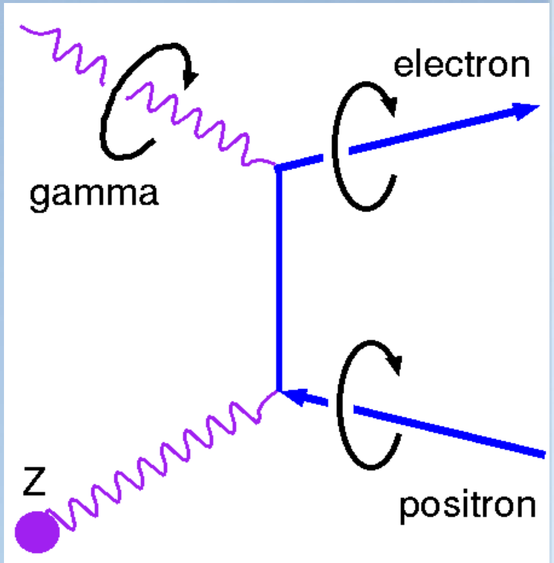
$$X_0 = \frac{716.4 [g.cm^{-2}] A}{Z(Z+1) \ln (287/\sqrt{Z})}$$



Courtesy of T.Kamitani

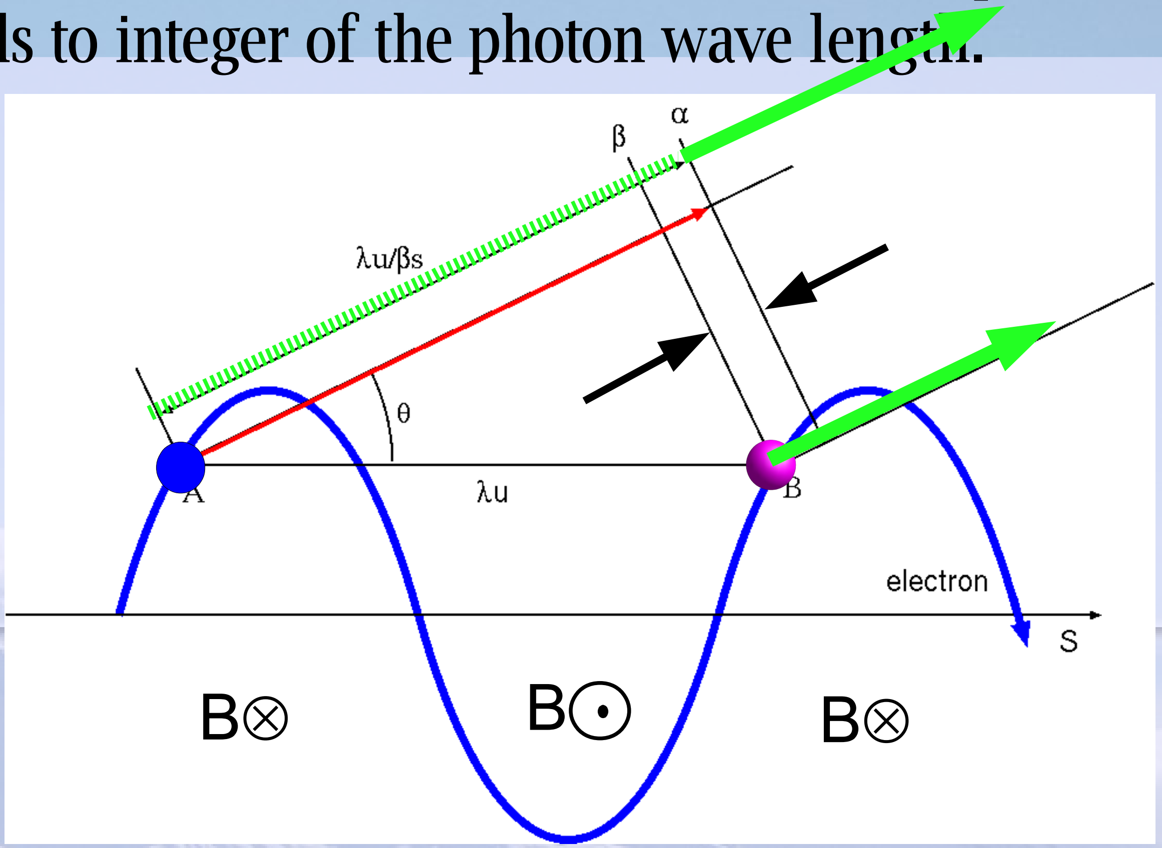
Direct Pair Creation

- 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)

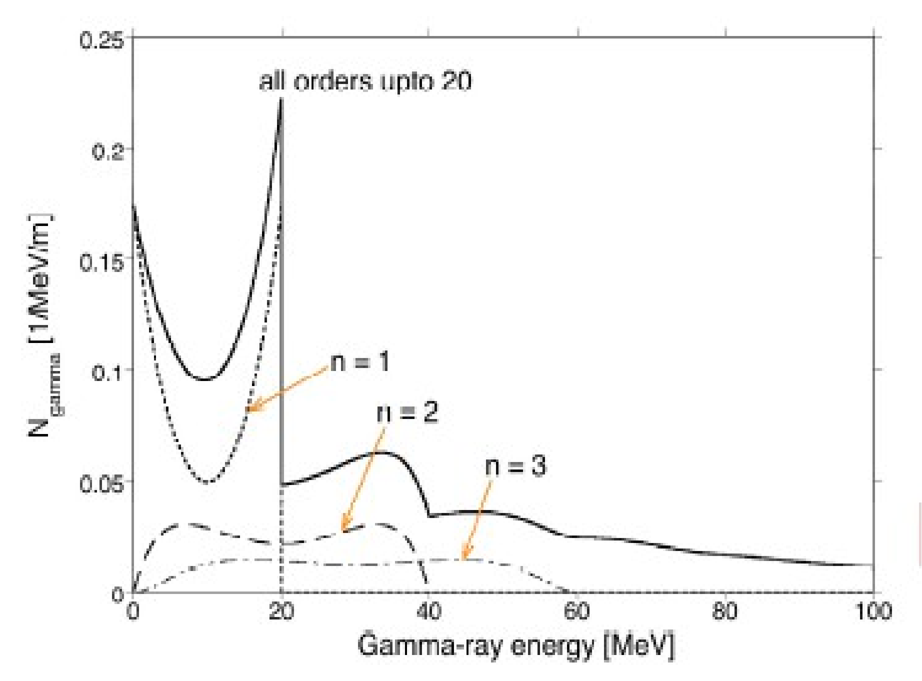
Lienard-Wiechert form (ω photon angular, Ω is solid angle, **n** is unit vector to observation)

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

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

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

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



Undulator Radiation (3)

- The cut off photon energy from undulator is rewritten as

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

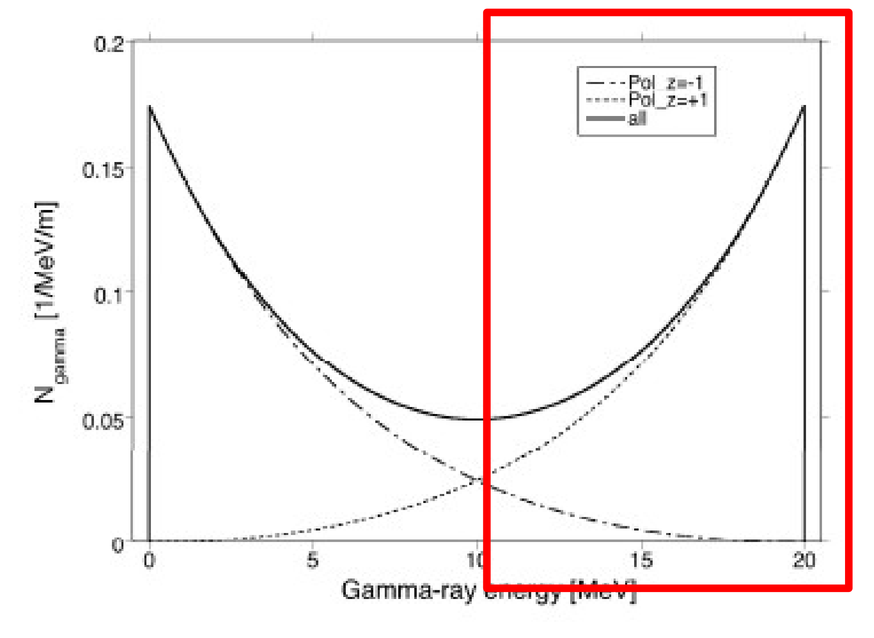
$$\omega_0 = \frac{2\pi\beta c}{\lambda_u} \qquad (3-13)$$

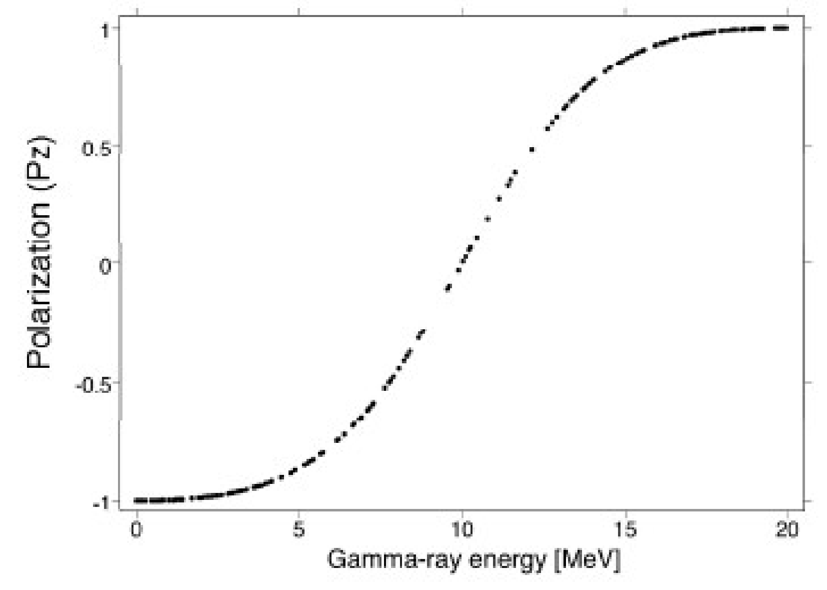
- The undulator radiation = electron and “photon ($\hbar\omega_0$)“ scattering.
  - Photon wave length = undulator period.
  - The photon energy is boosted by γ^2.

► 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.





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

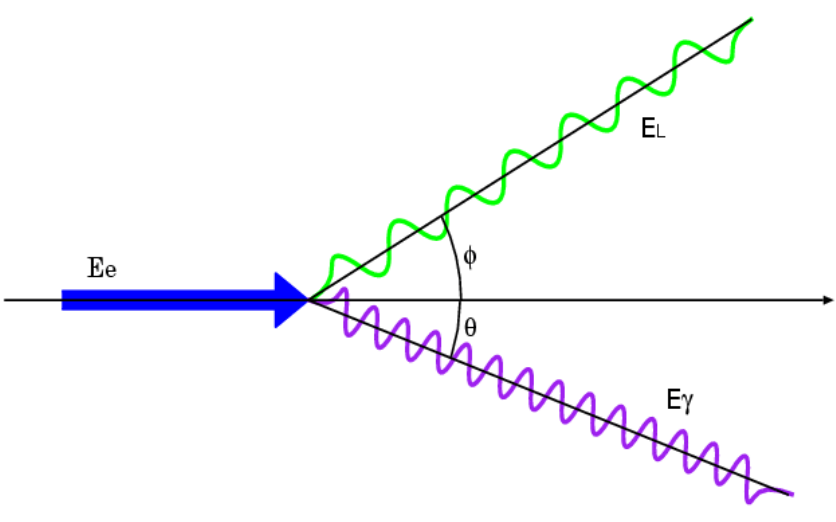
$$\theta=\frac{1}{\gamma}\sqrt{n\frac{\omega_n(1+K^2)}{\omega}-1-K^2}\quad(4-2)$$

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

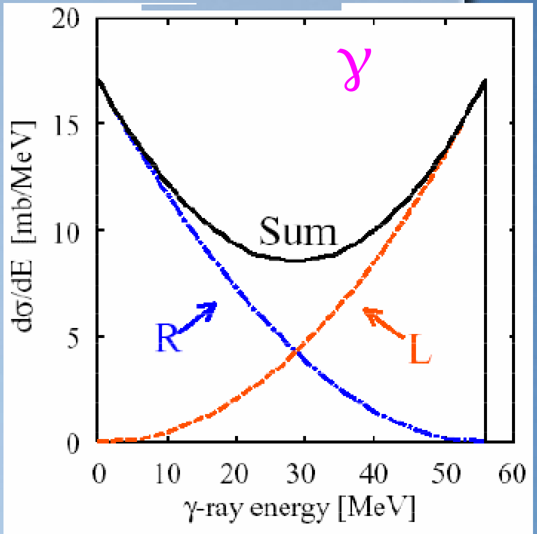
$$E_\gamma \sim 4\gamma^2 \hbar \frac{2\pi c}{\lambda_L} \qquad (3-17)$$

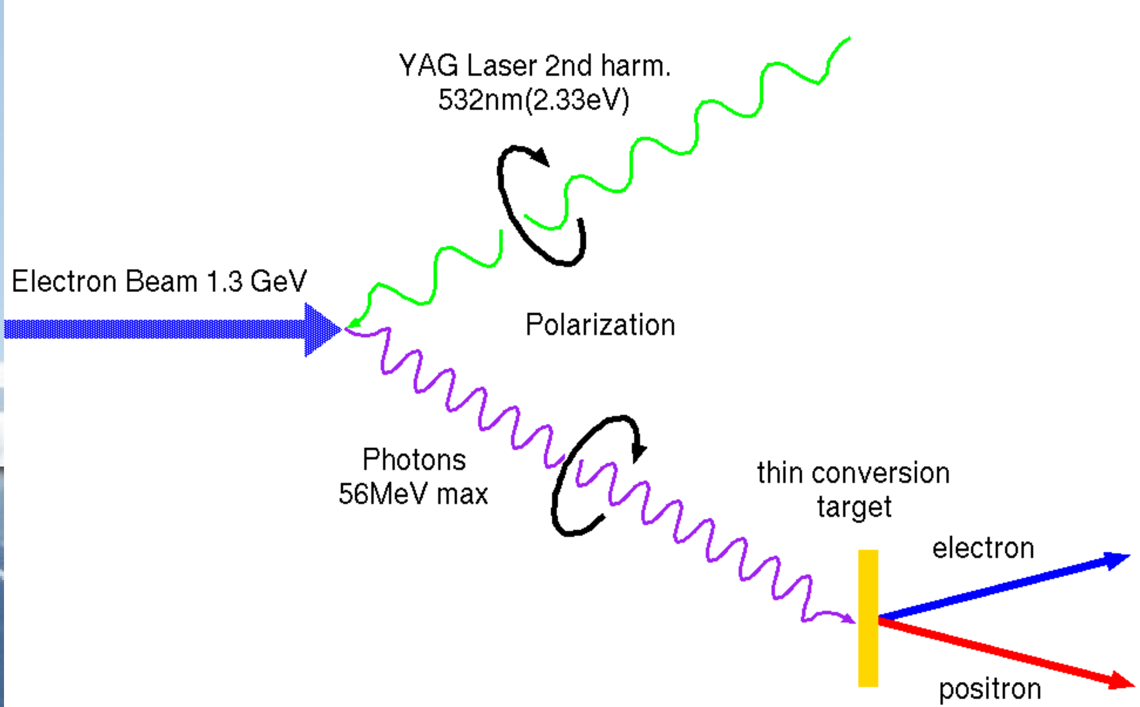
where λ_L is laser wave length.

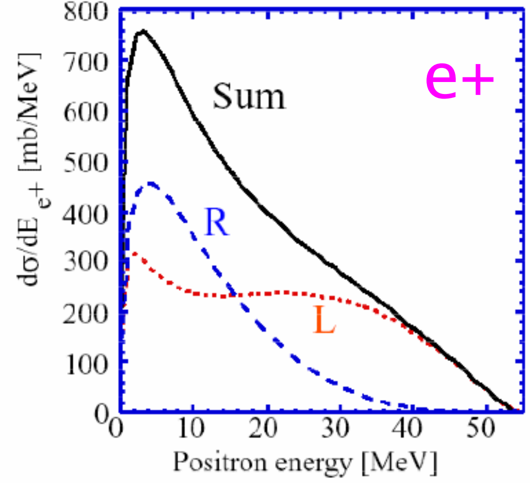
- High energy gamma (several 10s MeV) is obtained with few GeV electron beam.
- Laser focal length is limited to Rayleigh length. It is difficult to make a long "laser undulator".

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

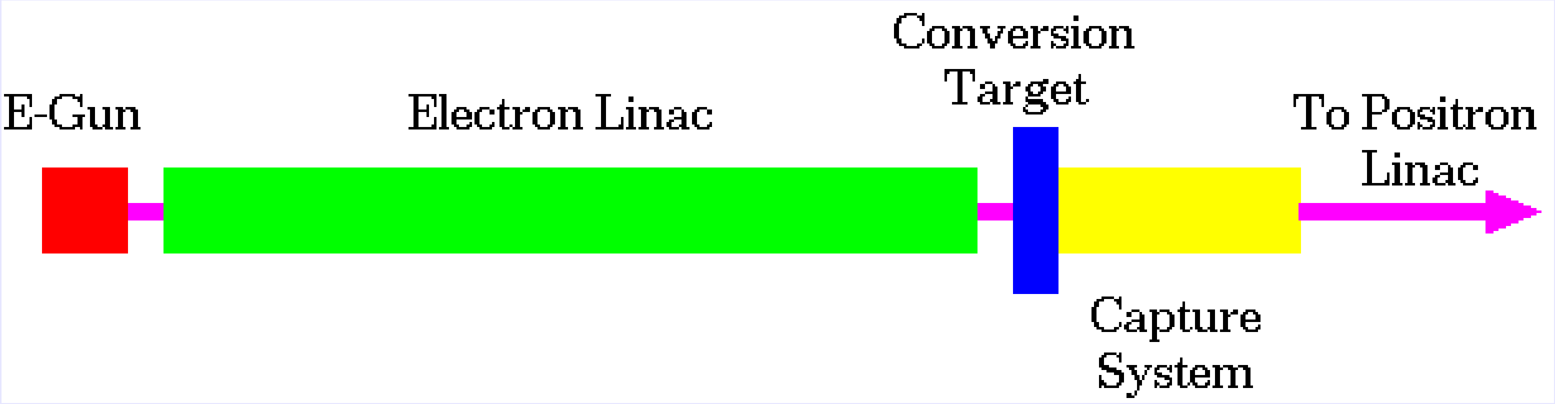
Conversion Target

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)

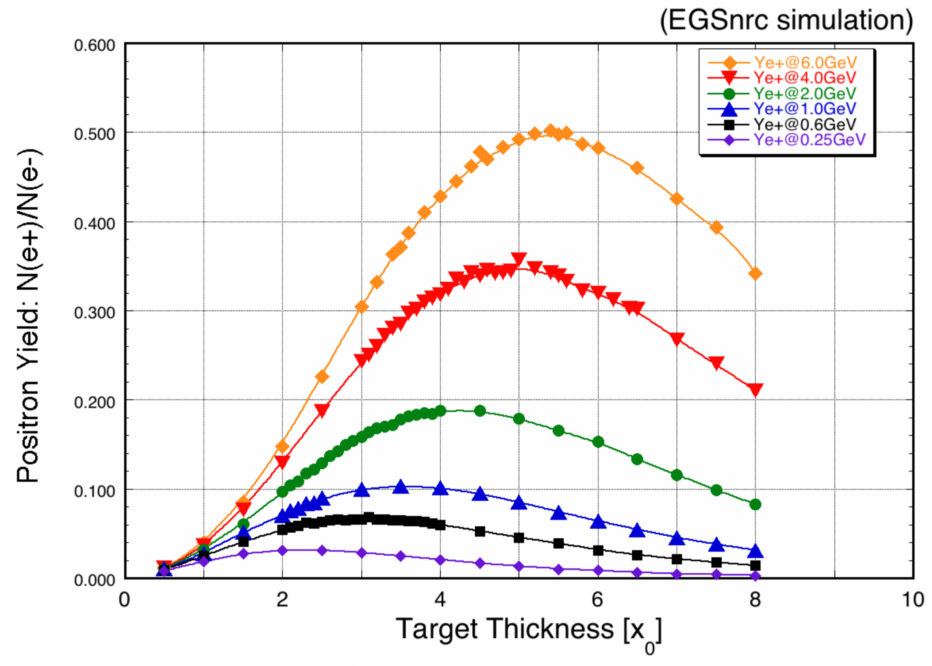
Thickness and material of the target for positron generation is determined by the shower max;

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

Positron yield η and normalized yield η_n are defined as;

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

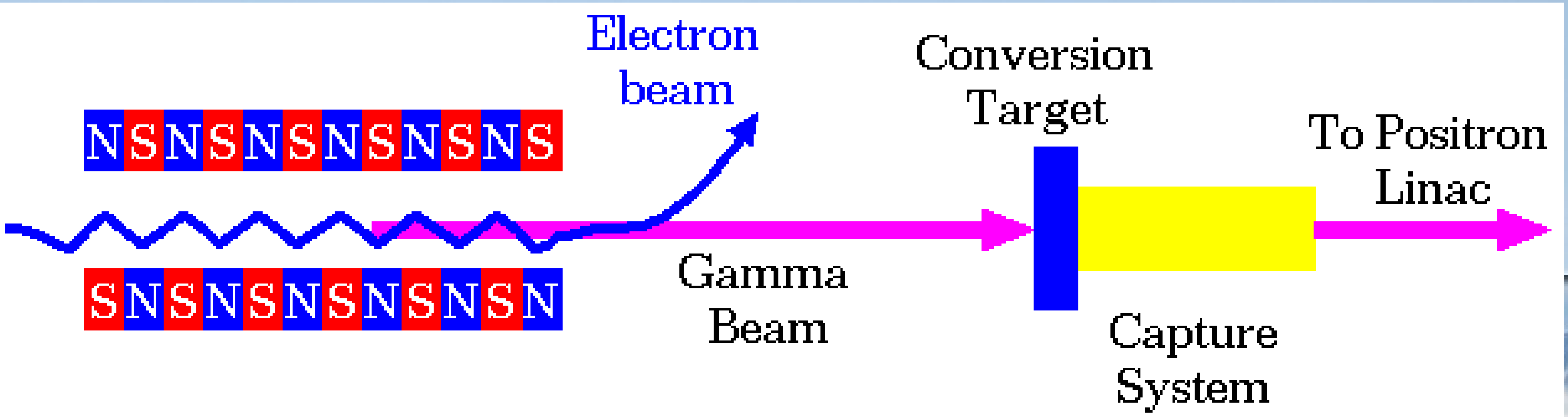
$$\eta_n = \frac{N_{pos}}{N_{ele}\,E_{ele}} \qquad (3-3)$$



Courtesy of T.Kamitani

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.

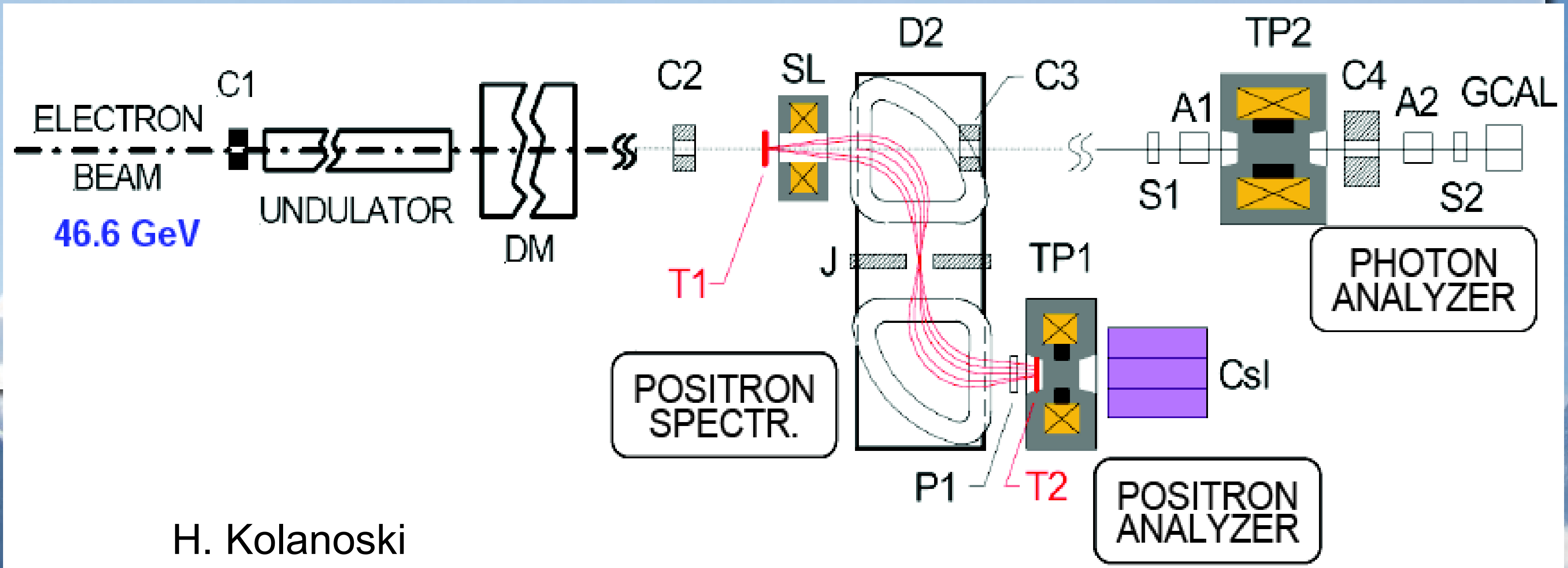


Undulator Scheme (2)

- 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.



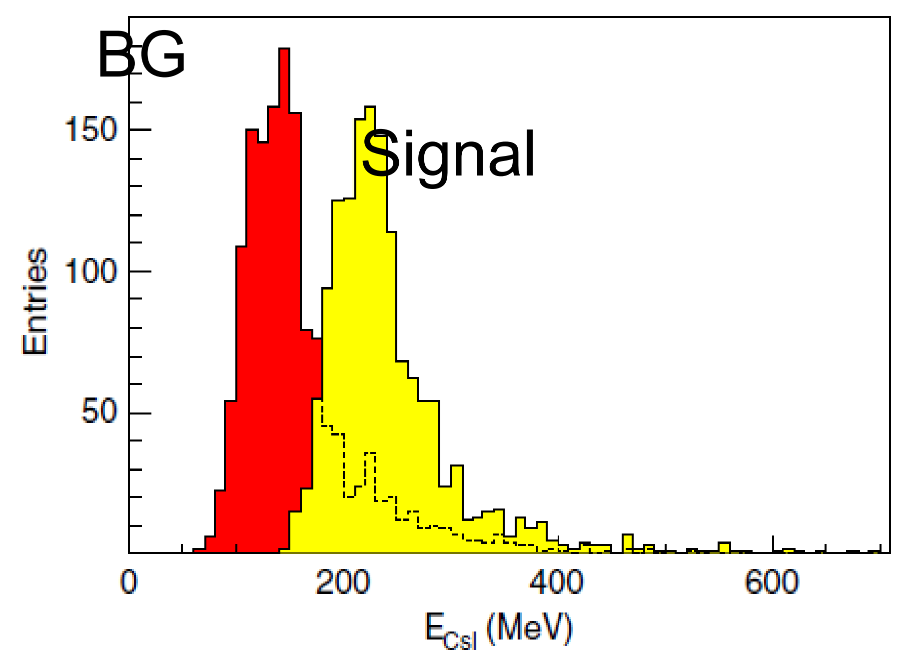
H. Kolanoski

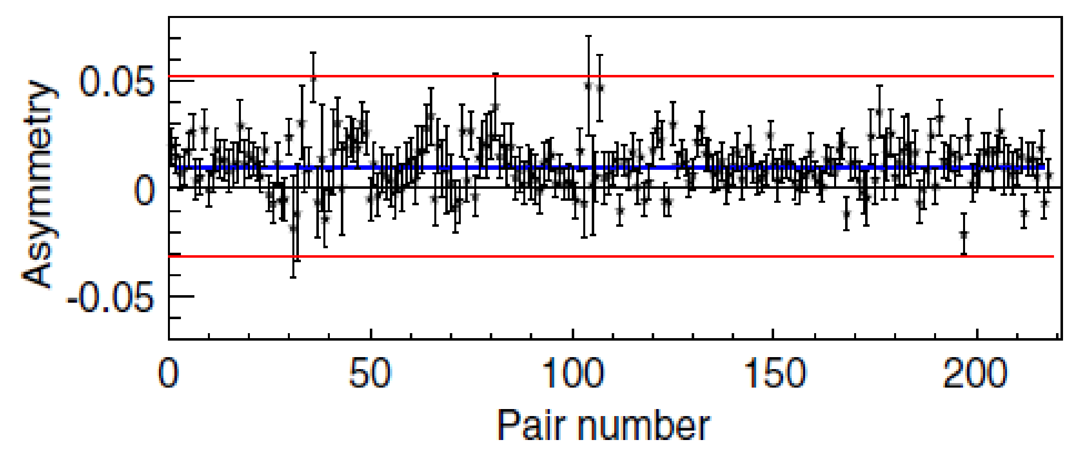
E166 (2)

- 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



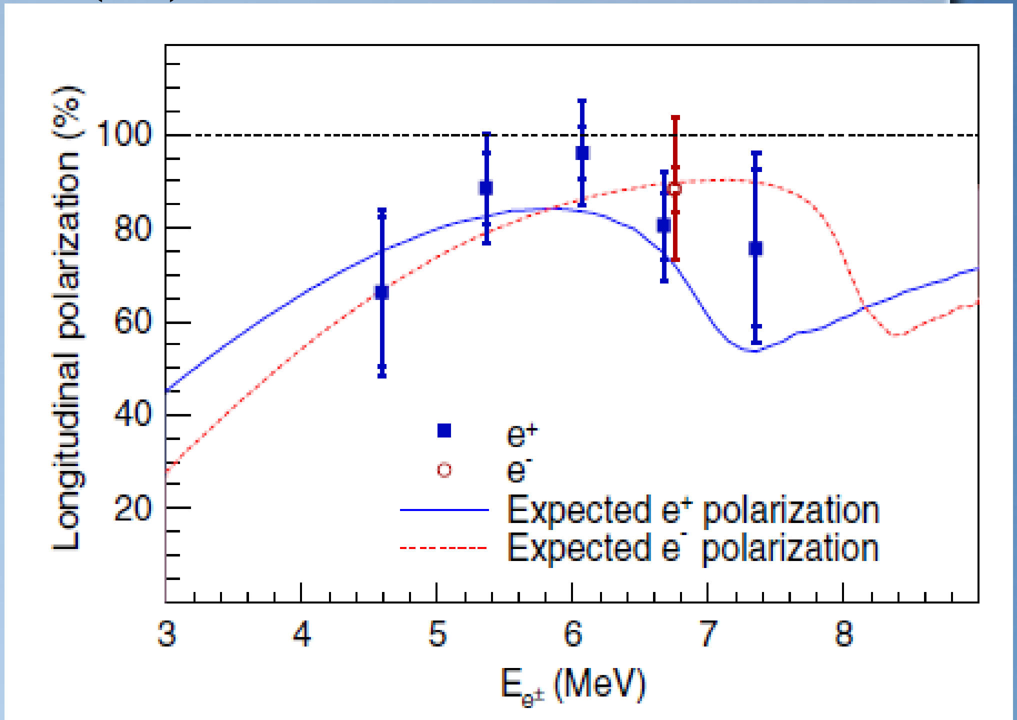


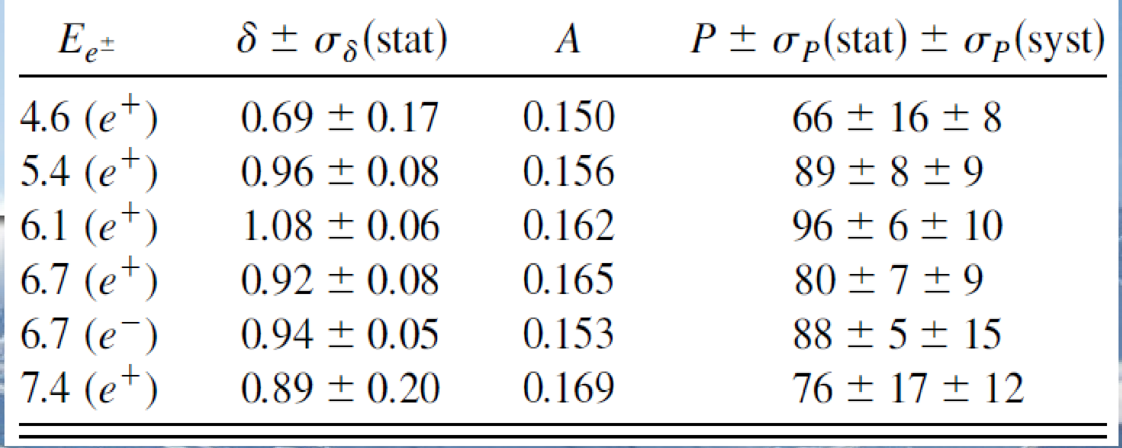
E166 (3)

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

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

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



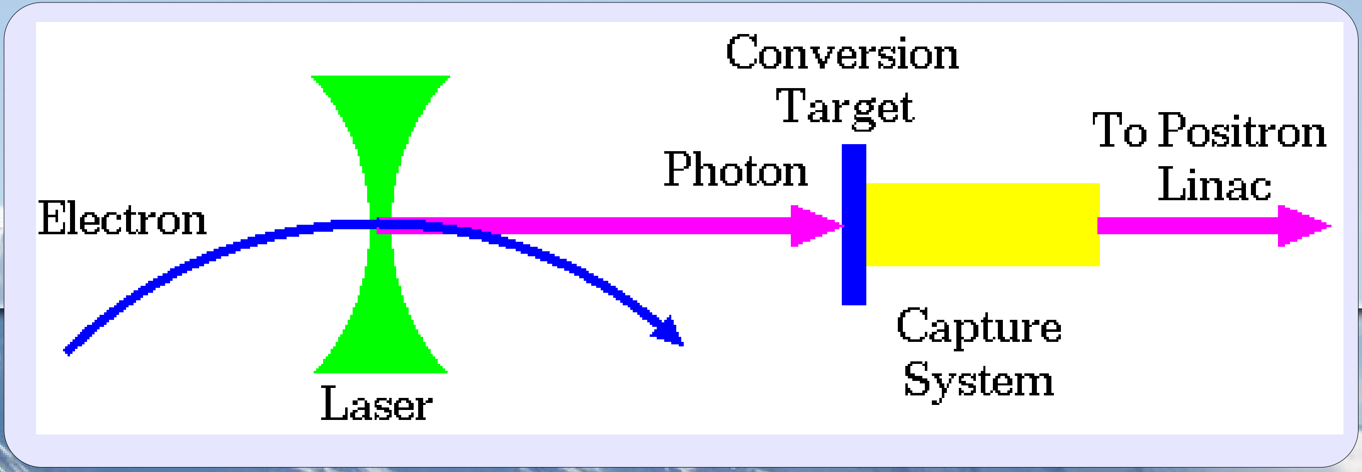


$E_{e^\pm}$	$\delta \pm \sigma_\delta$(stat)	A	$P \pm \sigma_P$(stat) $\pm \sigma_P$(syst)
4.6 (e^+)	0.69 ± 0.17	0.150	66 ± 16 ± 8
5.4 (e^+)	0.96 ± 0.08	0.156	89 ± 8 ± 9
6.1 (e^+)	1.08 ± 0.06	0.162	96 ± 6 ± 10
6.7 (e^+)	0.92 ± 0.08	0.165	80 ± 7 ± 9
6.7 (e^-)	0.94 ± 0.05	0.153	88 ± 5 ± 15
7.4 (e^+)	0.89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



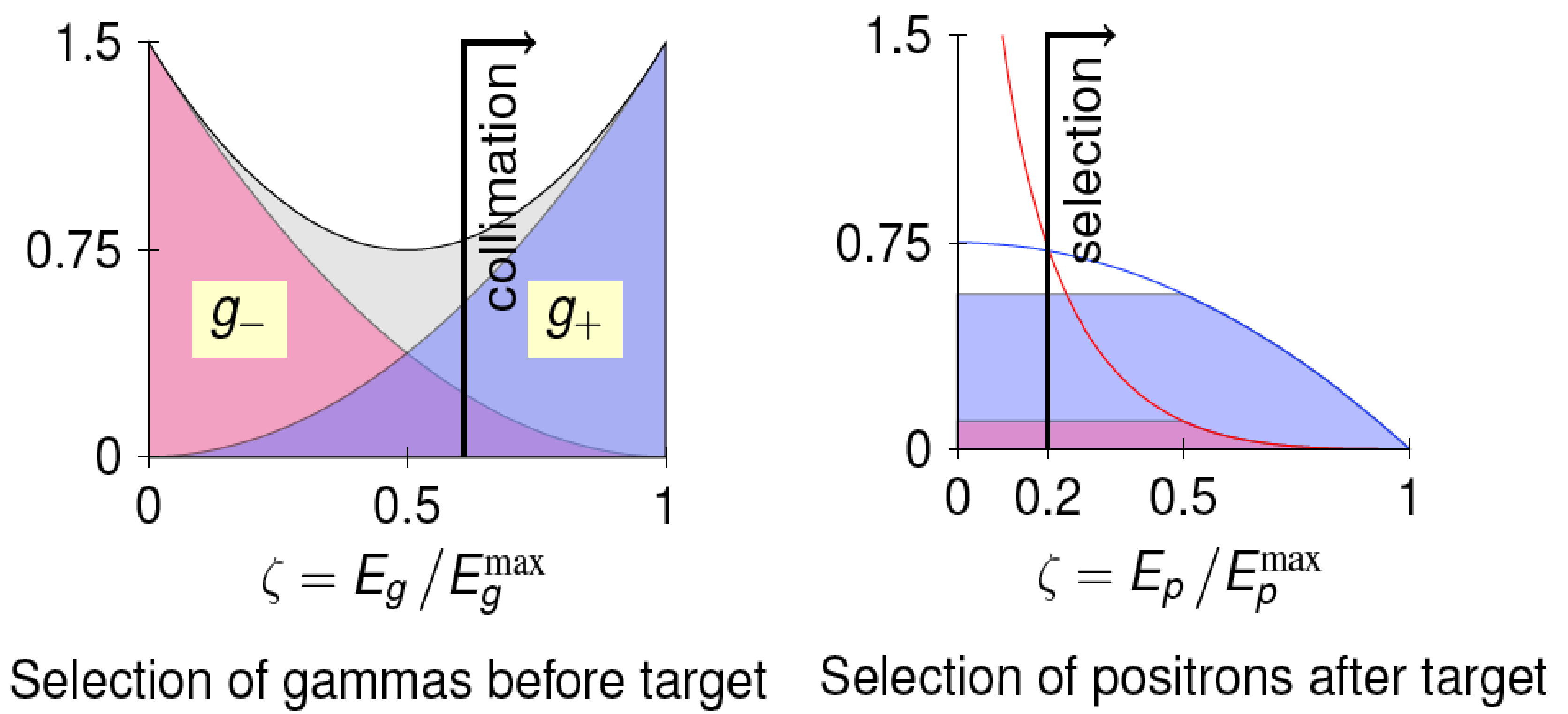
Compton Scheme (2)

- ► 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.
- ► To obtain enough amount of positron is a technical challenge.

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

Compton Scheme (3)

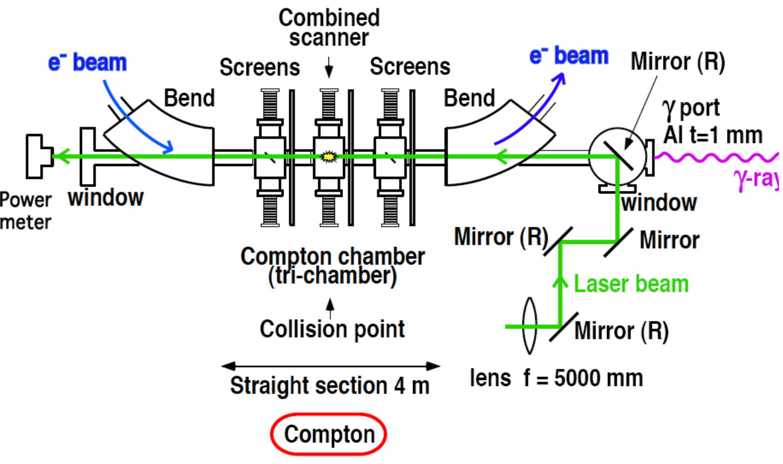
- Polarized gamma is obtained by collimation (pre-selection).
- The positron polarization is enhanced by the energy selection (post selection).

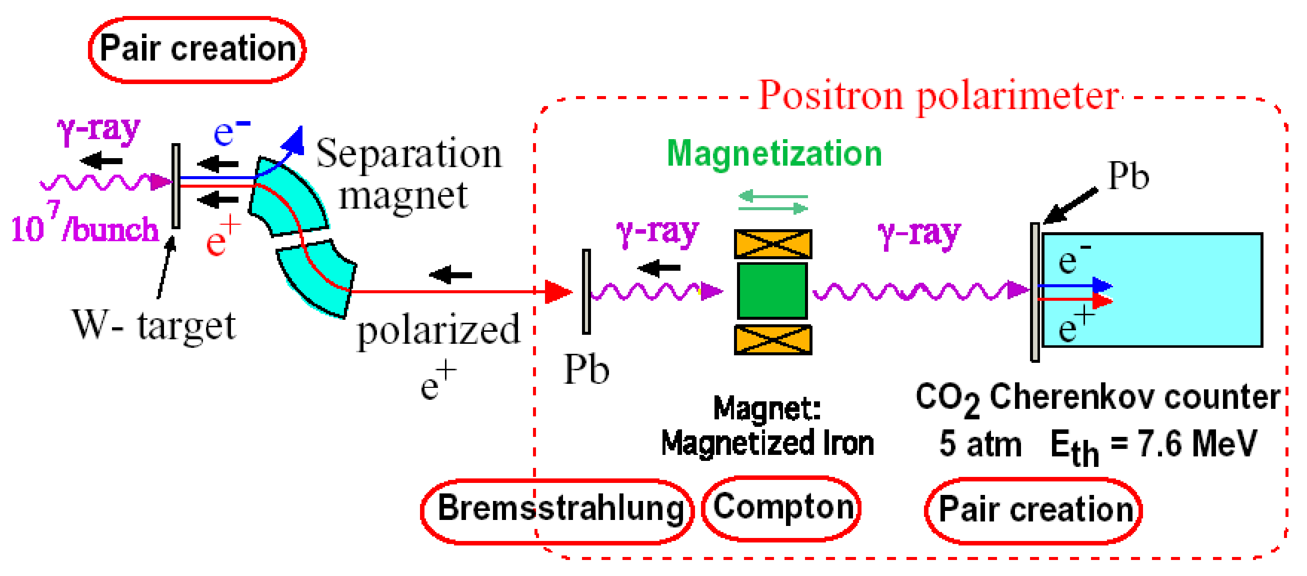


Selection of gammas before target

Selection of positrons after target

KEK-ATF experiment





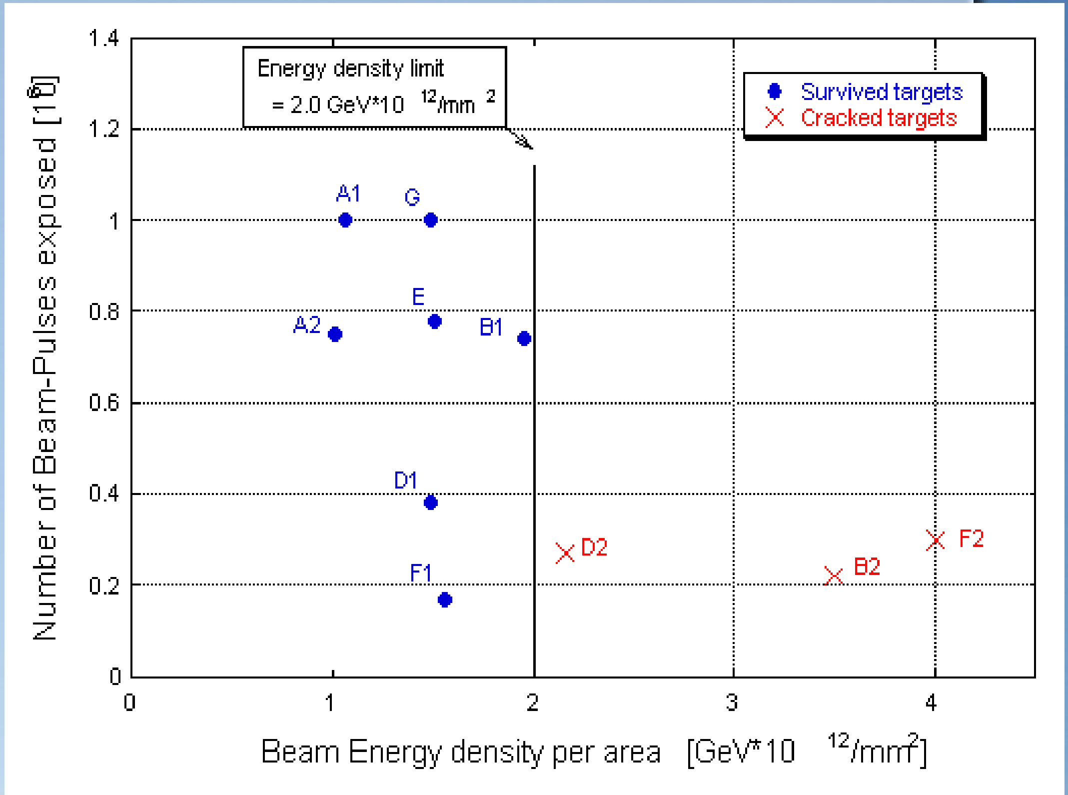
- Ne+(design) = 3 x 10^4/bunch
- Pol(estimation) = 80%
- Pol(experiment) ~ 73±15(stat)± 19(sys)%

Target Heat Load

- A fraction of electron (gamma) energy is deposited in the target as thermal energy.
- An actual limit on the positron generation is given by the target destruction.
- The destruction can be occurred several processes,
  - Melting,
  - Fatigue,
  - Destruction by thermal shock wave,
  - Radiation damage, etc.
- The heat load is heavier for electron driven than gamma driven, because of the higher beam energy.

Damage Threshold (1)

- Damage threshold of electron driven (W-Re target) 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)

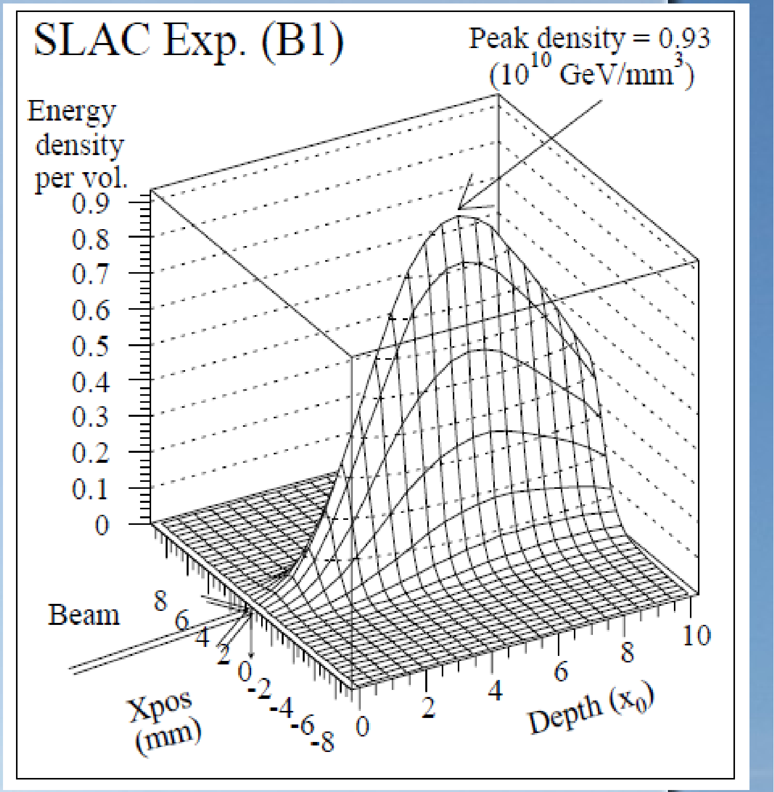
To evaluate the universal damage threshold, the energy deposited density in the SLAC experiment is evaluated as

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

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

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,

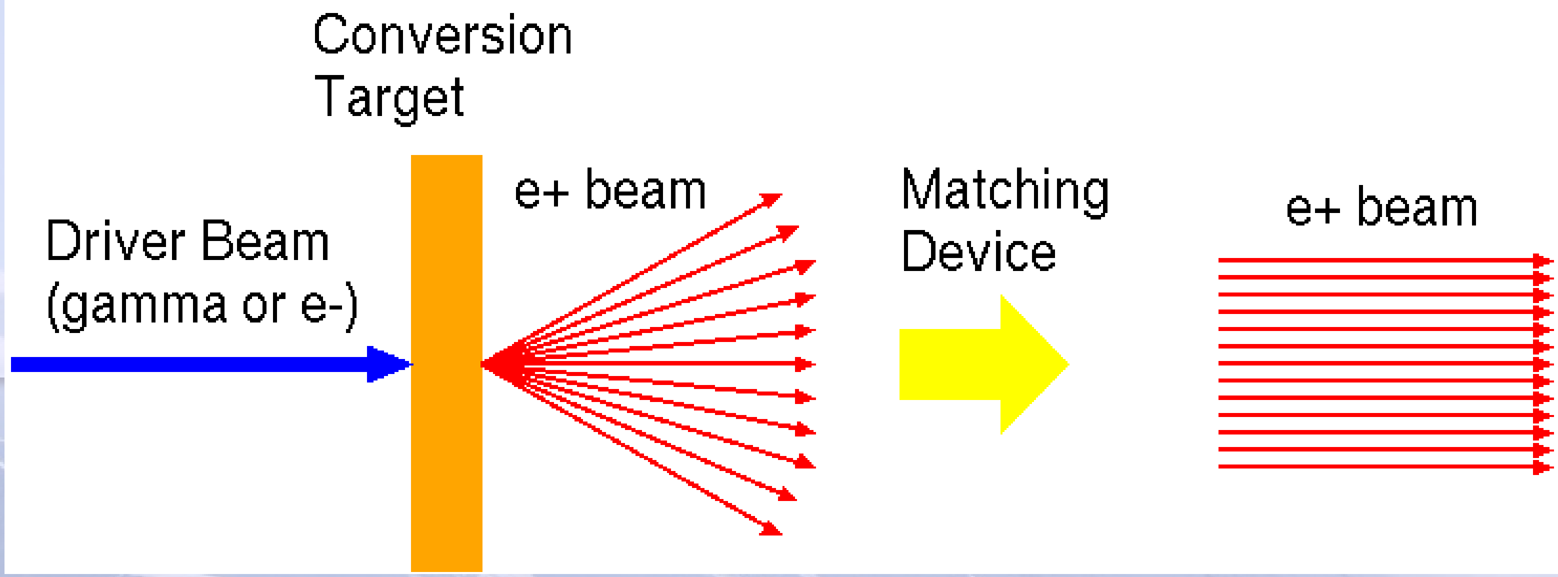
$$\rho = 35 [J/g]$$



T. Kamitani

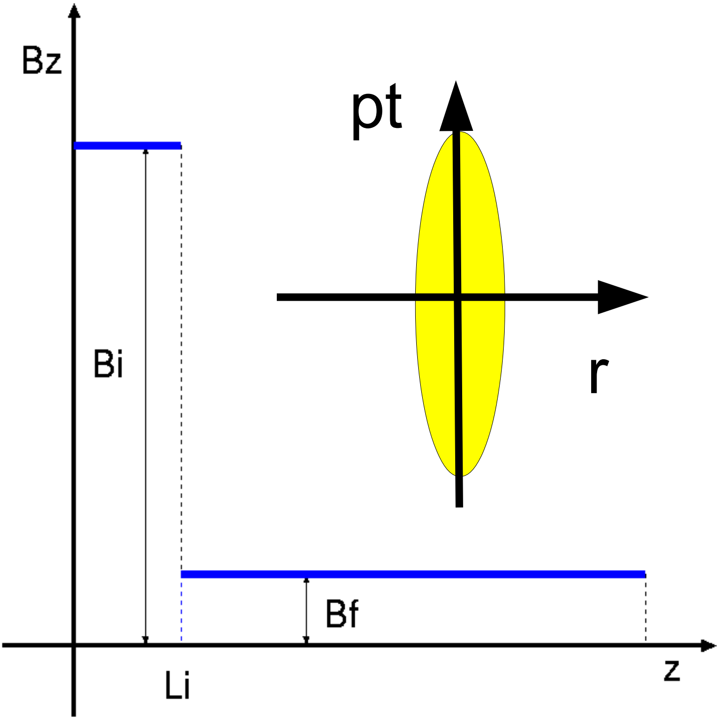
Positron Capture

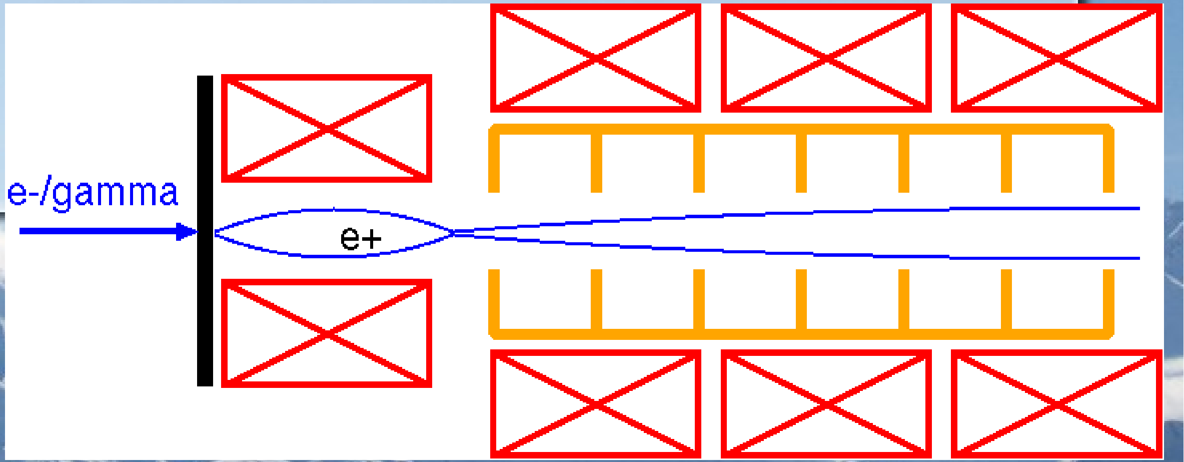
- The generated positrons are distributed in a small spot size and in a large momentum space. To convert it to the parallel beam, a couple of solenoid-like magnetic field with different profile are employed.
  - QWT (Quarter Wave Transformer)
  - AMD (Adiabatic Matching Device)



QWT(1)

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





QWT(2)

Positrons are circulated with radius ρ.

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

Time to travel πρ in xy plane,

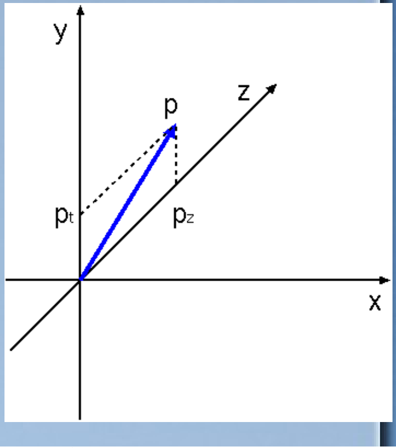
$$t_{xy} = \frac{\gamma m \pi \rho}{p_{t0}} = \frac{\gamma m \pi}{eB_i} \qquad (2-2)$$

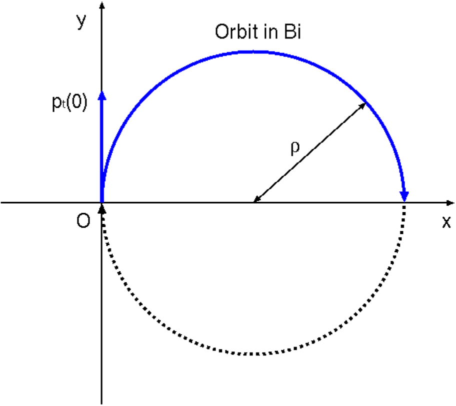
Time to travels L_i

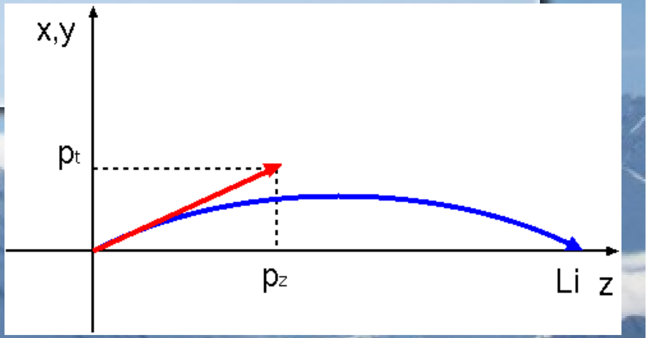
$$t_z = \frac{L_i m \gamma}{p_z} \qquad (2-3)$$

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

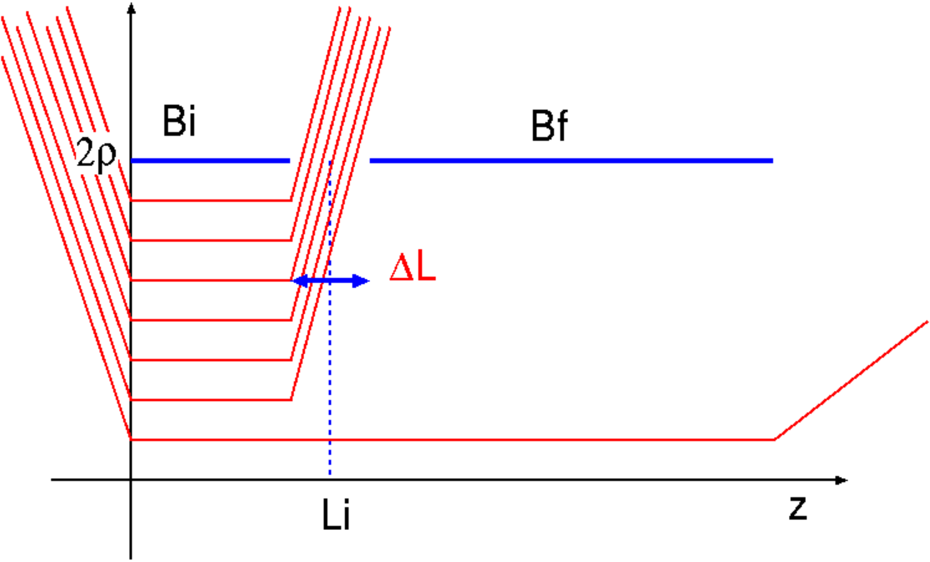
$$\Phi_i = \pi (2\rho)^2 B_i \quad (2-5)$$

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

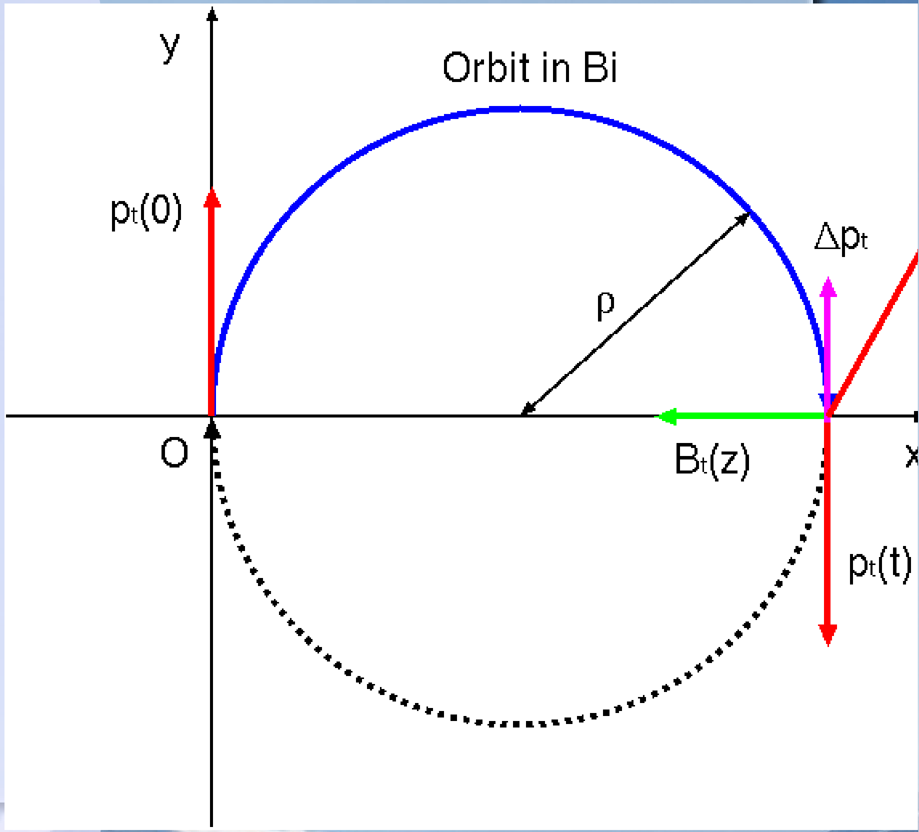
$$\frac{dp_t(t)}{dt} = e v_z B_t(z) \quad (2-9)$$

Integrating this equation, total momentum change is

$$\begin{aligned} \Delta p_t &= e v_z \int B_t(z)\, dt \\ &= e v_z \int B_t(z) \frac{dz}{v_z} \\ &= e \rho (B_i - B_f) \quad (2-10) \end{aligned}$$

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

$$\begin{aligned} p_t(t) &= p_{t0} - \Delta p_t = p_{t0} - \frac{p_{t0}}{B_i}(B_i - B_f) \\ &= p_{t0} \frac{B_f}{B_i} \quad (2-11) \end{aligned}$$



QWT(5)

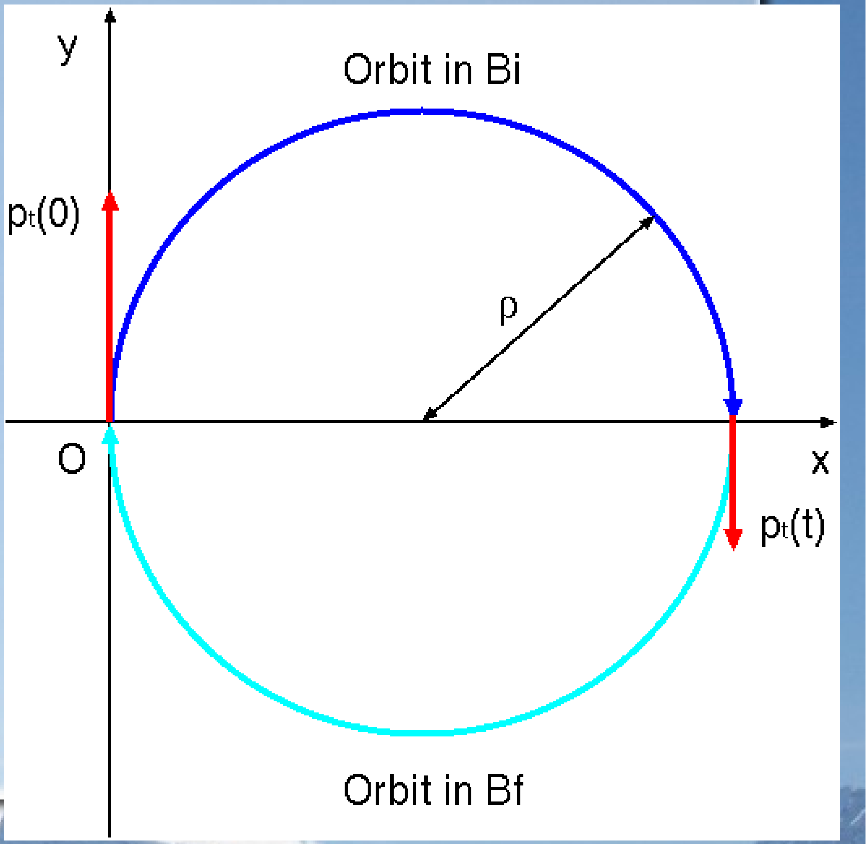
Pt(t) after the kick is

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

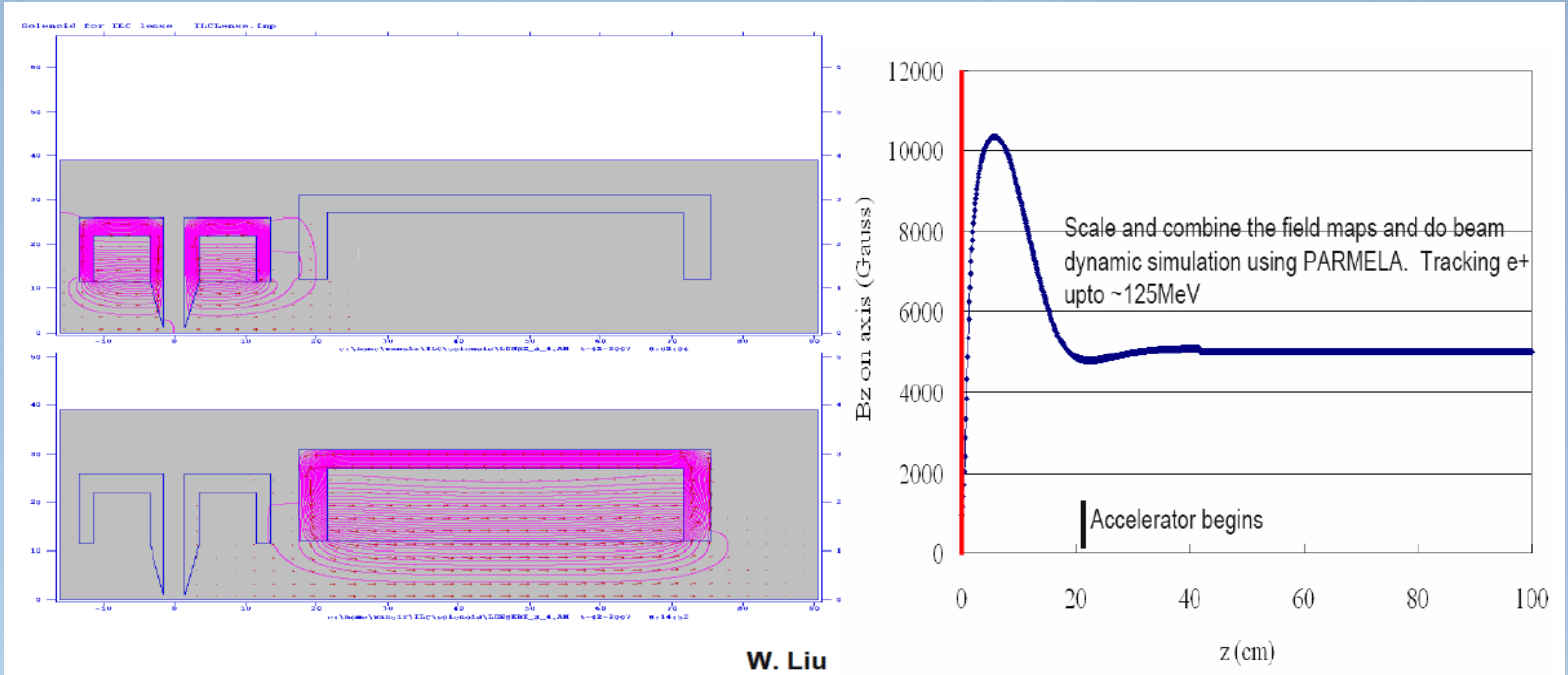
Radius of circulating motion of this particle in B_f is

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

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



QWT(6)



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

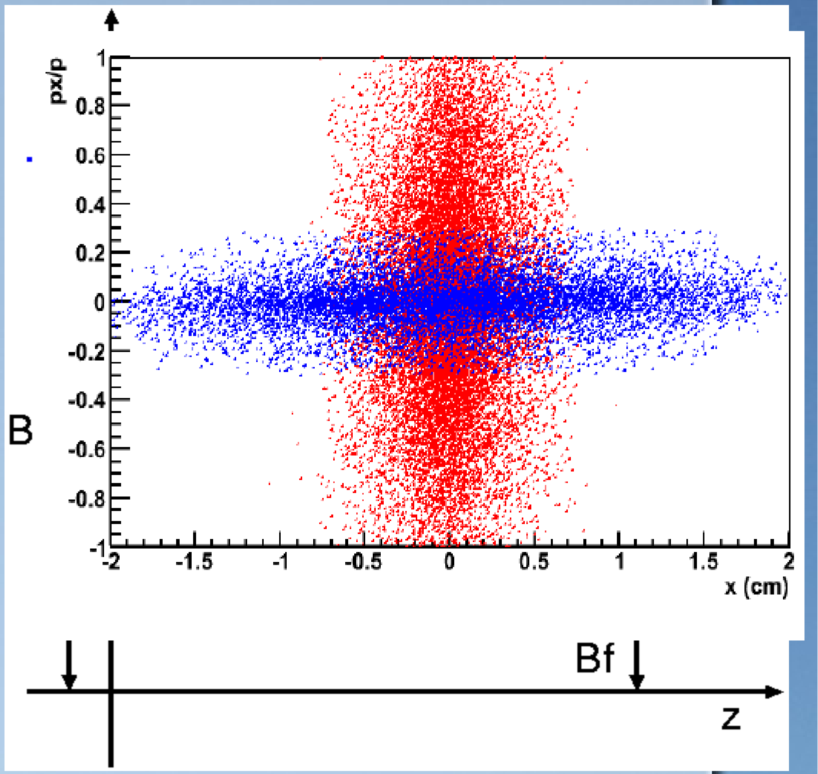
W. Liu

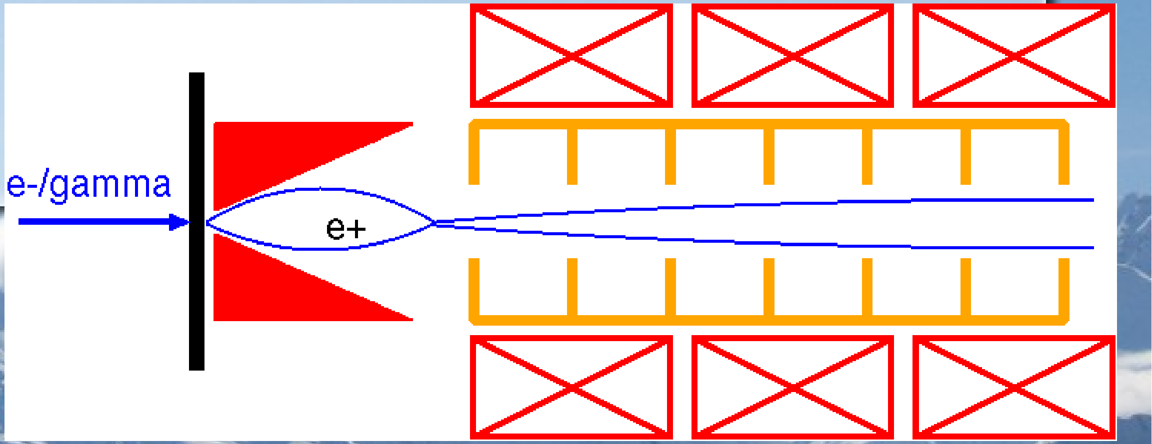
- Initial strong solenoid magnet with bucking to cancel B field on target.
- B_f is 0.5 T.
- NC L-band accelerator is placed in B_f region.

AMD(1)

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

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





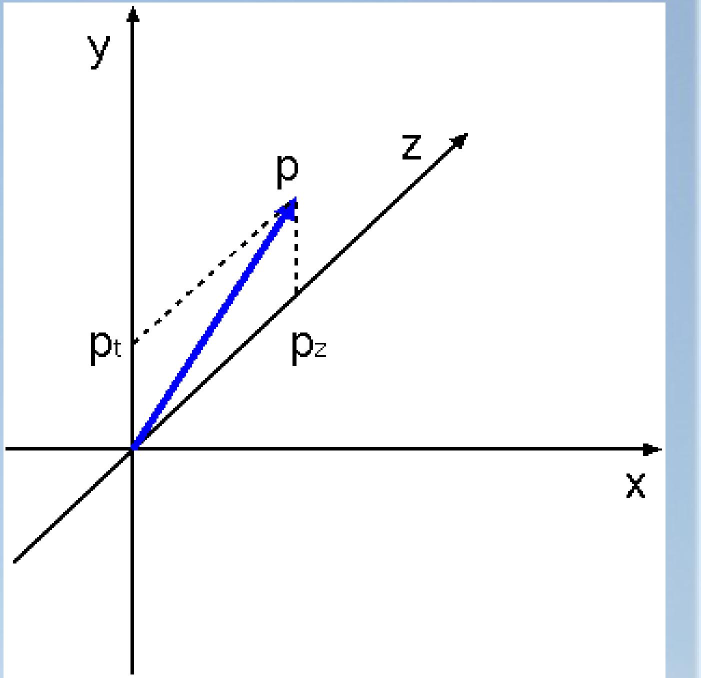
AMD (2)

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,

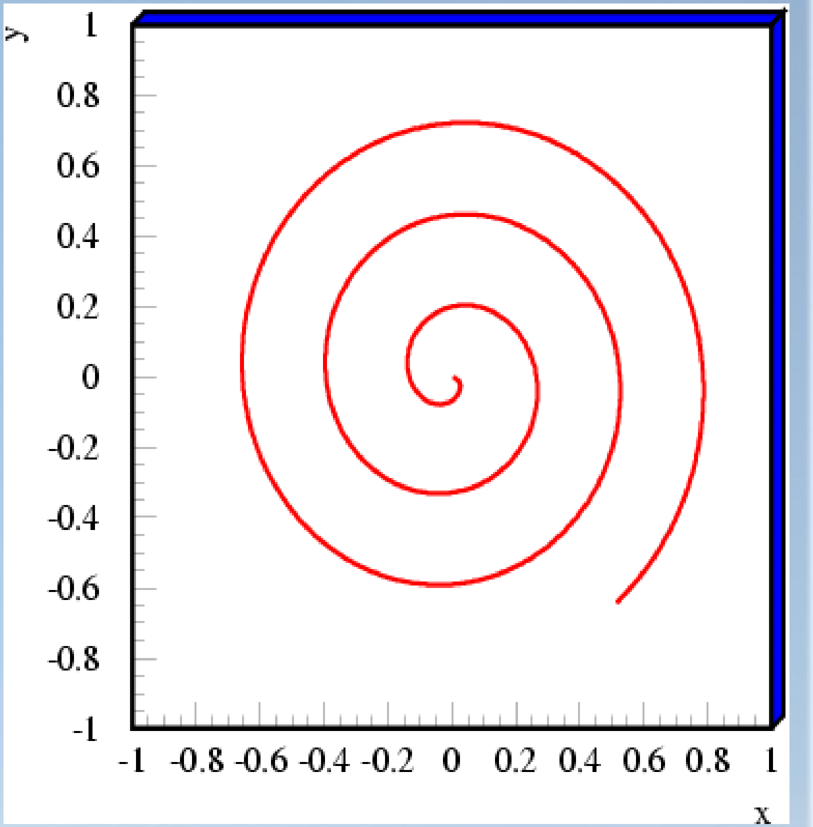
$$\frac{p_t(z)^2}{eB(z)} = \frac{p_{t0}^2}{eB_i} \quad (2-21)$$

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

The radius is

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

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



AMD(5)

Pt at the exit of AMD is

$$p_t = \sqrt{\frac{B_f}{B_i}}\, p_{t0} \qquad (2-25)$$

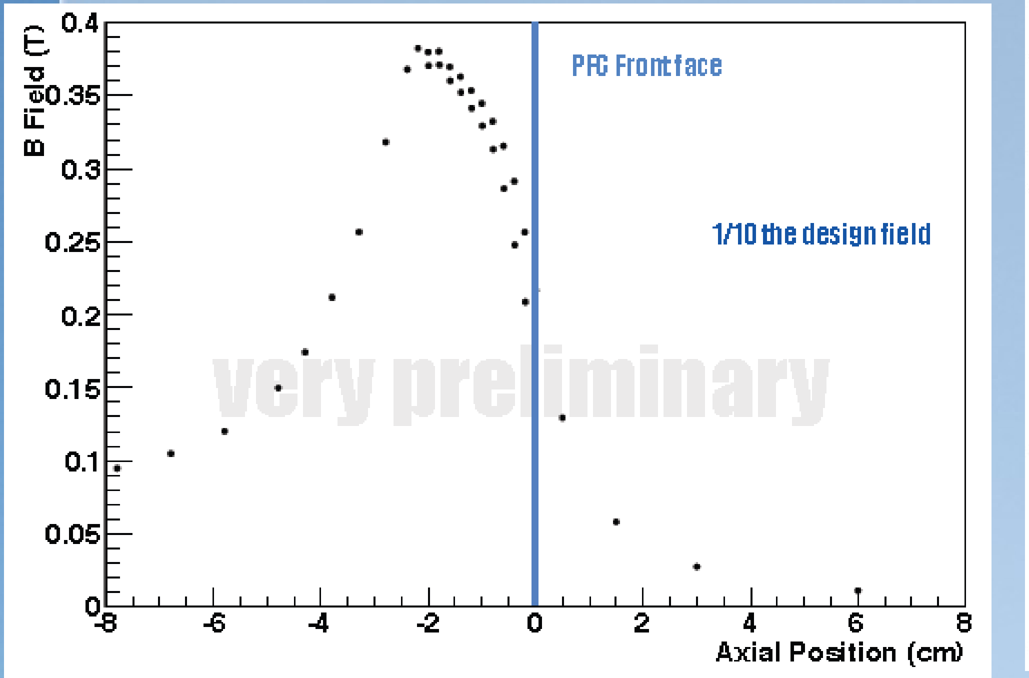
Acceptance on transverse momentum (aperture of accelerator)

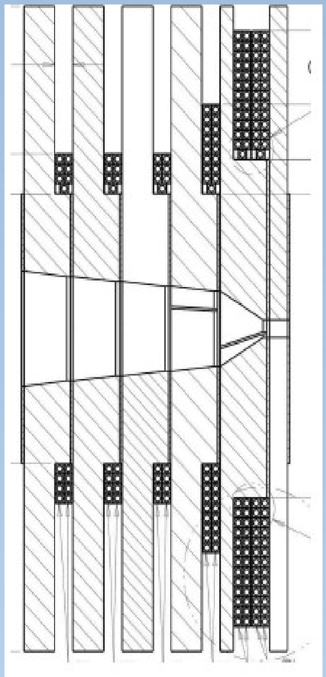
$$p_t < \frac{a}{2} e \sqrt{B_f B_i} \qquad (2-27)$$

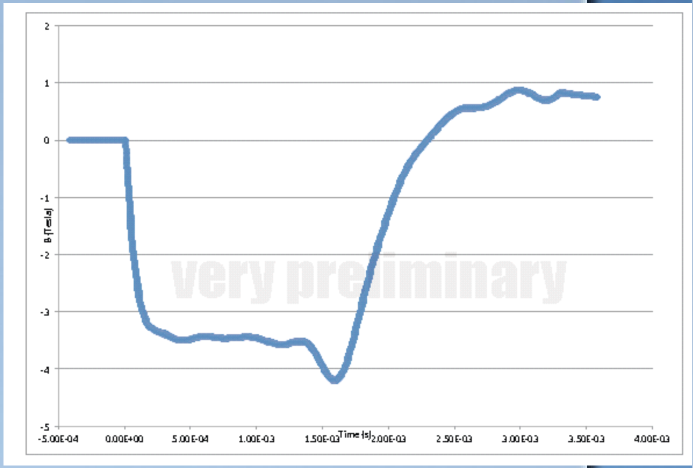
Acceptance on longitudinal momentum (adiabatic condition)

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

AMD(6)





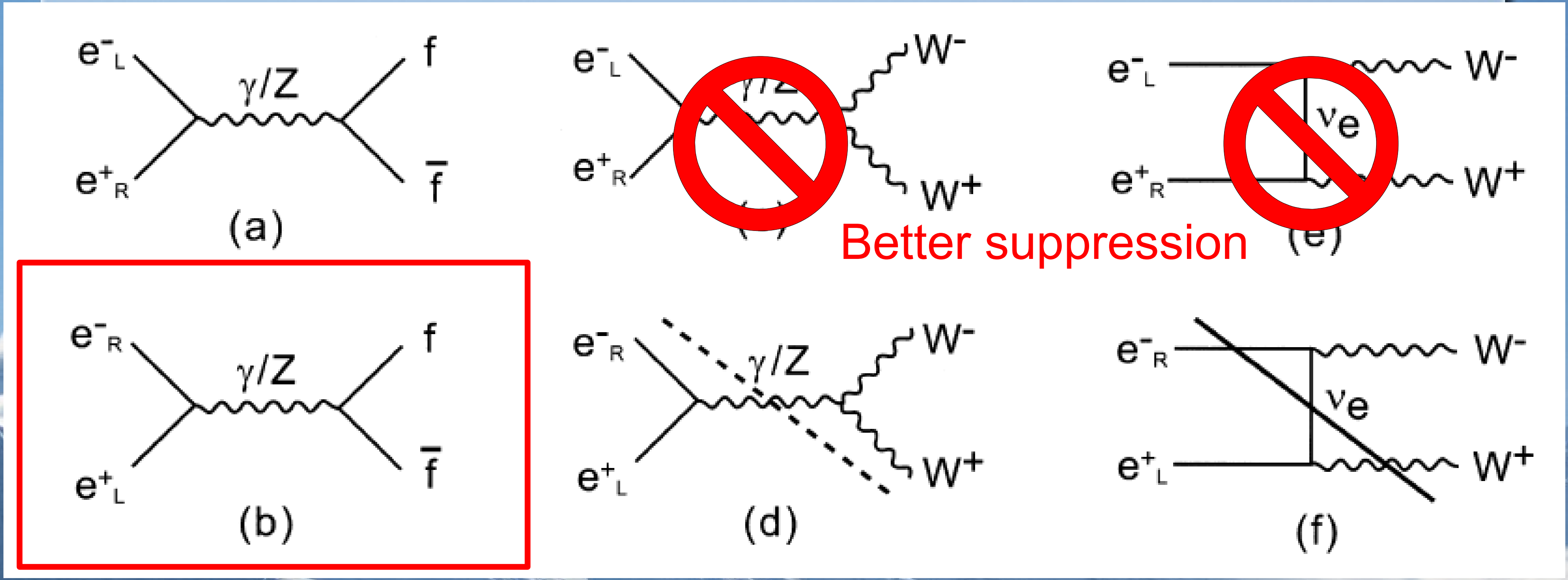


- AMD field is produced by flux-concentrator.
- Primary coil induces eddy current in the inner conductor.
- Because of the tapered shape of the inner conductor, the magnetic field is concentrated.

Positron Source For LC

Positron Polarization

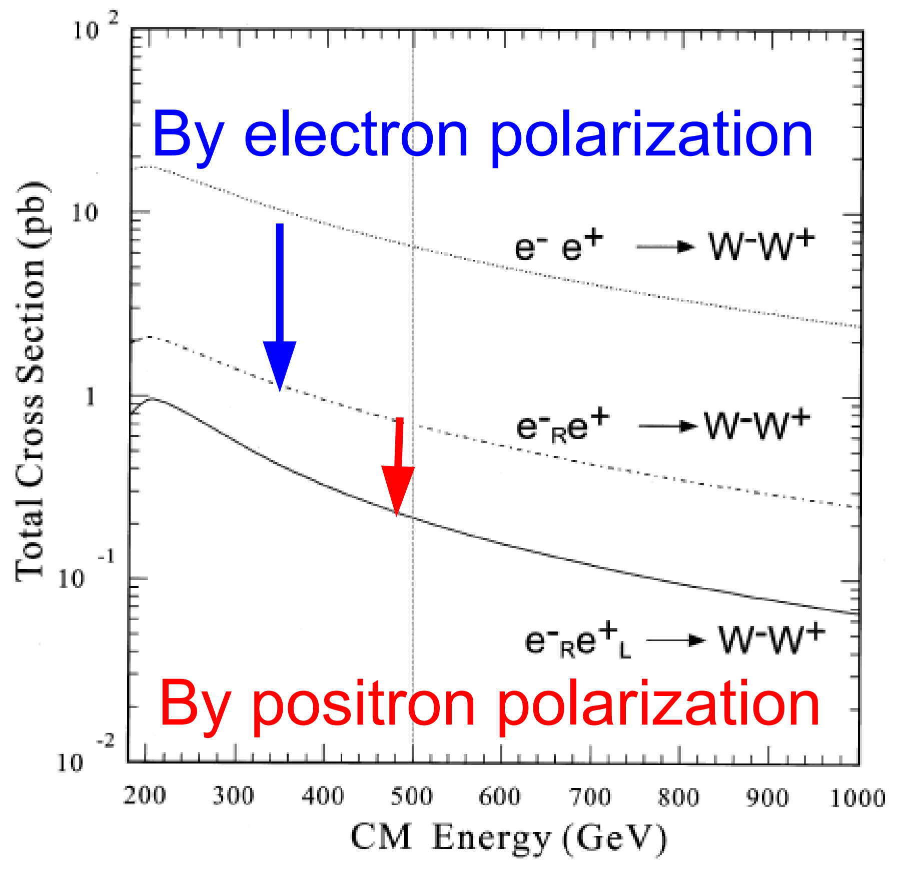
- Since the high electron polarization is expected as high as 90%, the positron polarization is helpful, but not mandate



Better suppression

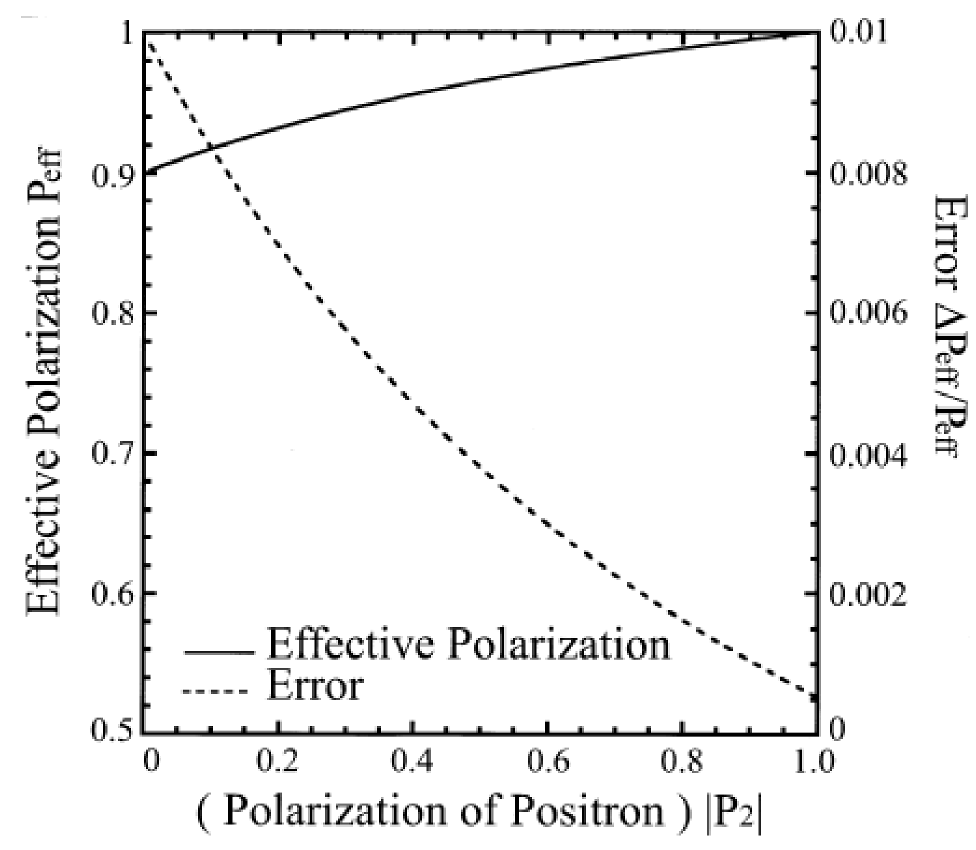
Effective Polarization

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



By electron polarization

By positron polarization



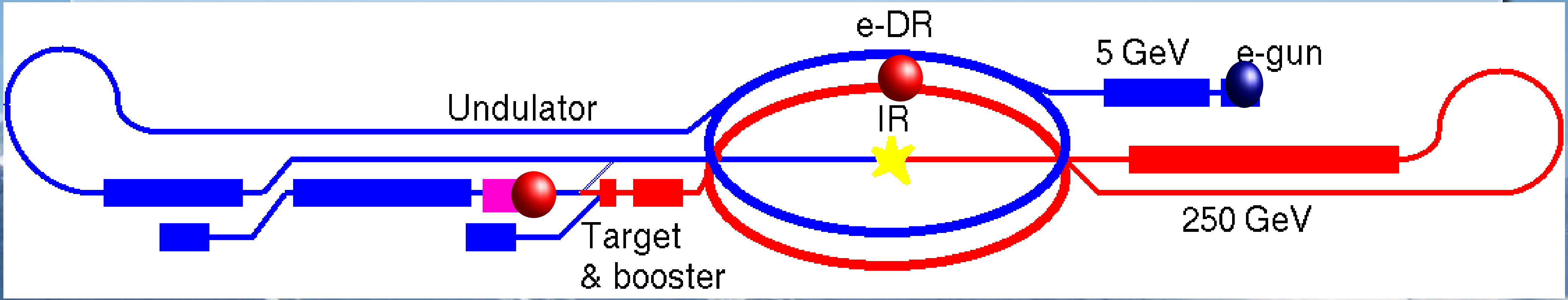
Parameters

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

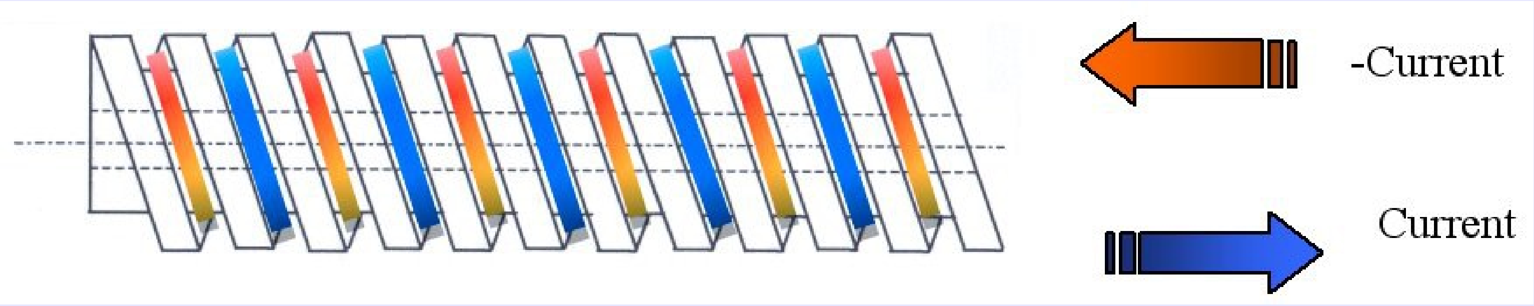
- It is the first undulator based positron soure in the world.
- 250GeV electrons generate gammas.
- Gamma rays are converted to positron.
- 5 GeV positron booster.

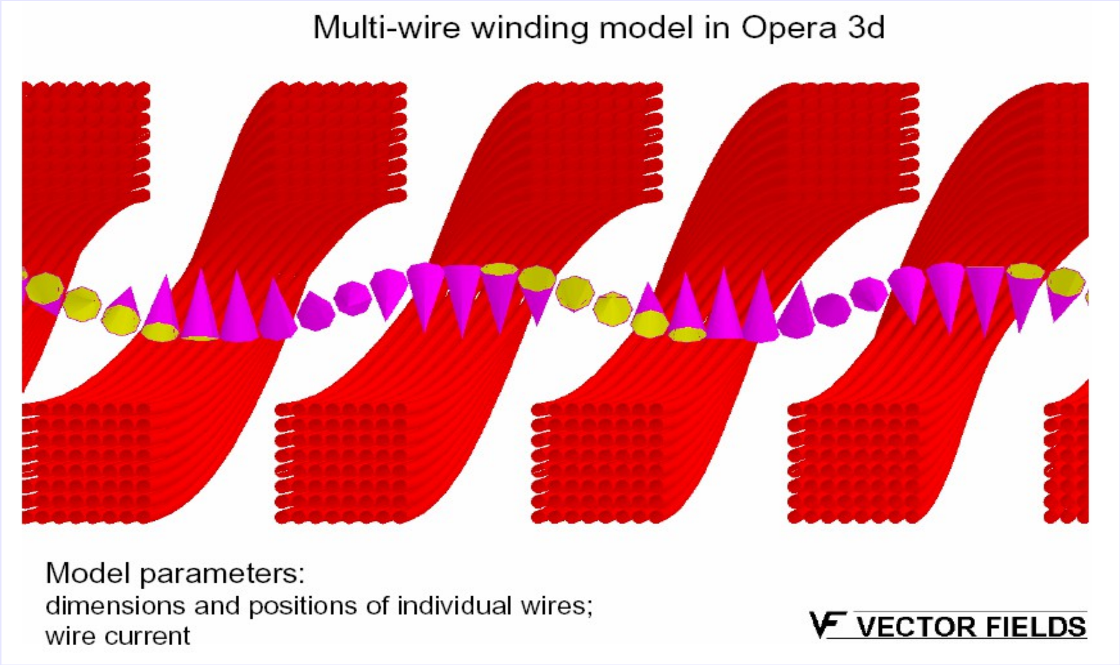


System Specifications

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	30-60	%

Helical Undulator




Multi-wire winding model in Opera 3d

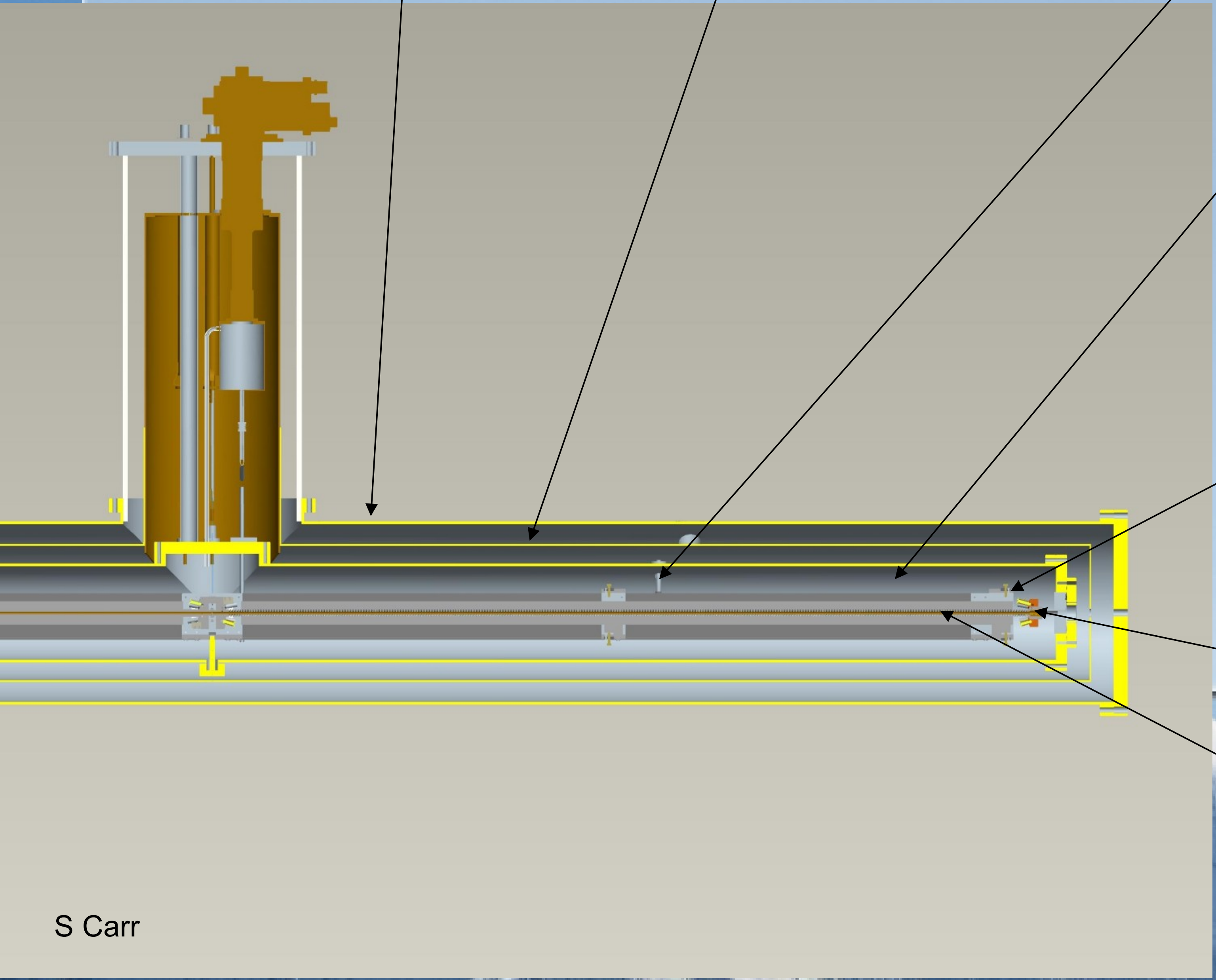
Model parameters:
dimensions and positions of individual wires;
wire current

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

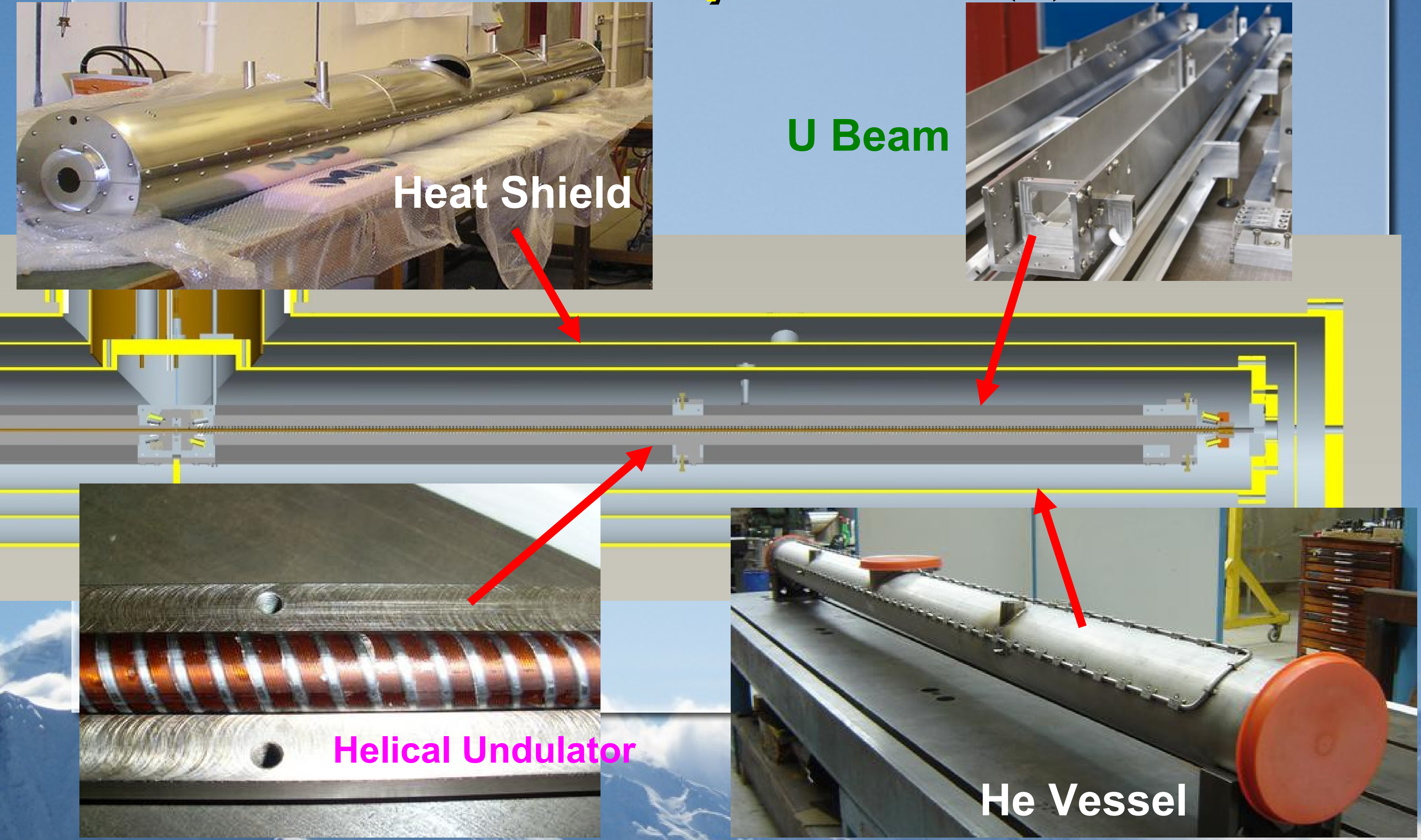
U Beam used to support/align the magnet.

Beam Tube

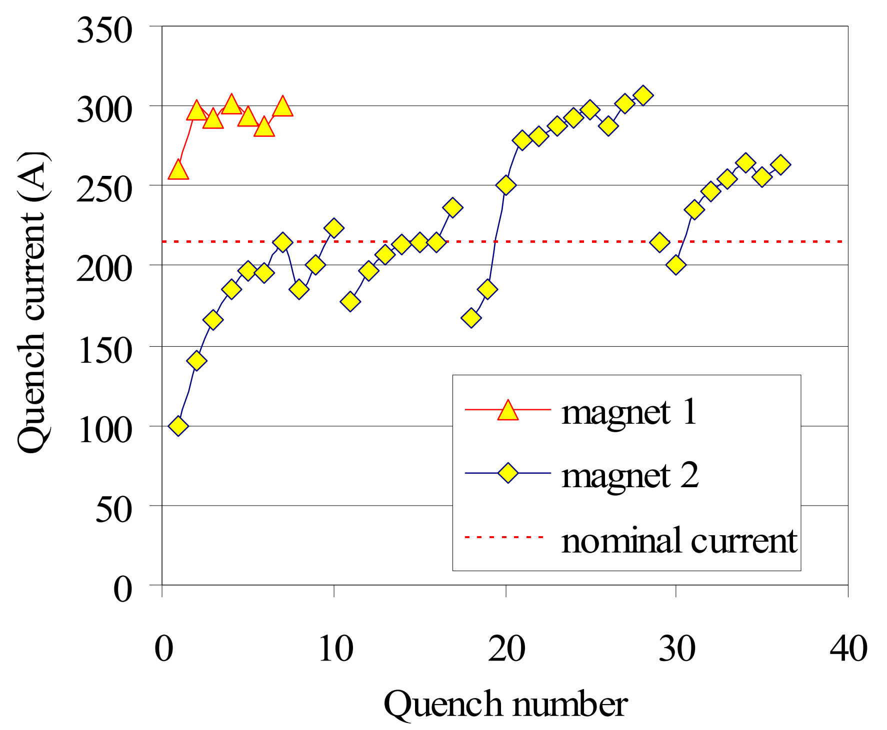
Magnet cooled to 4.2K by liq He in bath.

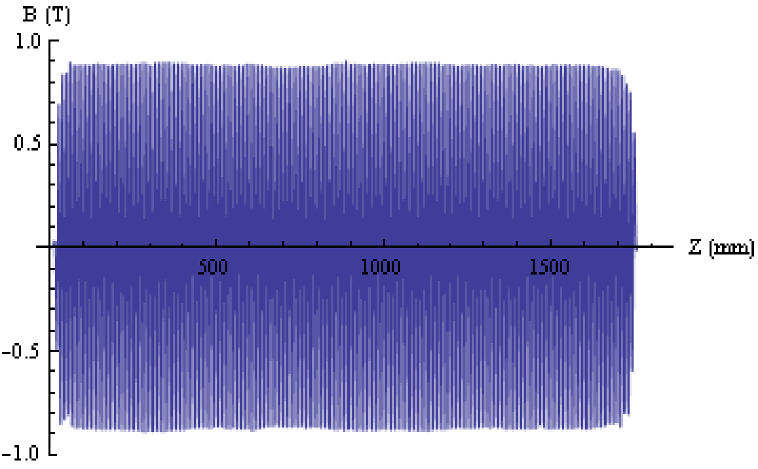
S Carr

Undulator Cryomodule (2)



Undulator: Field test

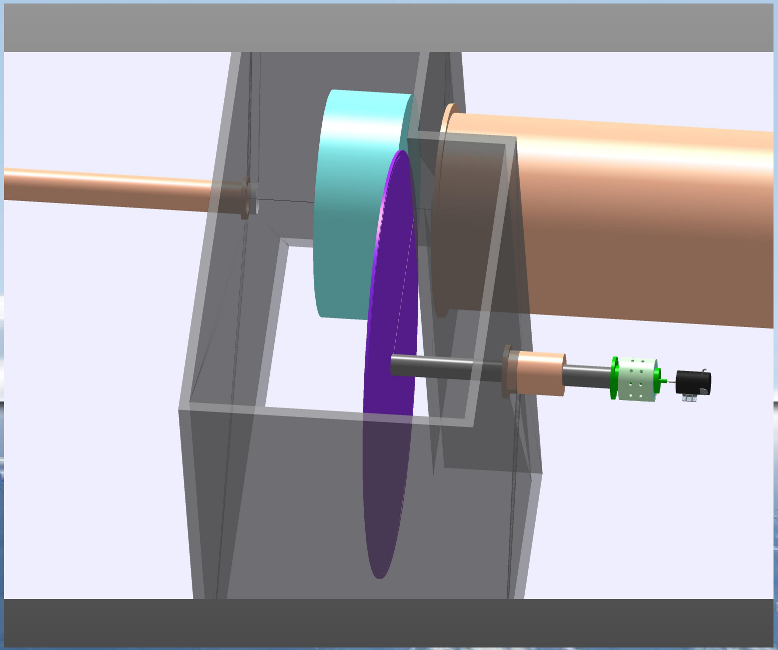


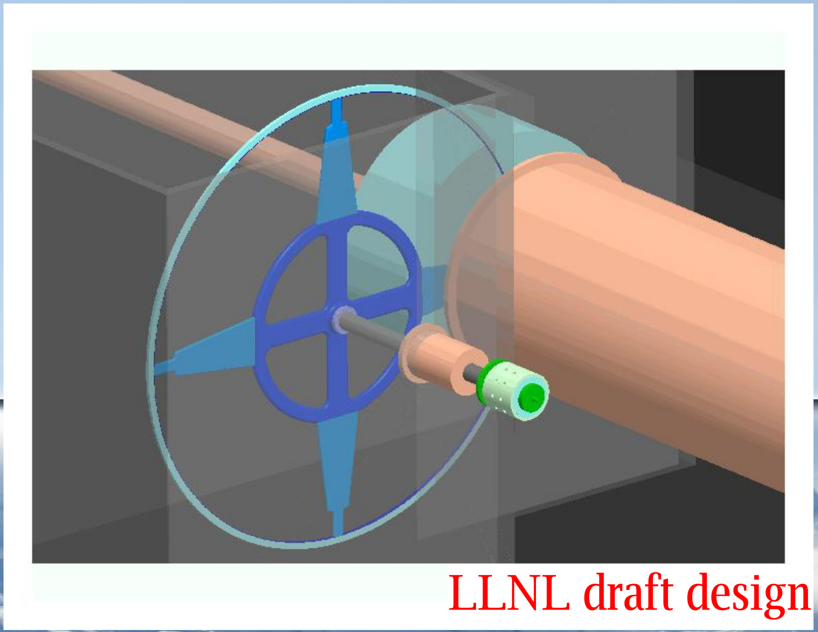


- All two magnets finally satisfied the specification.
- Field profile is measured by hall probe, showing a good quality.

Target

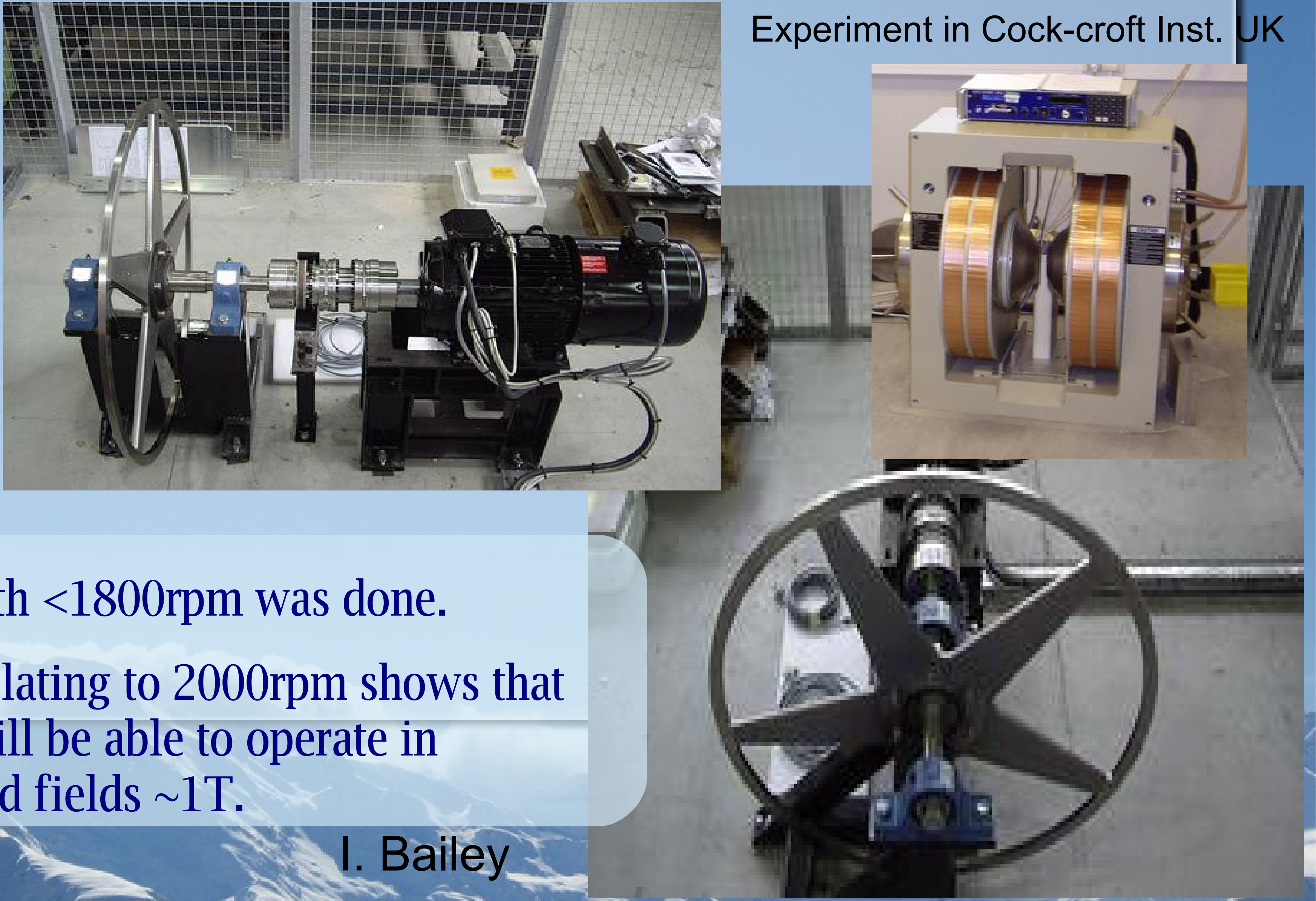
- Target : Ti-6% Al-4% V with 0.4 X_0, rotating with tangential speed 100 m/s .
- Beam spot : 15 mm
- Heat load by gamma : 18 kW
- Heat load by Eddy current :20kW (rim) when the target is immersed in B field.
- Vacuum seal is a technical issue.





LLNL draft design

Target Prototype



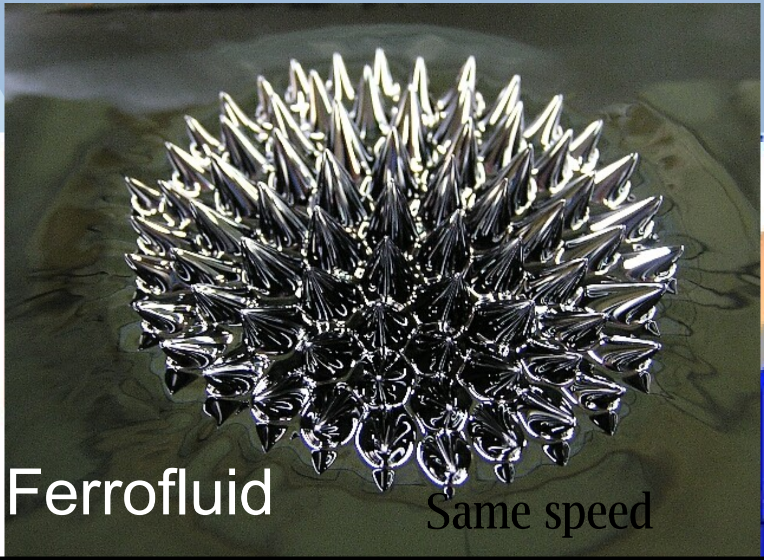
Experiment in Cock-croft Inst. UK

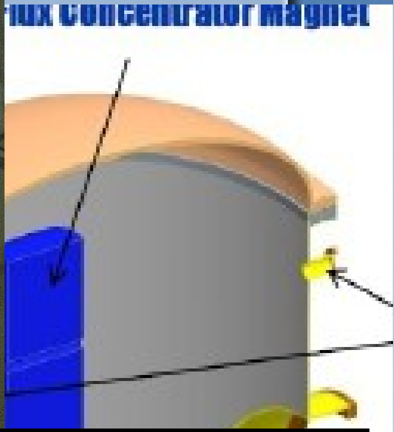
- Test with <1800rpm was done.
- Extrapolating to 2000rpm shows that wheel will be able to operate in immersed fields ~1T.

I. Bailey

Target Design

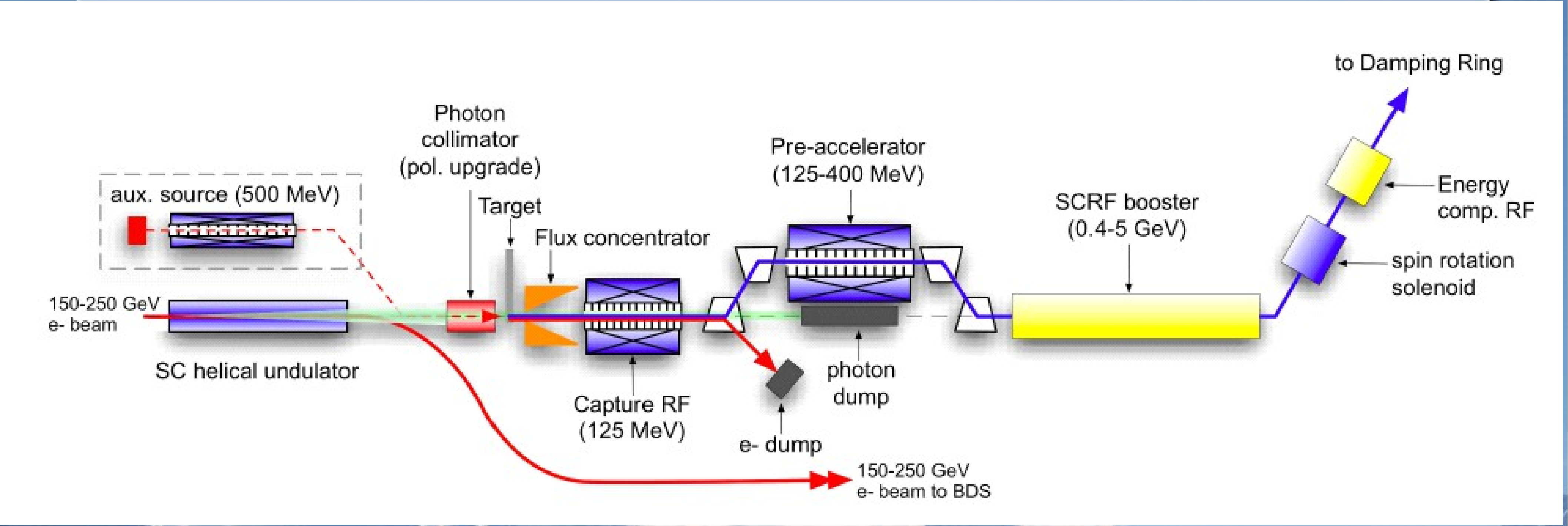
- The target should be fastly rotated (100m/s, 2000rpm) in high vacuum, 1e-7Pa.
- We need a good vacuum seal with the rotation rod.
- Magnetic fluid seal is a candidate.
- Need a system integration to demonstrate the technical feasiblity.



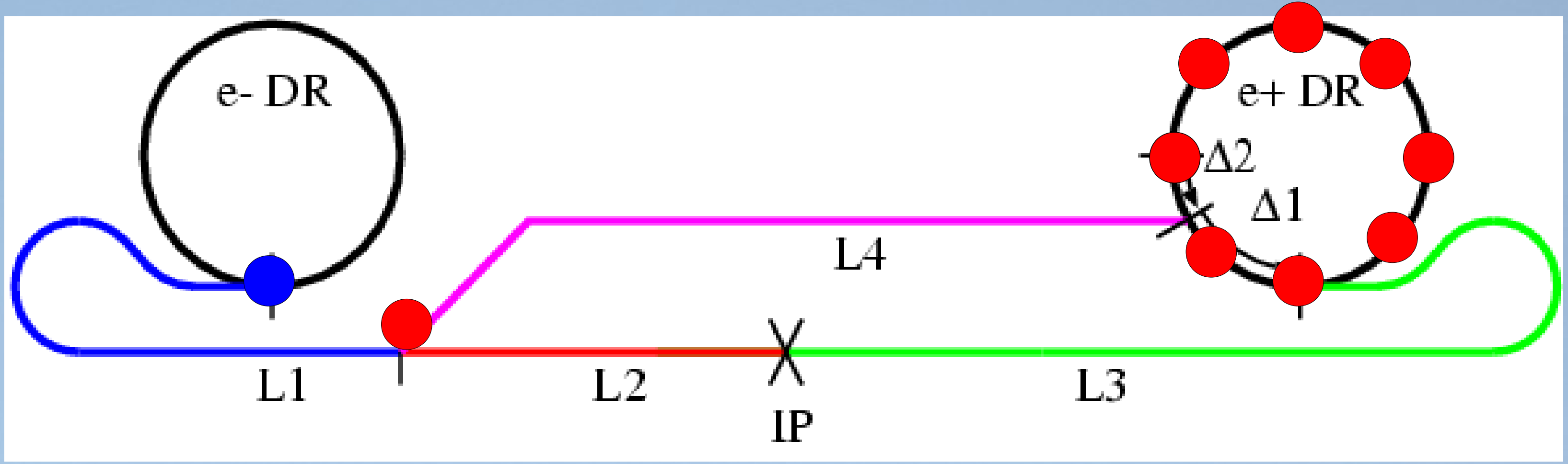


JR East

ILC Undulator Positron Source Layout



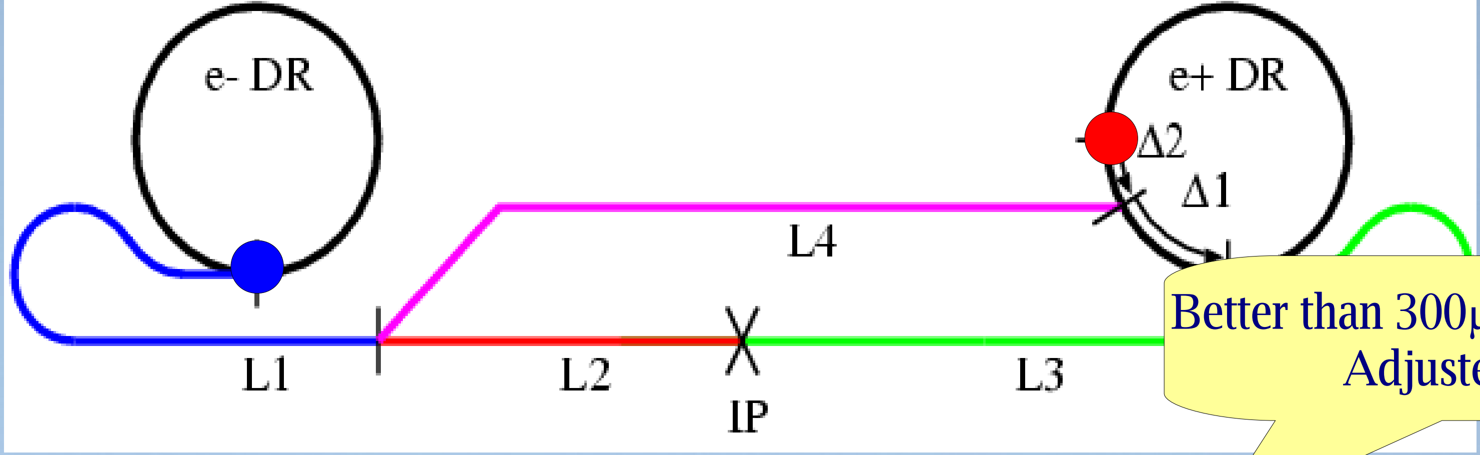
Path Length Condition



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

Pathlength condtion:

Self-reproduction + collission



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

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

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

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

Physical path length has to be adjusted.

Adjustment

Installation accuracy OPERA's study

- 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.
- To examine the super-light speed nutrino, distance from the tunnel entrance to OPERA detector was measured with survey mete, 10.5km±20cm.
- The accuracy in 15km ILC tunnel could be 30cm, worse than 5mm.

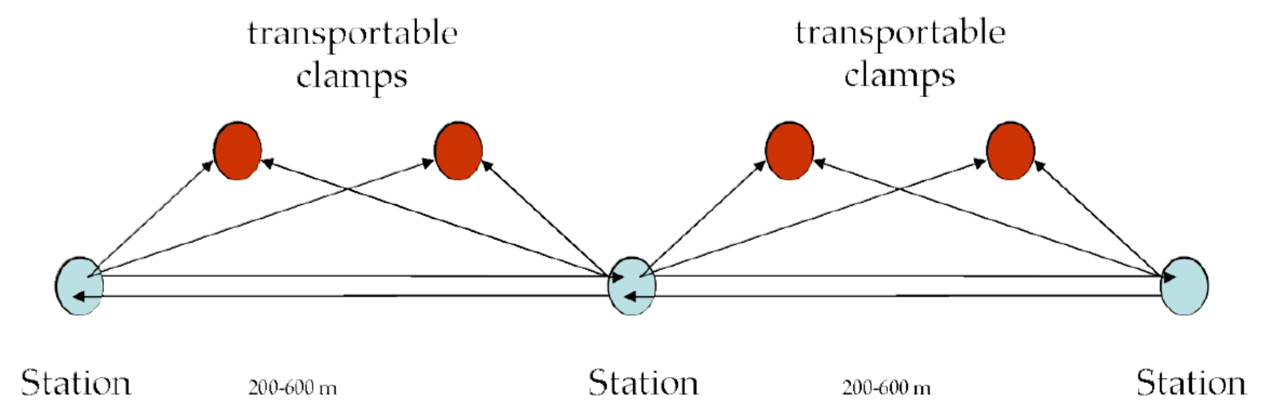
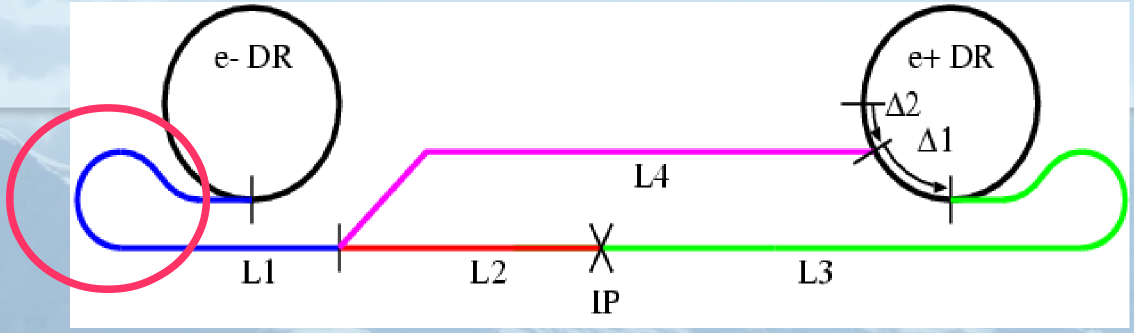


Figure 2: The traverse surveying pattern

OPERA　Public Note132 v3

Pathlength Adjustment

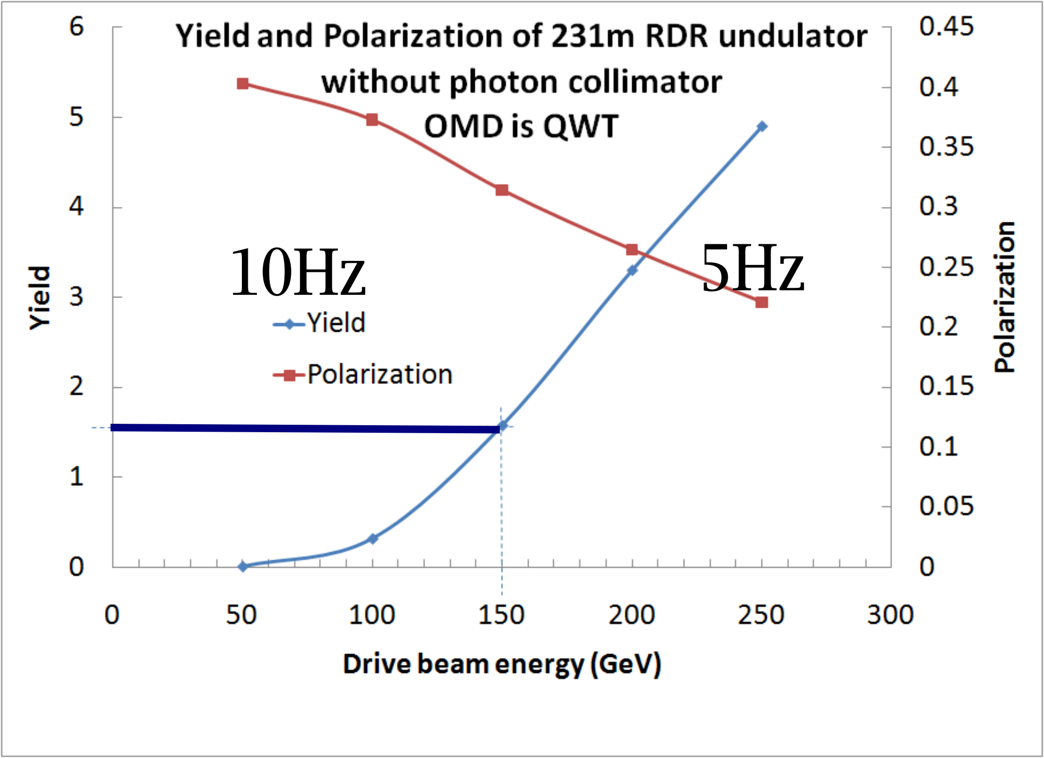
- To adjust 30cm by 50 chicane sections with 1m shift, the total length could be 1500m. It is unrealistic.
- DR circumference C_{DR} can be adjusted by RF frequency with extremely good accuracy. In early comissioning, the adjustment length can be estimated by varying C_{DR}.
- The physical pathlength 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.



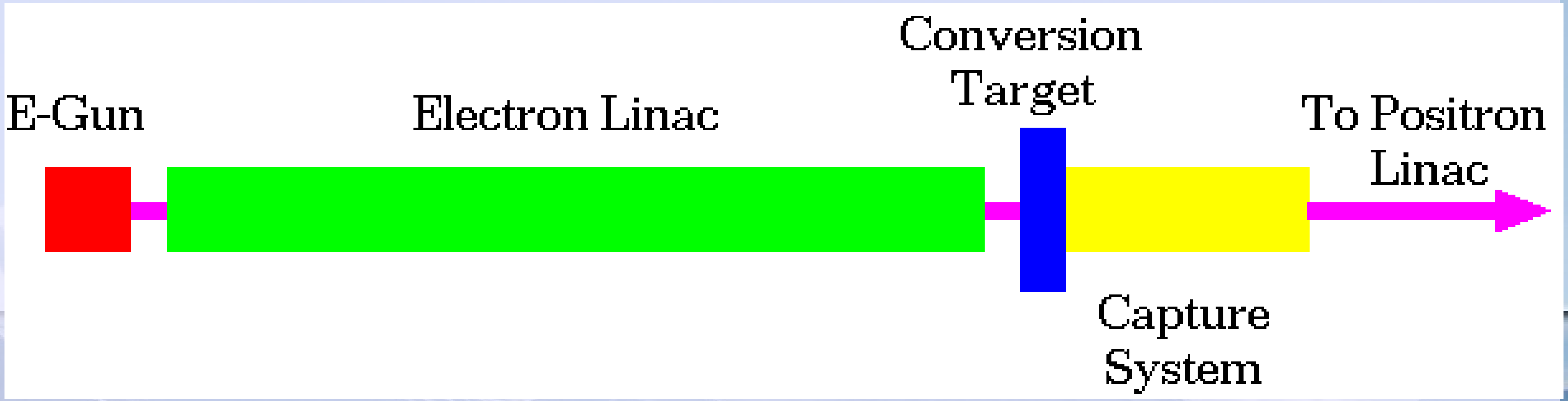
Alternate Linac Operation

Need more electricity

Energy	Reaction	Physics Goal	Linac
91 GeV	$e^+e^-\to Z$	ultra-precision EW	10Hz
160 GeV	$e^+e^-\to WW$	ultra-precision Wmass	10Hz
250 GeV	$e^+e^-\to Zh$	precision Higgs coupling	10Hz
350-450 GeV	$e^+e^-\to tt$ $e^+e^-\to WW$ $e^+e^-\to \nu\bar{\nu}h$	top quark mass and coupling precision W coupling precision Higgs coupling	5Hz
500 GeV	$e^+e^-\to f\bar{f}$ $e^+e^-\to t\bar{t}h$ $e^+e^-\to Zhh$ $e^+e^-\to \tilde{\chi}\tilde{\chi}$ $e^+e^-\to AH, H^+H^-$	precision search for Z' Higgs coupling to top Higgs self coupling search for super-symmtery search for extended Higgs sector	5Hz
1000GeV	*and more..*		5Hz

Electron Driven Scheme

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



Why is it so diffucult?

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

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

#of bunch

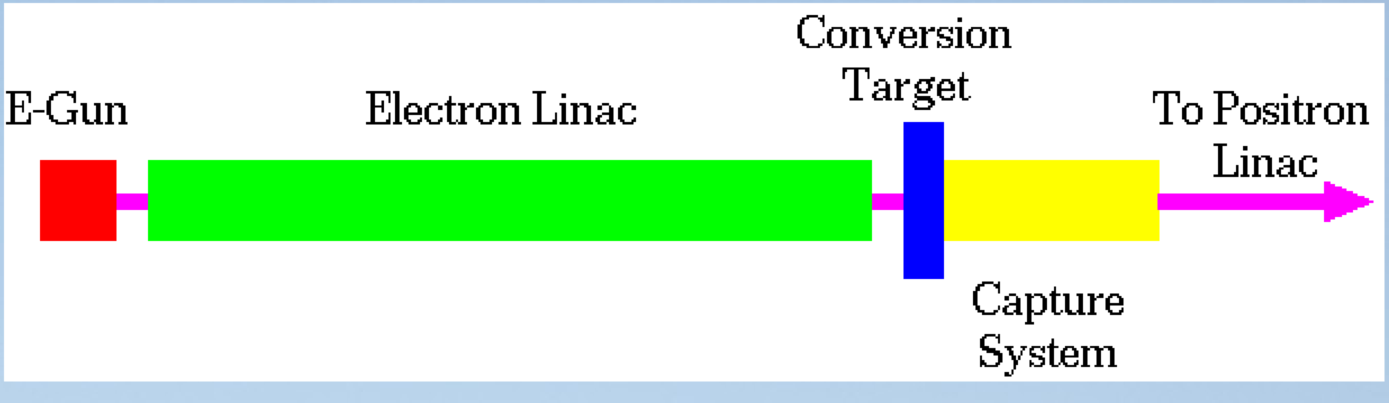
$$PEDD \sim \kappa \frac{E(GeV)Q(nC)}{V\rho} \frac{2r N_b}{vt_p}$$

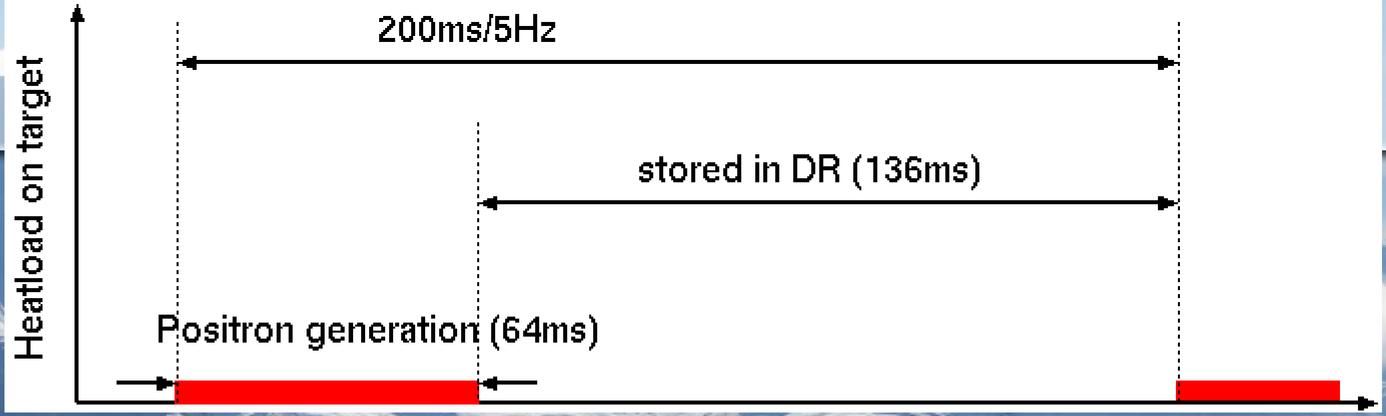
target speed

Pulse duration

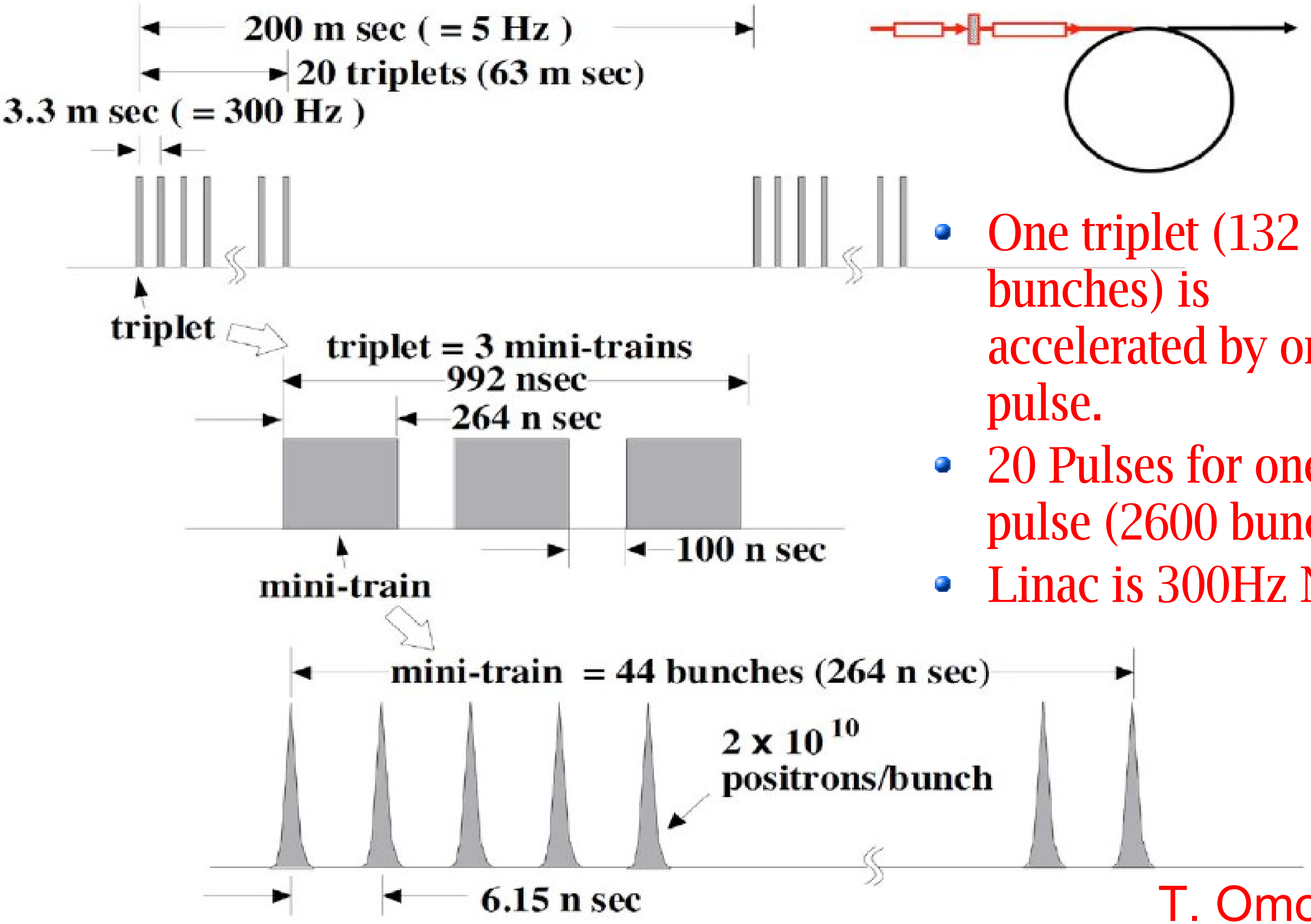
Pulse Structure Manipulation

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





300Hz Generation

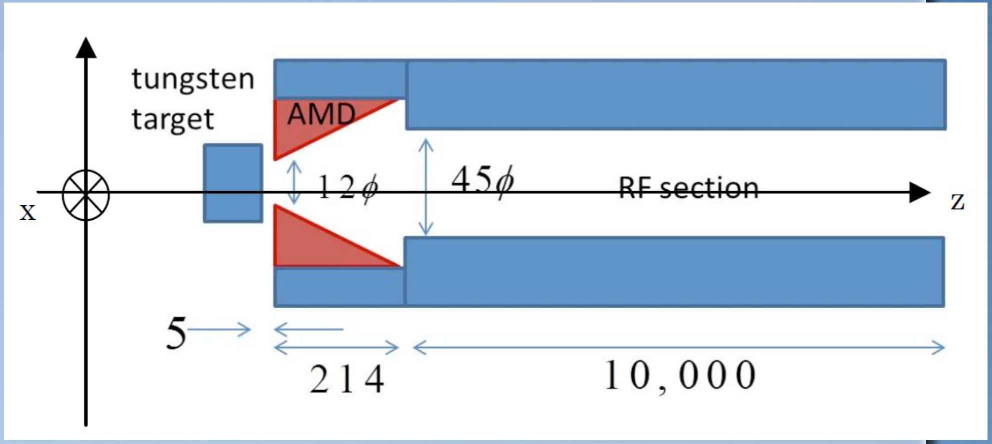


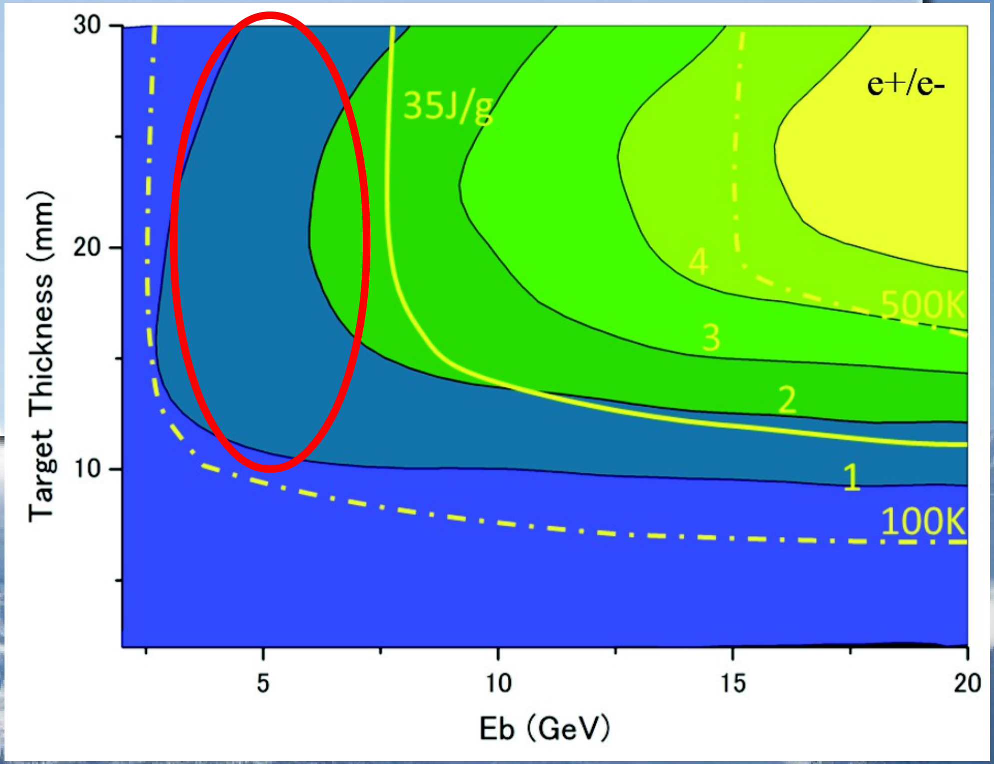
- One triplet (132 bunches) is accelerated by one RF pulse.
- 20 Pulses for one ILC pulse (2600 bunches).
- Linac is 300Hz NC.

T. Omori

Target PEDD

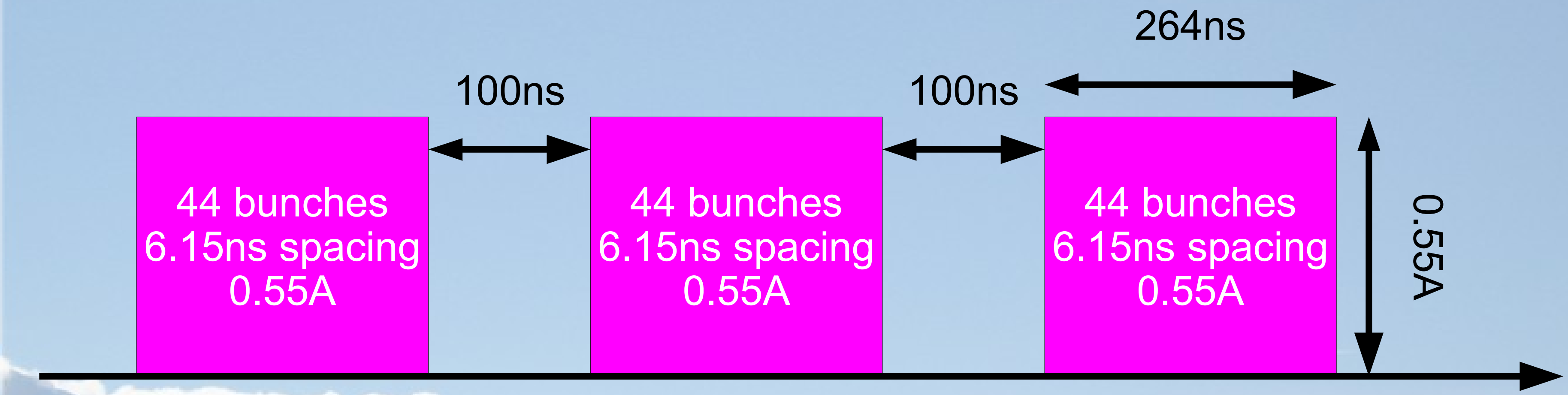
- Because there is no overlap between triplets, we consider only PEDD by one triplet.
- Energy by one triplet (132 bunches) deposited on a same spot.
- PEDD and e+ yield is evaluated.
- There is workable area;
  - PEDD < 35J/g
  - Yield e+/e- >1.5





Pulse Structure and Beamloading

- Positrons are accelerated by triplet multi-bunch pulse.
- The triplet pulse is repeated in 300Hz.
- Transient beamloading should be compensated, otherwise, the beam is not accepted by DR.



Beamloading Compensation by AM

- Beamloading compensation by AM (Amplitude Modulation) is considered.
- By solving RF enevelope giving a flat acceleration for the triplet, the acceleration field with the beamloading becomes flat.

Acceleration voltage by a flat RF (E_0),

Beamloading term

$$V(t) = E_0 L + \frac{r_0 L I_0}{2(1-e^{-2\tau})}\left[\frac{\omega}{Q} e^{-2\tau}(t-t_f) - 1 + e^{2\tau - \frac{\omega}{Q}t}\right].$$

To compensate the transient beamloading, AM is introduced as follows,

$$E(t) = E_0 U(t) + E_1 U(t-t_f) - E_2(t-t_f)U(t-t_f) + E_2(t-2t_f)U(t-2t_f),$$

For steady beam loading suppression

For transient beam loading suppression

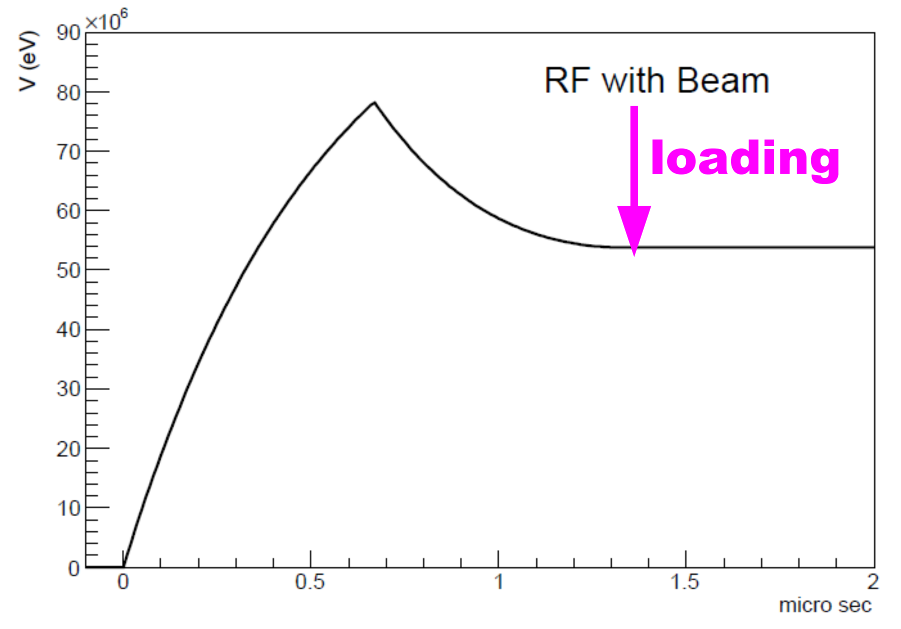
Beamloading Compensation by AM

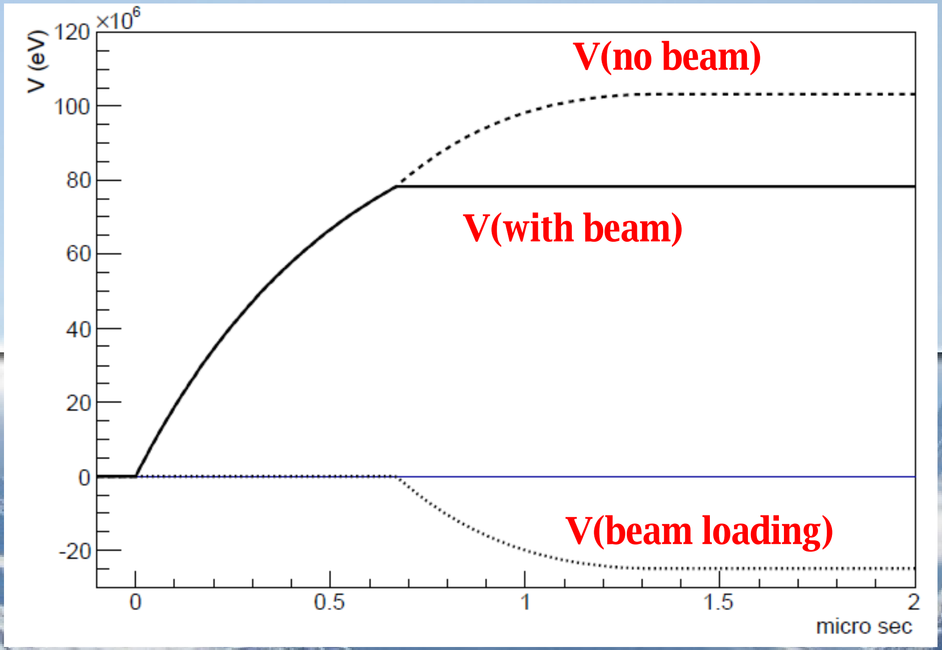
Acceleration voltage by AM RF ($E_0 + E_1 + E_2$),

$$\begin{aligned} V(t) &= E_0 L + \frac{L}{1-e^{-2\tau}}\left(E_1 + \frac{Q}{\omega}E_2\right)\left(1 - e^{-\frac{\omega}{Q}(t-t_f)}\right) - \frac{L}{1-e^{-2\tau}}E_2(t-t_f) \\ &\quad + \frac{r_0 L I_0}{2(1-e^{-2\tau})}\left[\frac{\omega}{Q}(t-t_i) - 1 + e^{-\frac{\omega}{Q}(t-t_f)}\right], \end{aligned}$$

Solution for the flat acceleration

$$\begin{aligned} E_1 &= \frac{r_0 I_0}{2}(1 - e^{-2\tau}), \\ E_2 &= \frac{r_0 I_0}{2}\frac{\omega}{Q}e^{-2\tau}, \end{aligned}$$

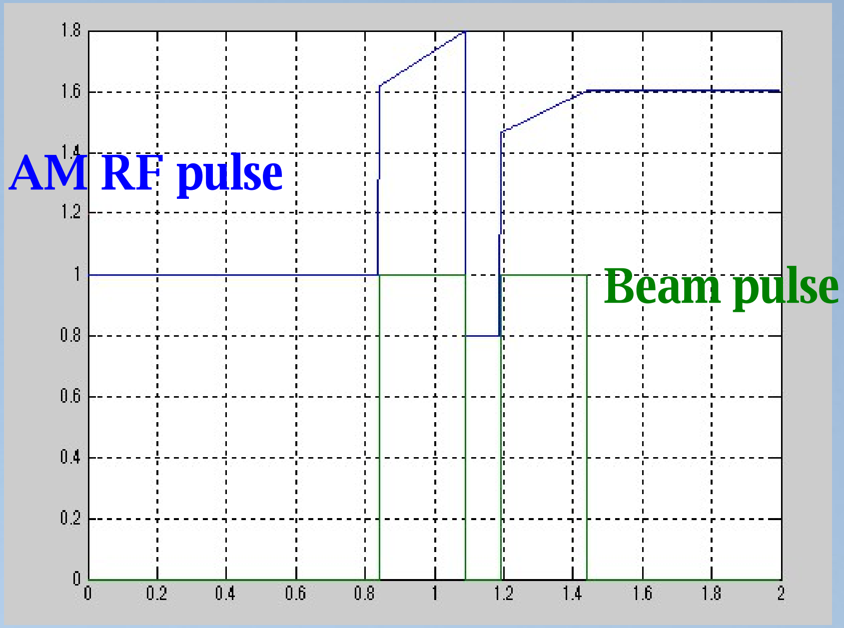


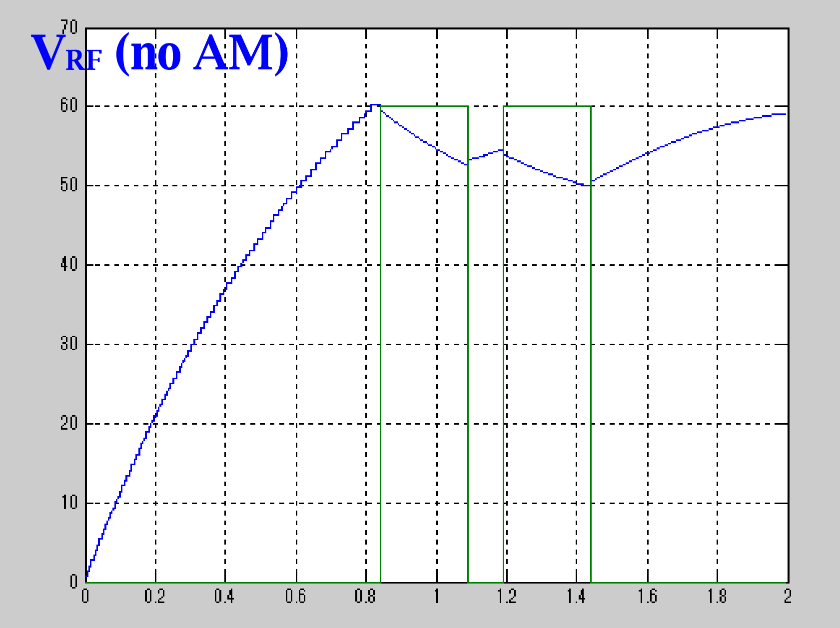


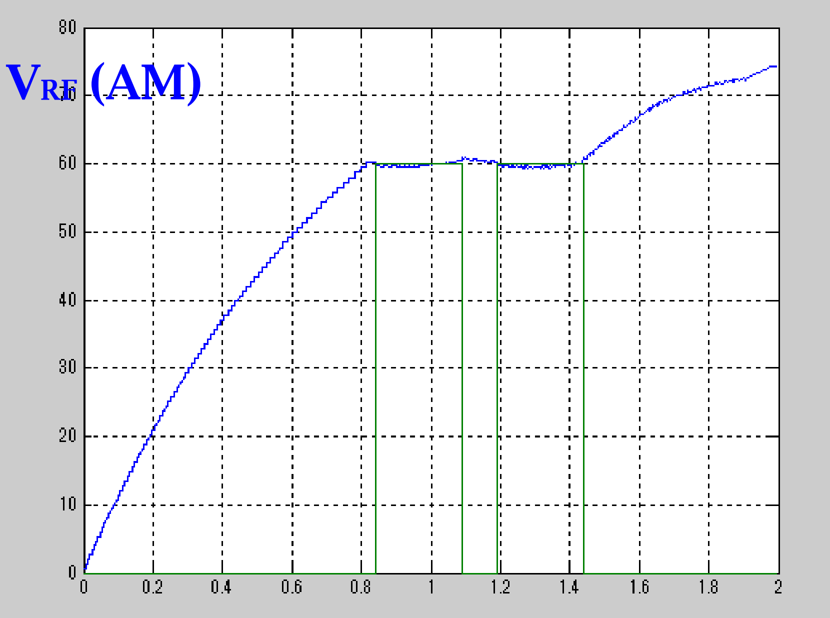
Multi-Pulse Acceleration

M. Satoh

- Same method can be extended to the multi-pulse case.
- AM should be applied to not only on the pulse head, but also pulse interval;

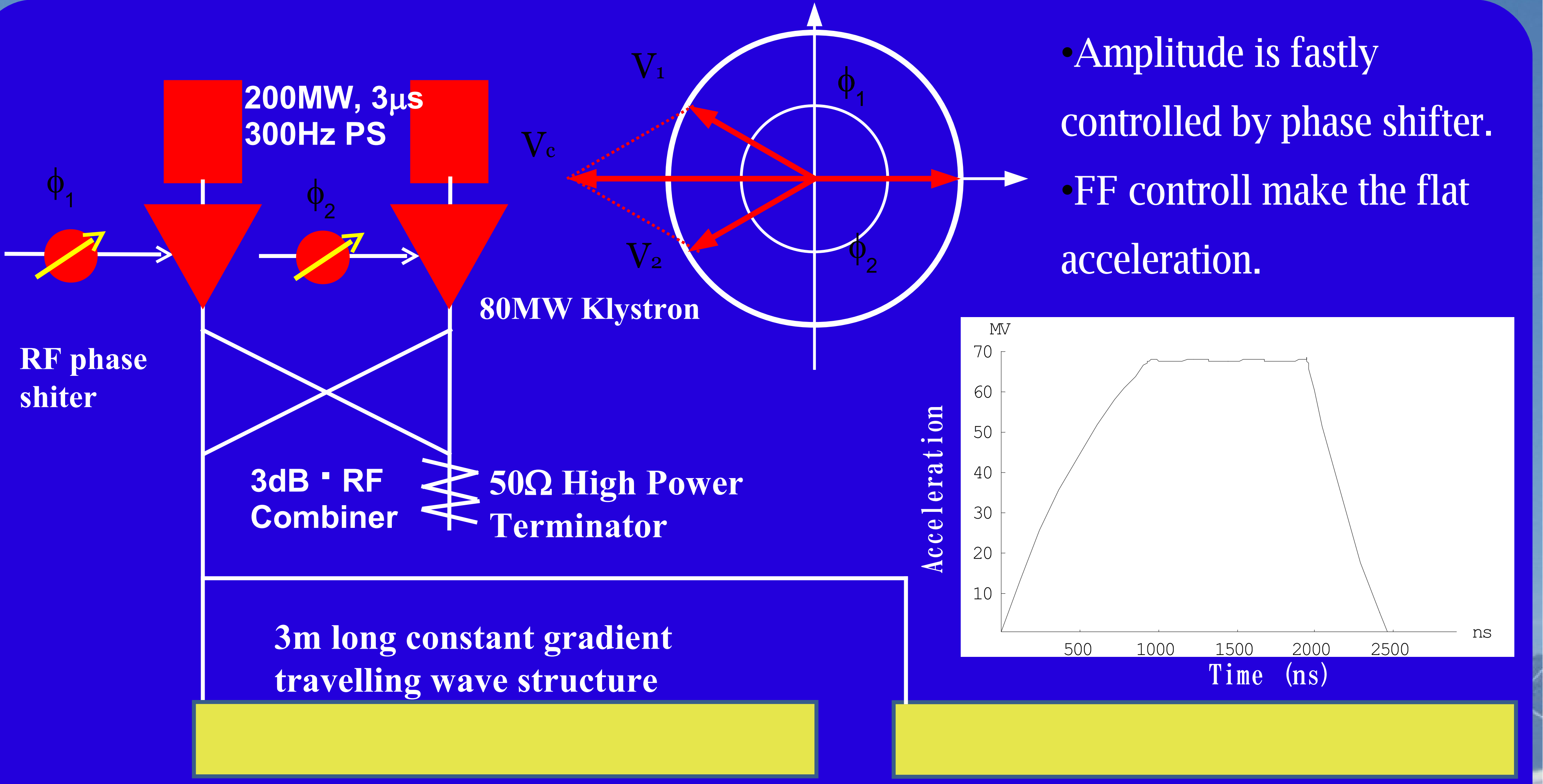






AM by phase shift

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



Positron Capture Simulation

- By assuming the beamloading compenstaion, any loading effect is not involved.
- e+ distribution was made by GEANT4.
- Tracking simulation in the injector section (<250MeV) by GPT; AMD positron capture (B_0~7.0T) followed by solenoid focusing section (0.5T) with S-band Acceleration tube (25MeV/m).
- Booster linac and EC (Energy Compressor) is treated as linear transformation.

e$^-$ linac

e+ capture

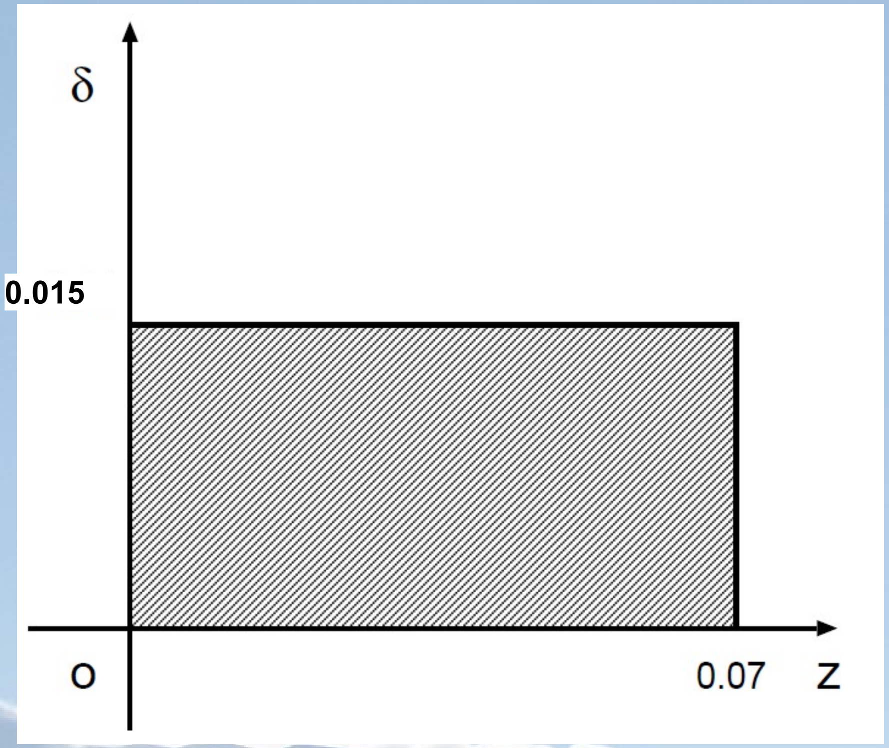
e+ booster

EC

DR

target

DR acceptance



- DR acceptance is
  - $\gamma A_x + \gamma A_y < 0.07$m
  - dE<1.5%, dz<0.07m (FW)
- By considering RF acceleration in S or L-band, wider dE is desirable even with less dz.

Phase-space Matching with EC

- EC (Energy Compressor is a reverse process of bunch compressor.
- Bunch compressor : energy spread → large, bunch length → short.
- Energy compressor: energy spread → short, bunch length → large

Bunch compressor

$$\begin{bmatrix} z(s) \\ \delta(s) \end{bmatrix} = \begin{bmatrix} 1 & R_{56} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} z(0) \\ \delta(0) \end{bmatrix}$$

$$= \begin{bmatrix} 0 & R_{56} \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} z(0) \\ \delta(0) \end{bmatrix}$$

Energy compressor

$$\begin{bmatrix} z(s) \\ \delta(s) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} 1 & R_{56} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} z(0) \\ \delta(0) \end{bmatrix}$$

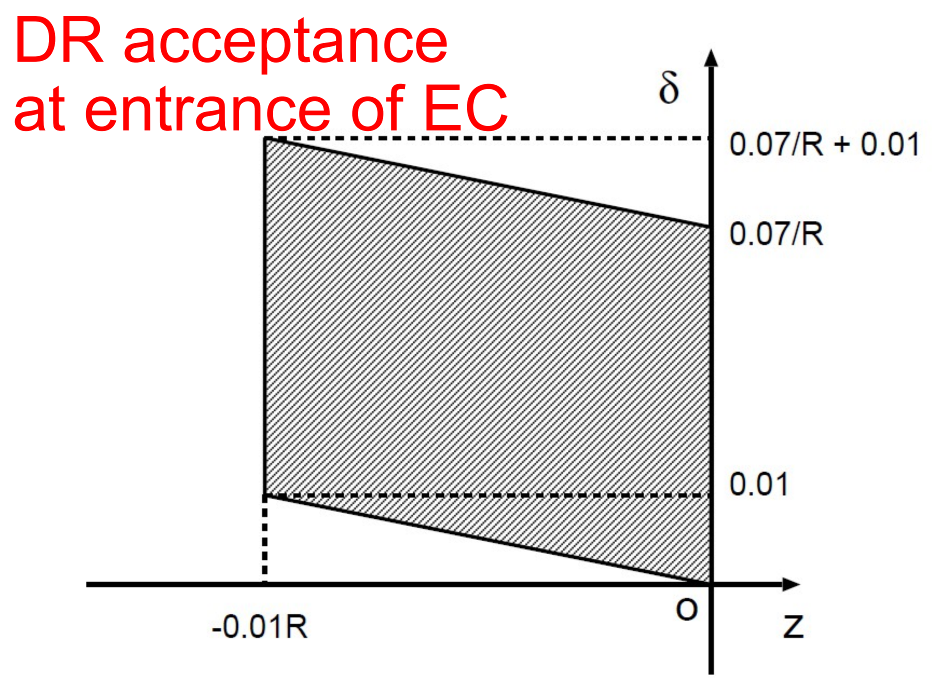
$$= \begin{bmatrix} 1 & R_{56} \\ R_{65} & 0 \end{bmatrix} \begin{bmatrix} z(0) \\ \delta(0) \end{bmatrix}$$

Phase-space Matching with EC

- Transfer matrix of EC ($R \equiv R_{56}$).
- r_1(EC entrance) is written by r_2 (EC exit).
- Effective DR acceptance is operable by EC(R).

$$M_{EC}(R)=\begin{bmatrix}1 & R\\ -1/R & 1\end{bmatrix}$$

$$r_1=\begin{bmatrix}1 & R\\ -1/R & 1\end{bmatrix}^{-1} r_2=\begin{bmatrix}-R\delta\\ \frac{z}{R}+\delta\end{bmatrix}$$


DR acceptance
at entrance of EC

Optimization

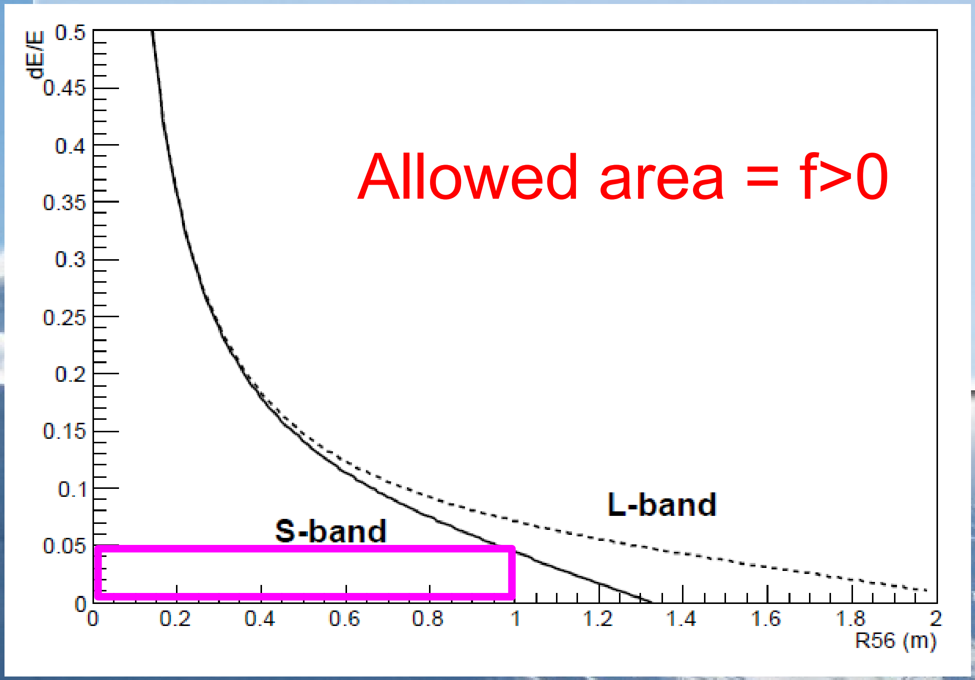
dE by RF

DR acceptance

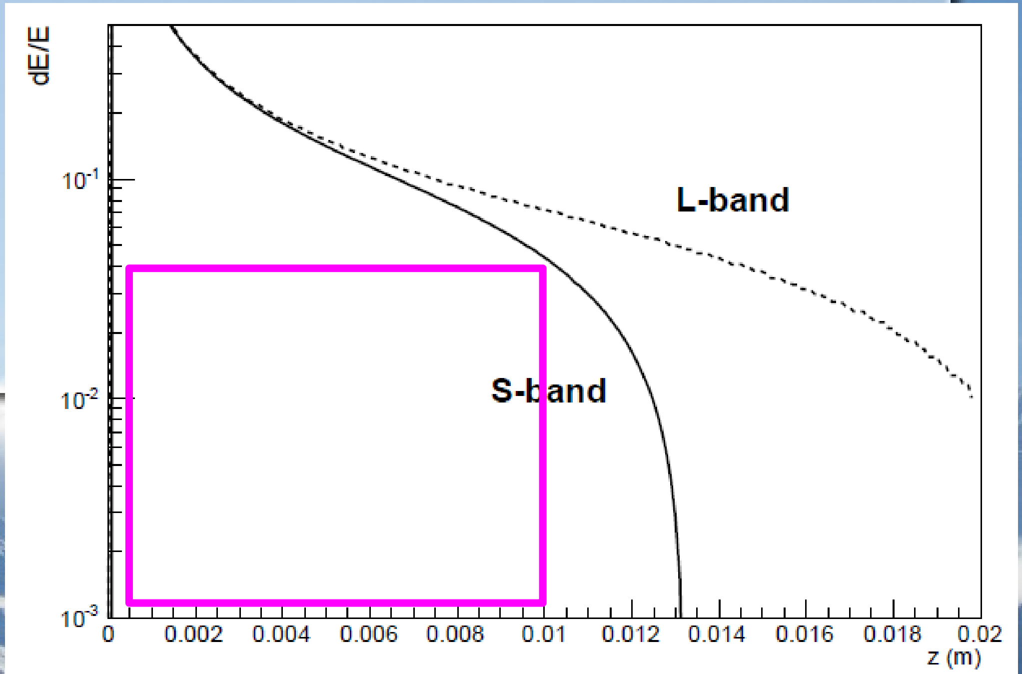
$$1-\cos\left(\omega\frac{0.015R}{2c}\right)+\delta<\frac{0.07}{R}+0.015$$

Initial dE

$$f(R)=\frac{0.07}{R}+0.015-1+\cos\left(\omega\frac{0.015R}{2c}\right)$$

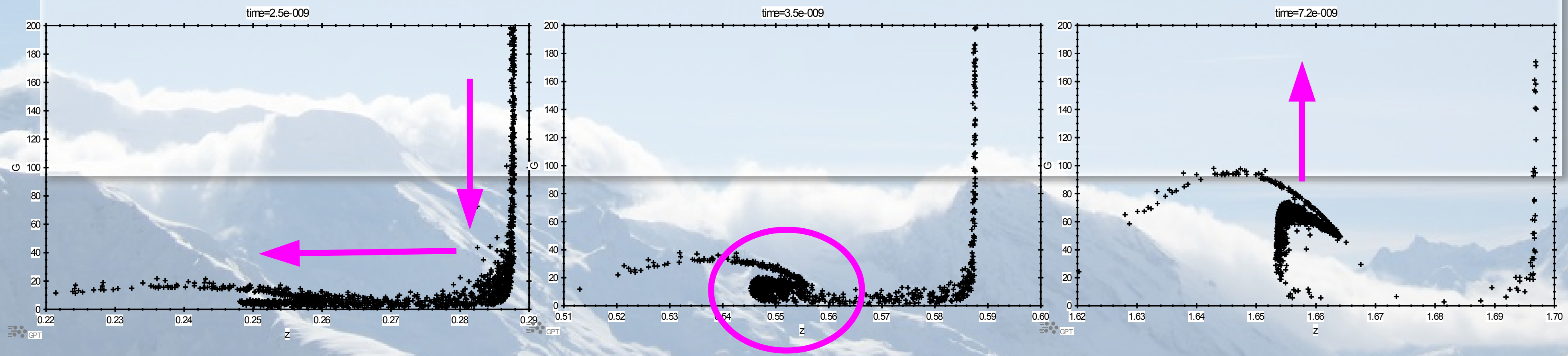


Allowed area = f>0



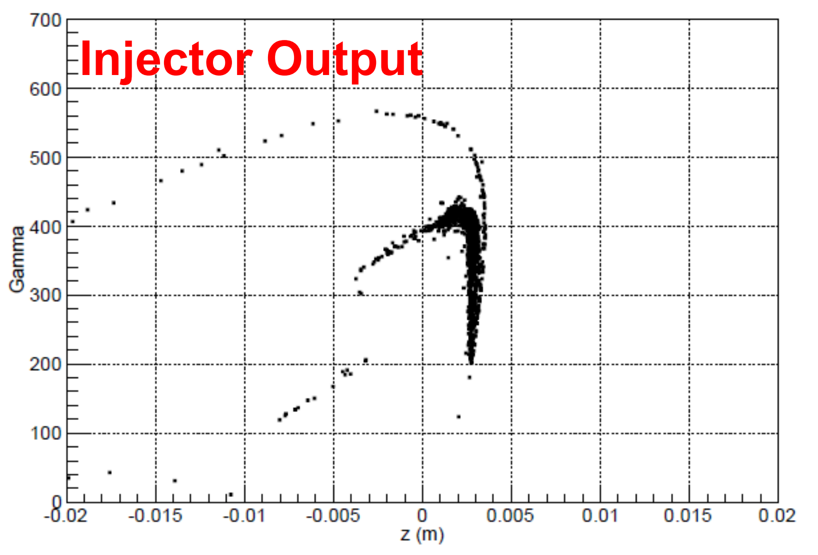
Decceleration Capture

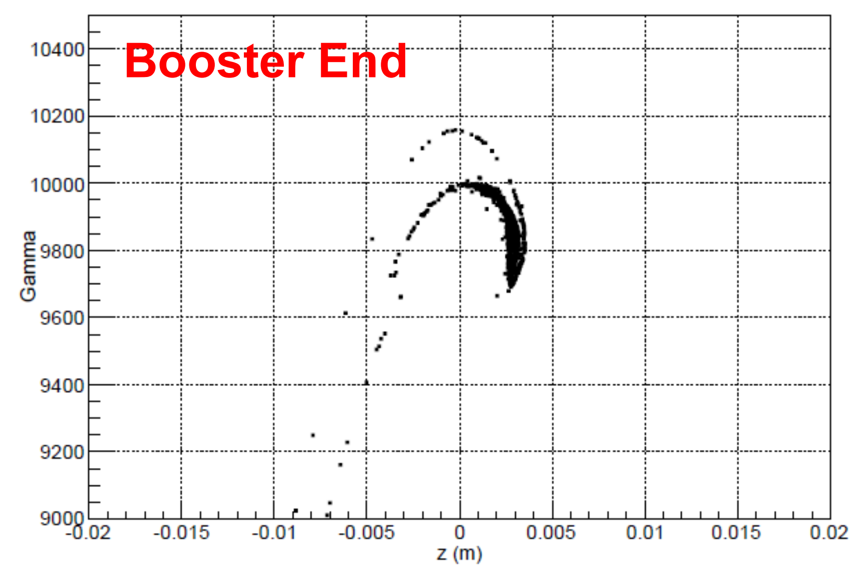
- The positron peak is on deceleration phase.
- These positrons are slipped down to the acceleration phase where these positrons are captured.
- Slight enhancement on the capture efficienty, and less longitudinal emittance (z-d).

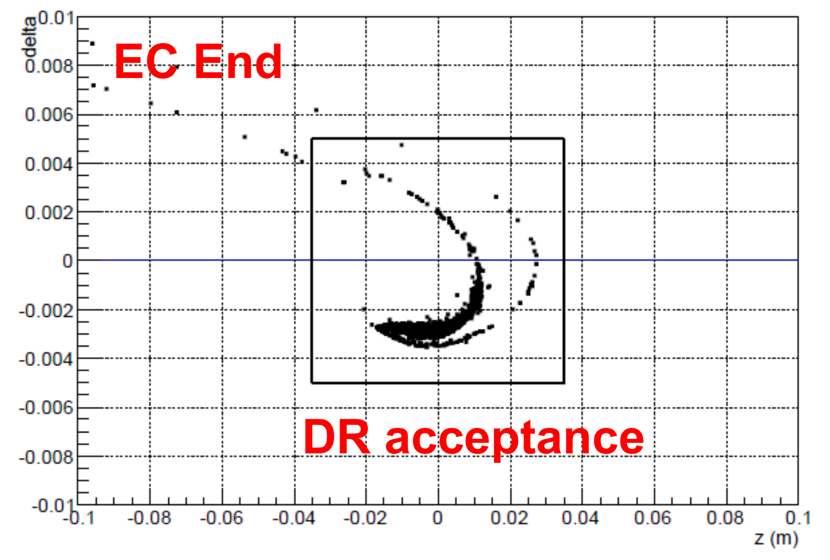


δ-z phase-space

- 1000 electrons on target.
- >8000 positrons are generated.
- 1100 positrons accepted by DR.
- The yield is 1.1 (e+/e-).
- 1.5 is likely to be realized by optimization.

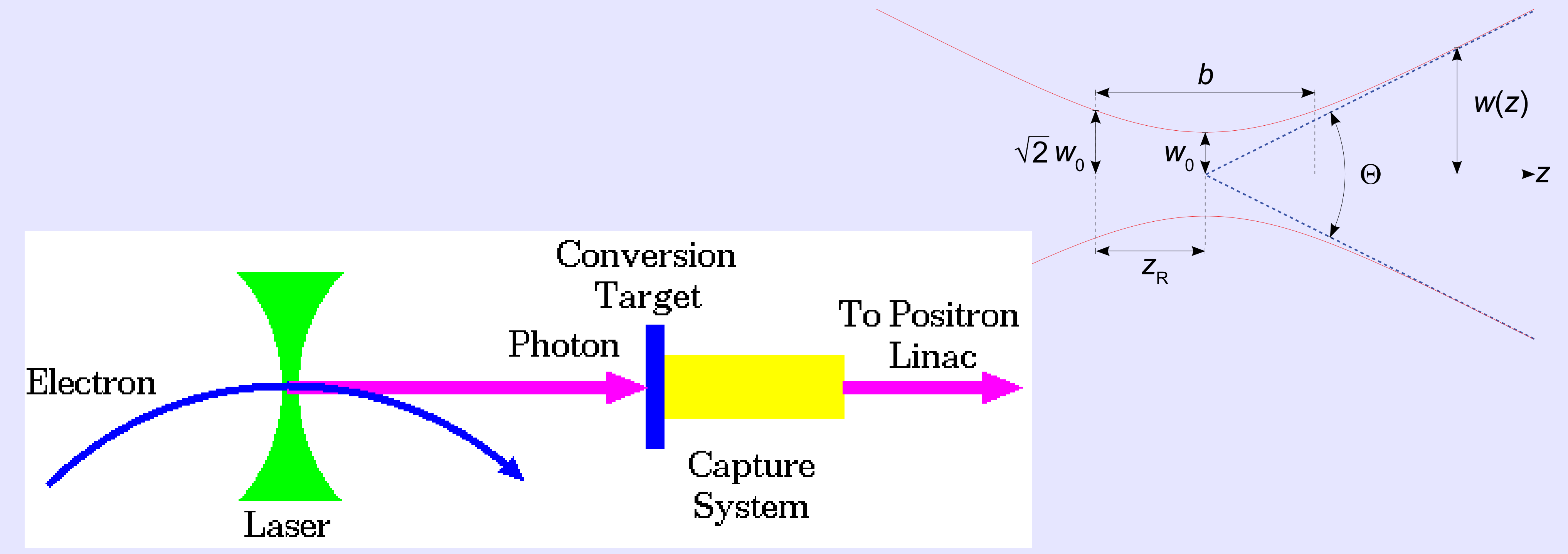






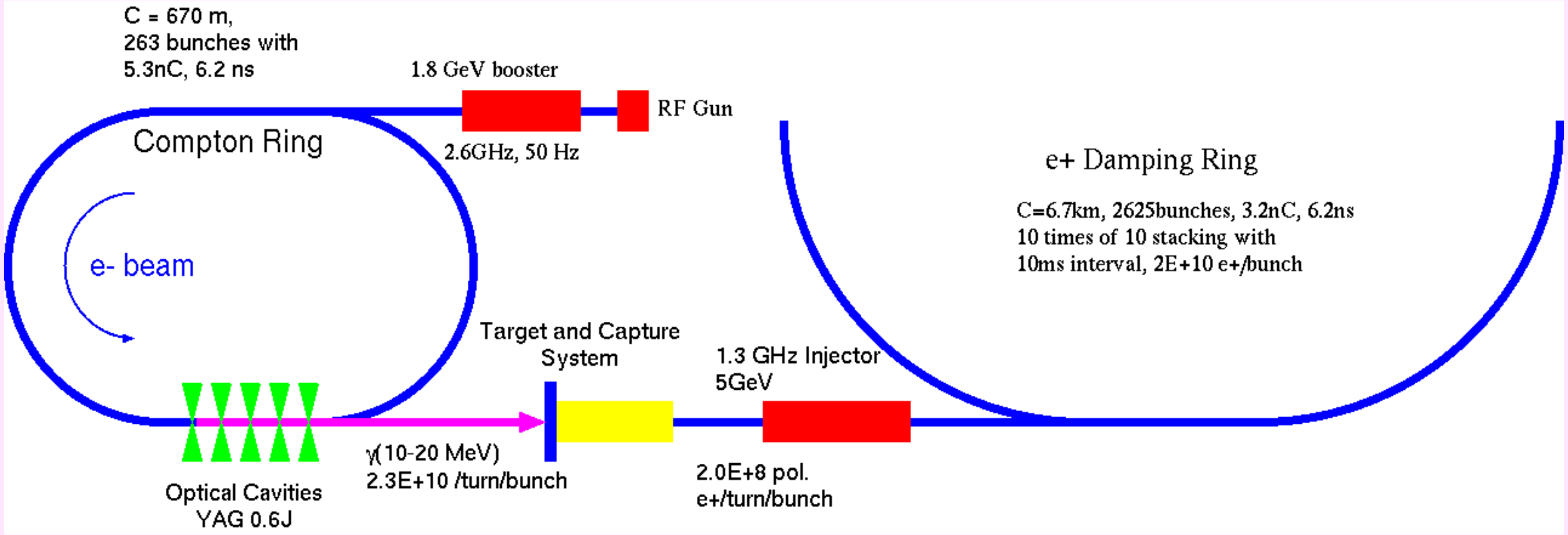
Laser Compton Scheme

- 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, because length of “Laser undulator” is limited to be Raylegh length.

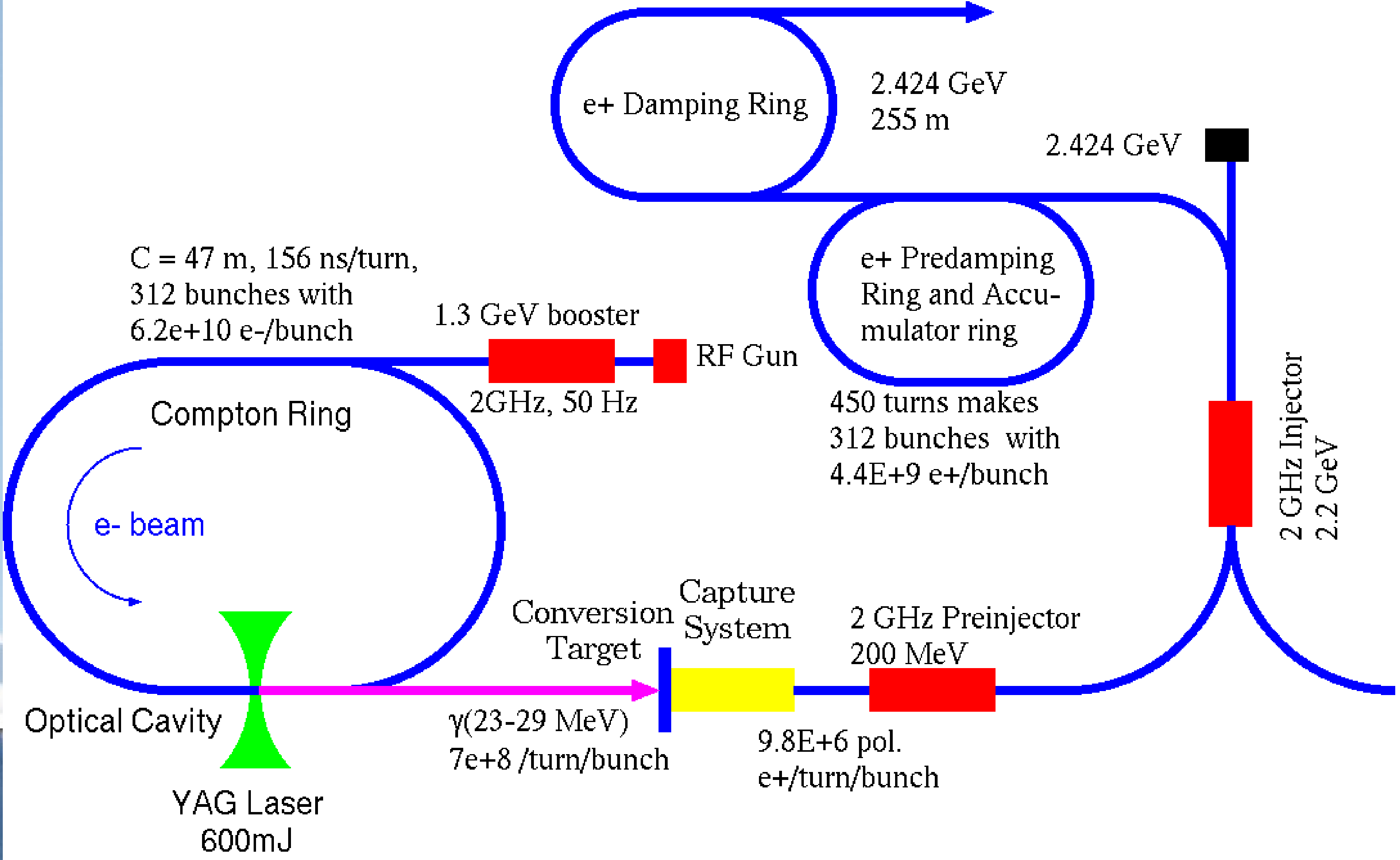


Compton Ring

- 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.

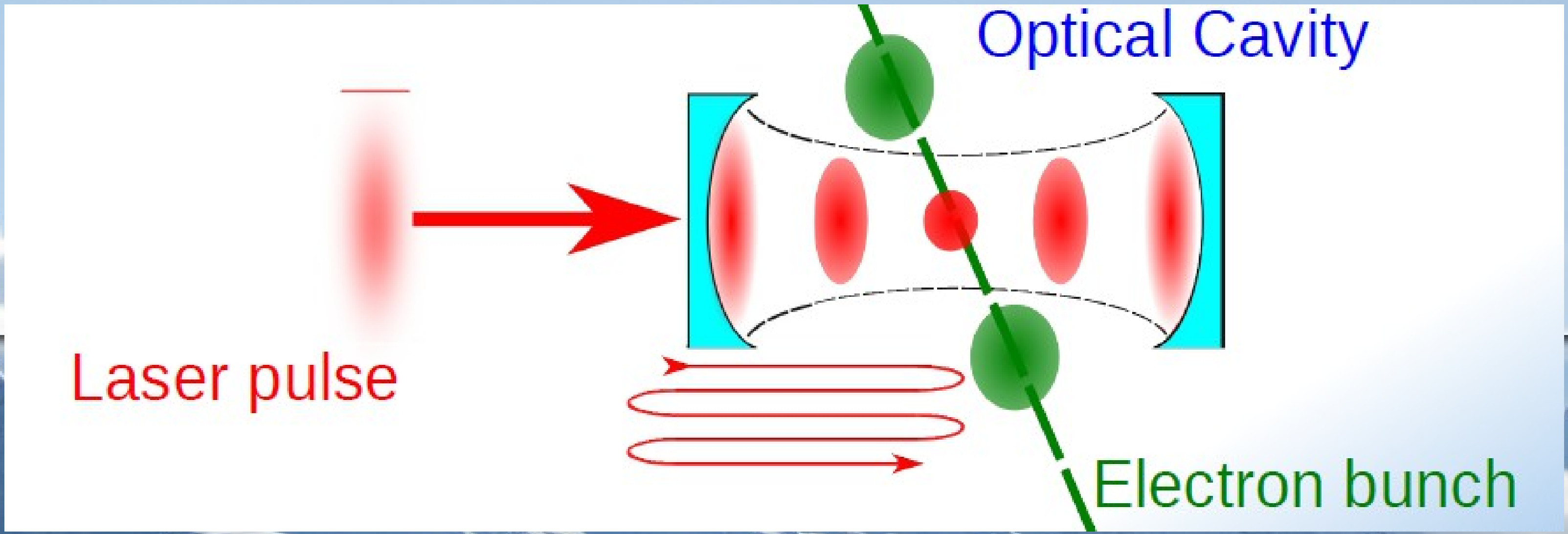


CLIC Compton Scheme



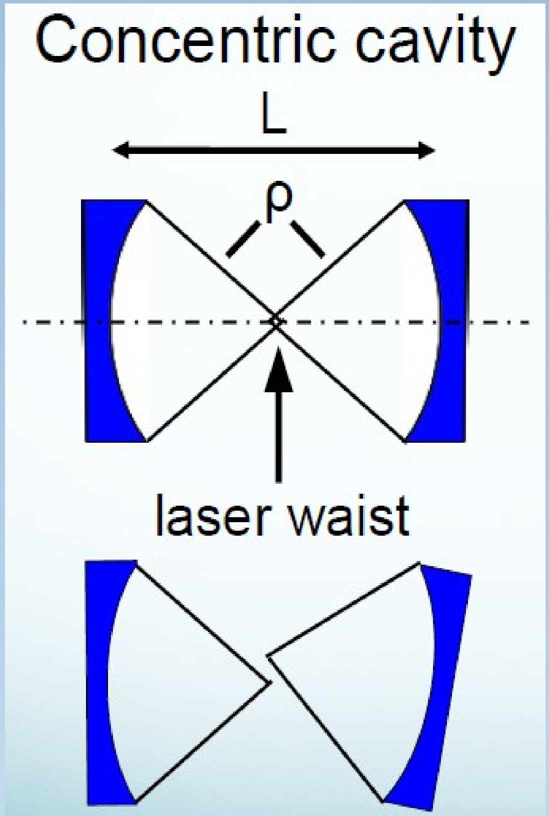
Pulse Stacking Cavity

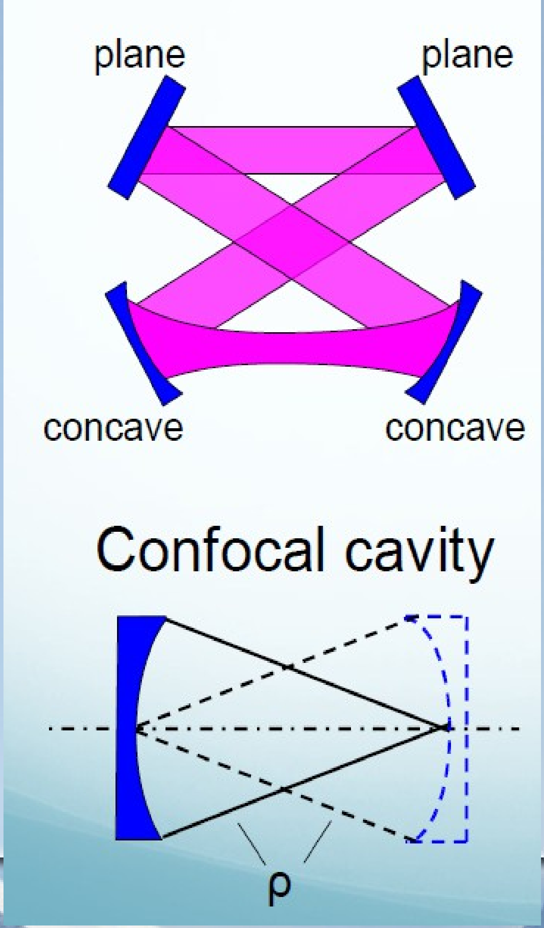
- Many laser pulses are stored and the power is enhanced by the pulse stacking.
- Pulsed laser is stacked when appropriate conditions of the external cavity are satisfied simultaneously for
  - Laser wave length $L_{cav}=m\frac{\lambda}{2}$
  - Mode-locking frequency $L_{cav}=nL_{rep}$



How many mirrors?

- 2 mirrors:
  - Simple,
  - unstable due to concentric geometry,
- 4 mirrors:
  - Complicated,
  - stable due to confocal geometry,

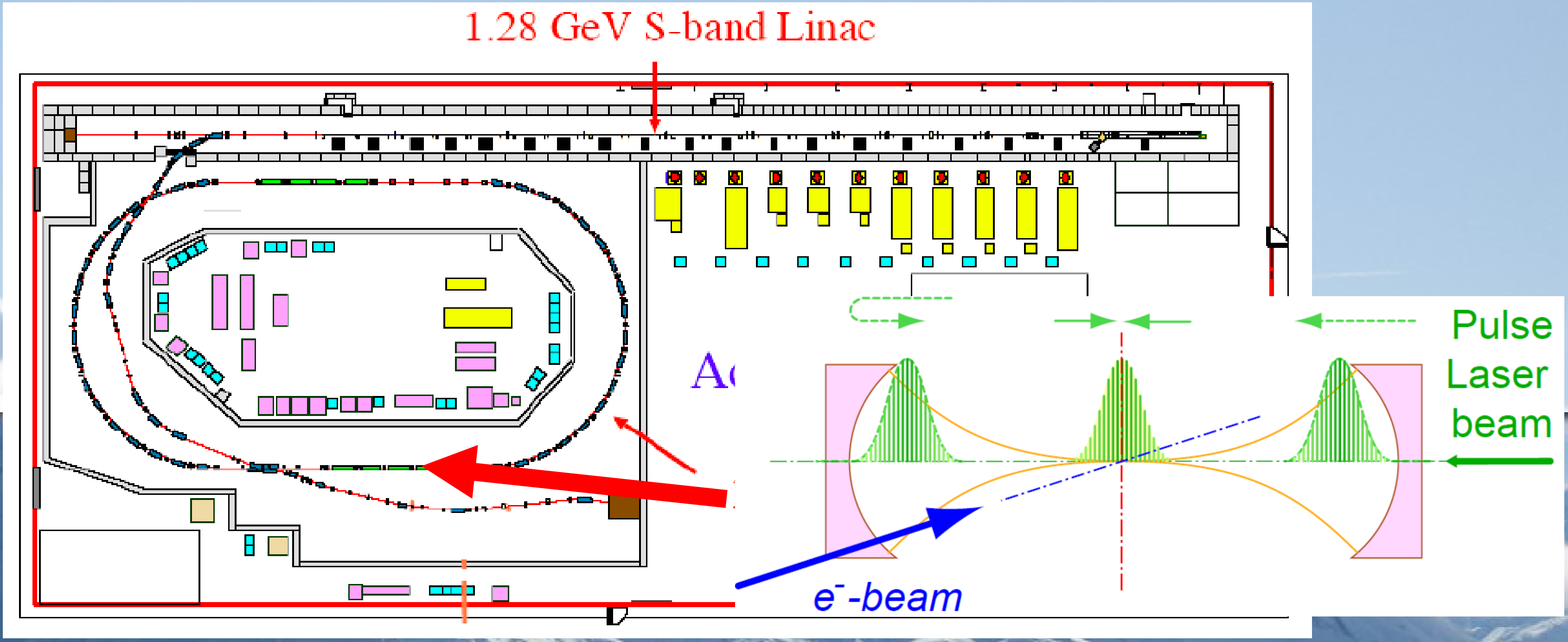




KEK-ATF experiment (1)

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.

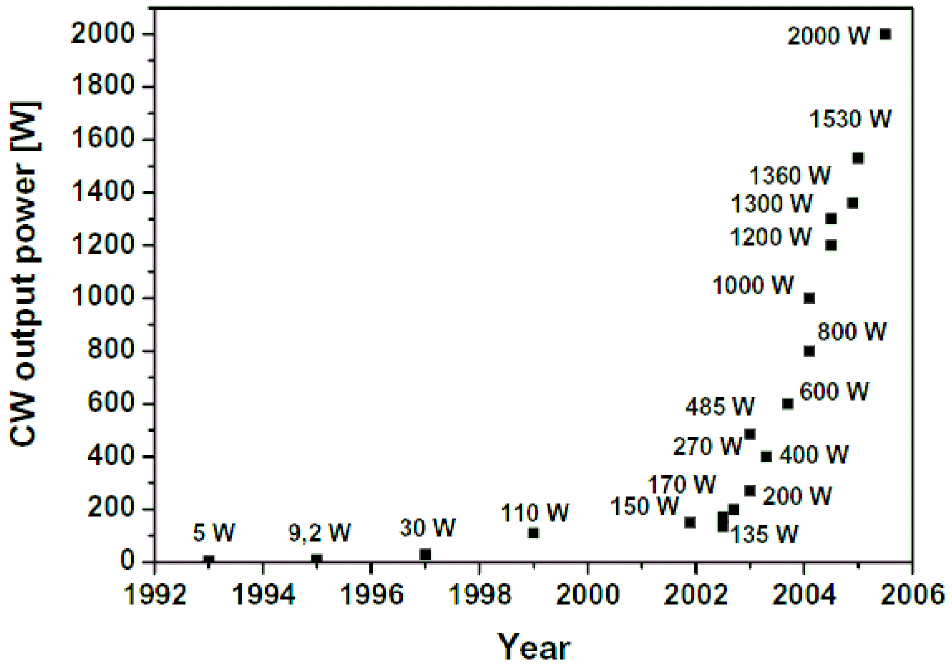
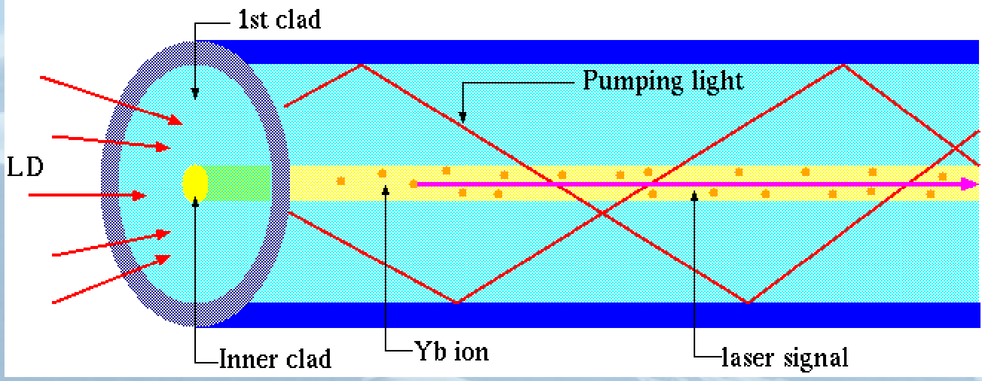


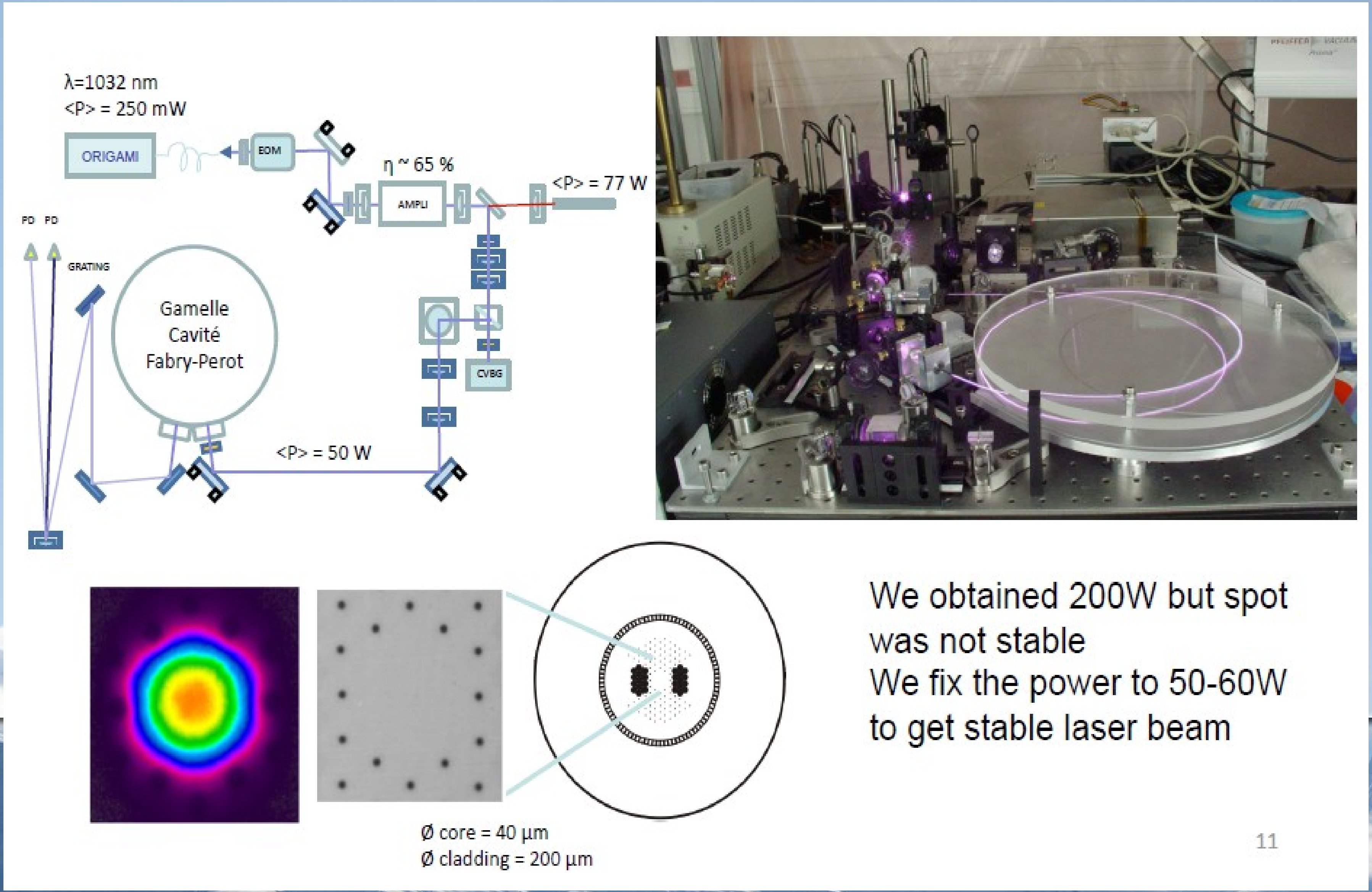
Fig. 4: Power evolution of cw double-clad fiber lasers with diffraction-limited beam quality over the last decade

J. Limpert



By M. Hanna

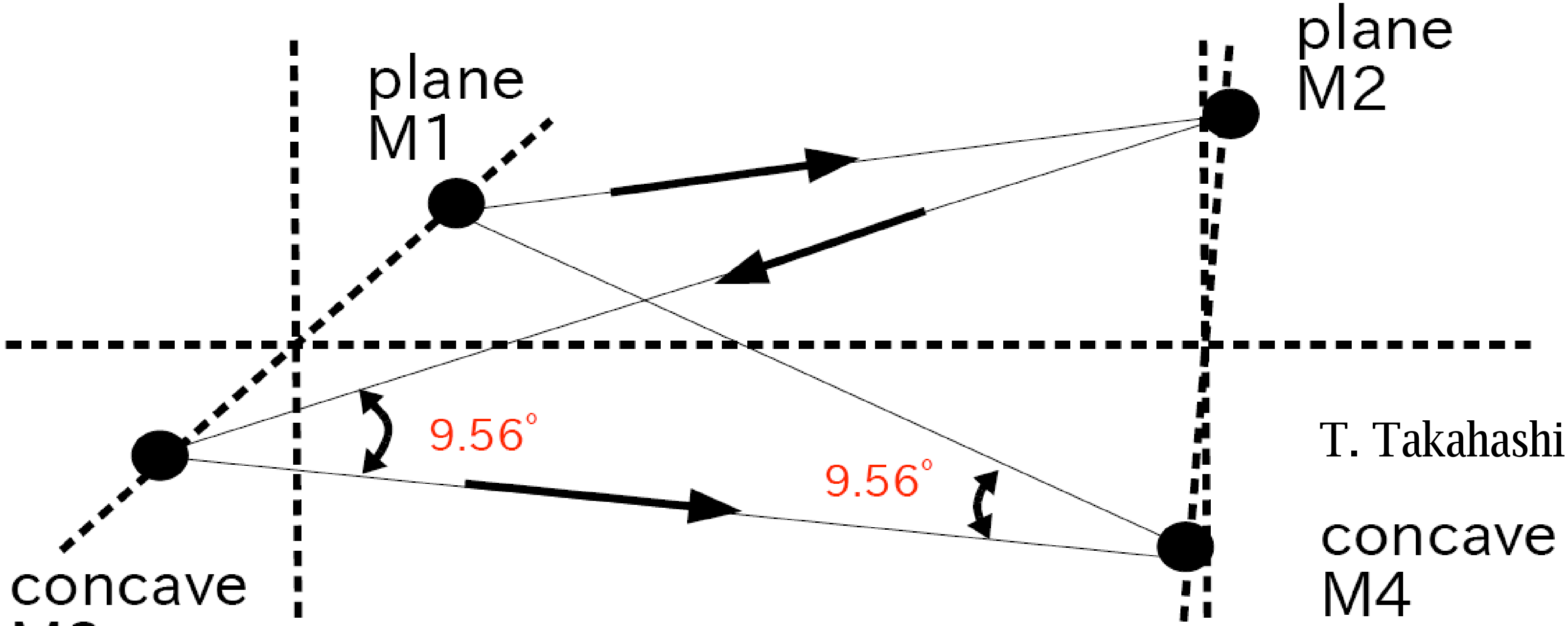
Fibre Laser (2)



We obtained 200W but spot was not stable

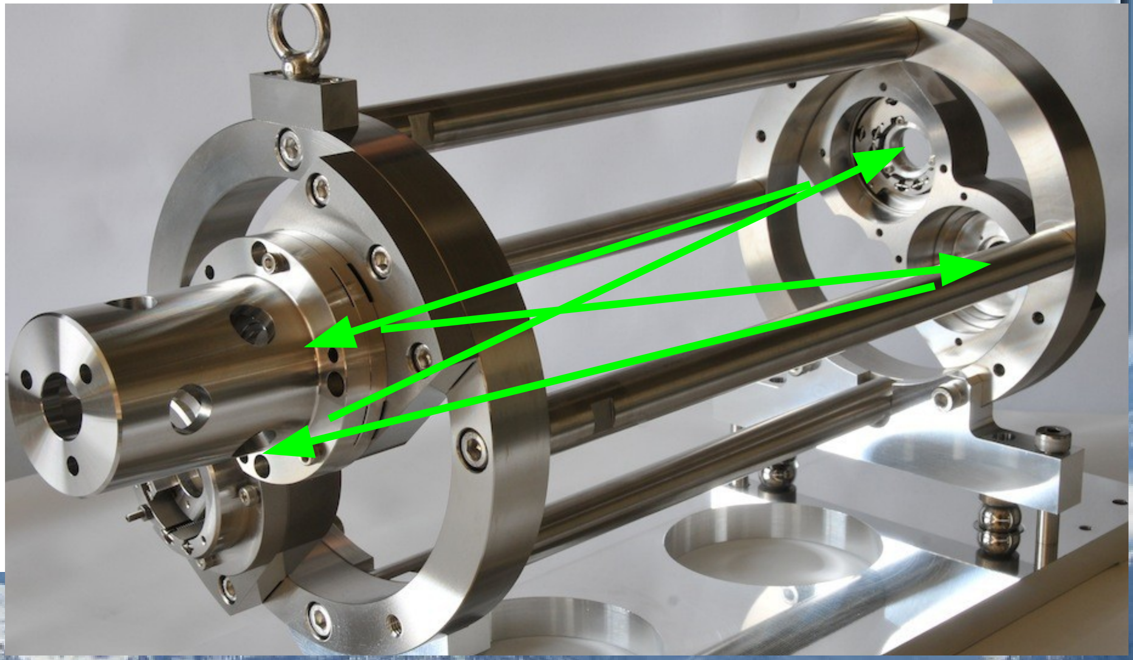
We fix the power to 50-60W to get stable laser beam

New 4 mirror cavity



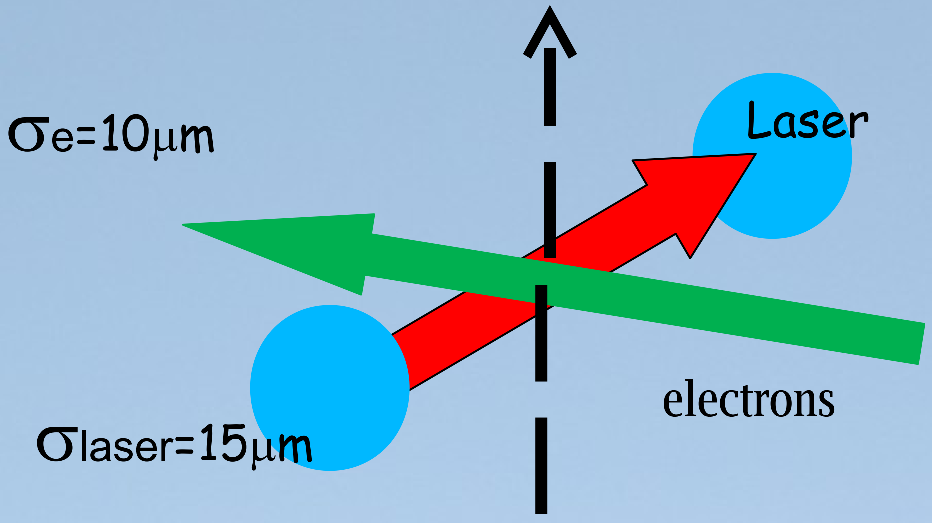
T. Takahashi(Posipol2012)

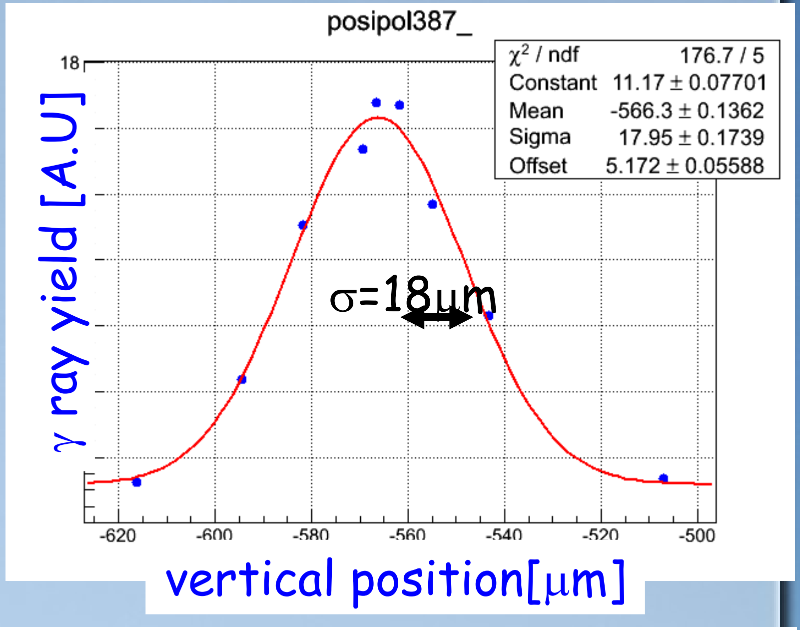
L1=M1-M2=420mm
L2=M2-M3=420mm
L3=M3-M4=420mm
L4=M4-M1=420mm

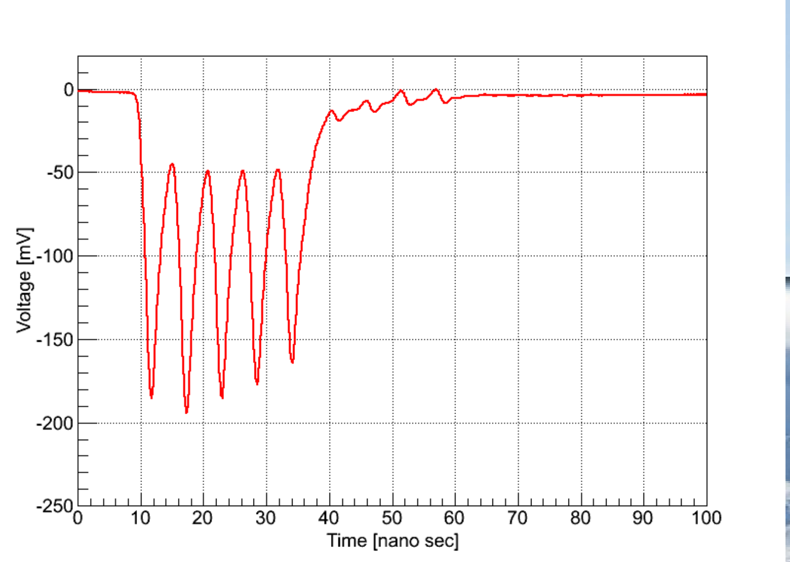


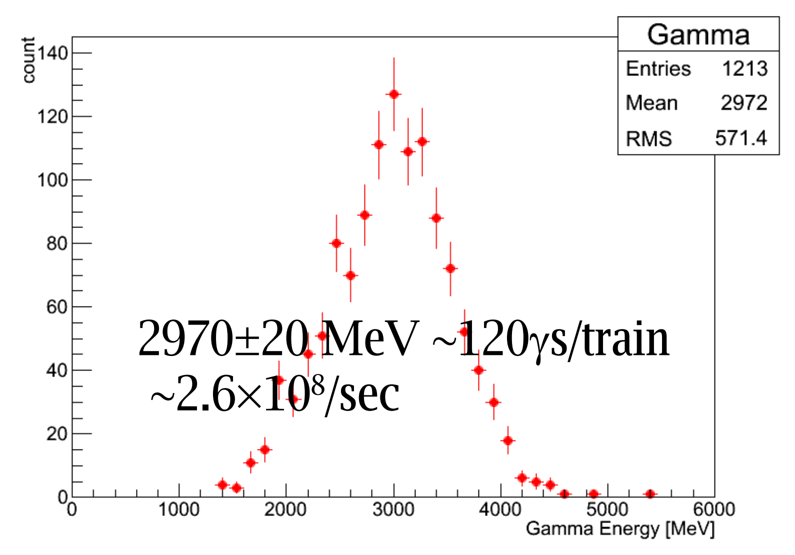
γ ray Generation at ATF

T. Takahashi(Posipol2012)







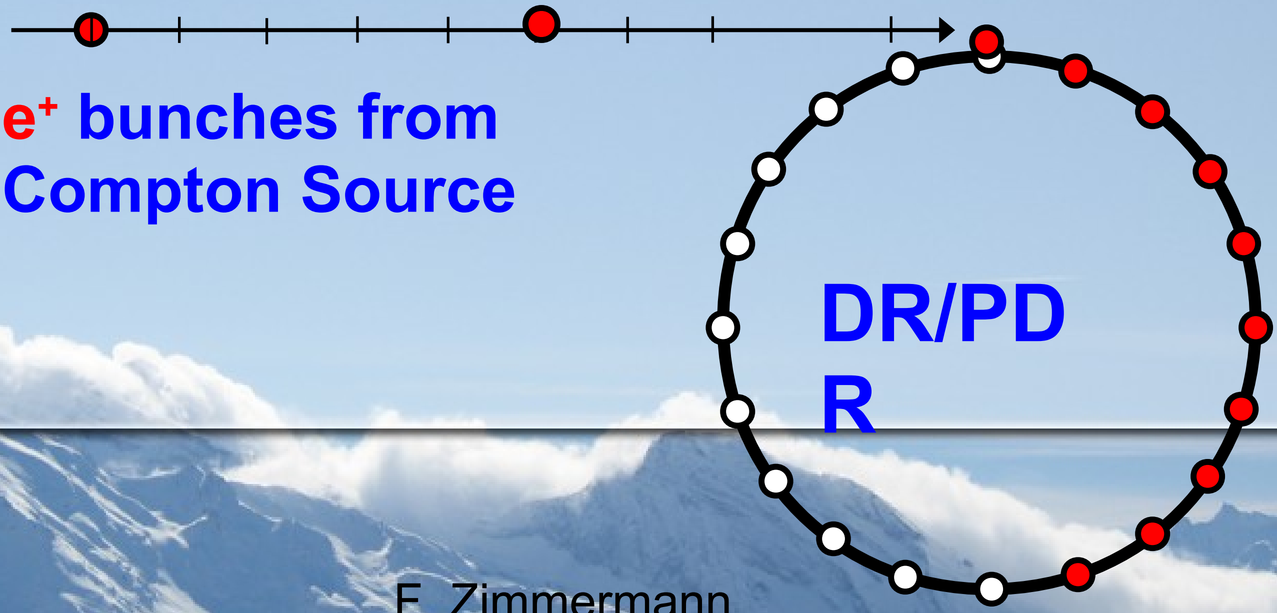


2970±20 MeV ~120γs/train

~2.6×10

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.



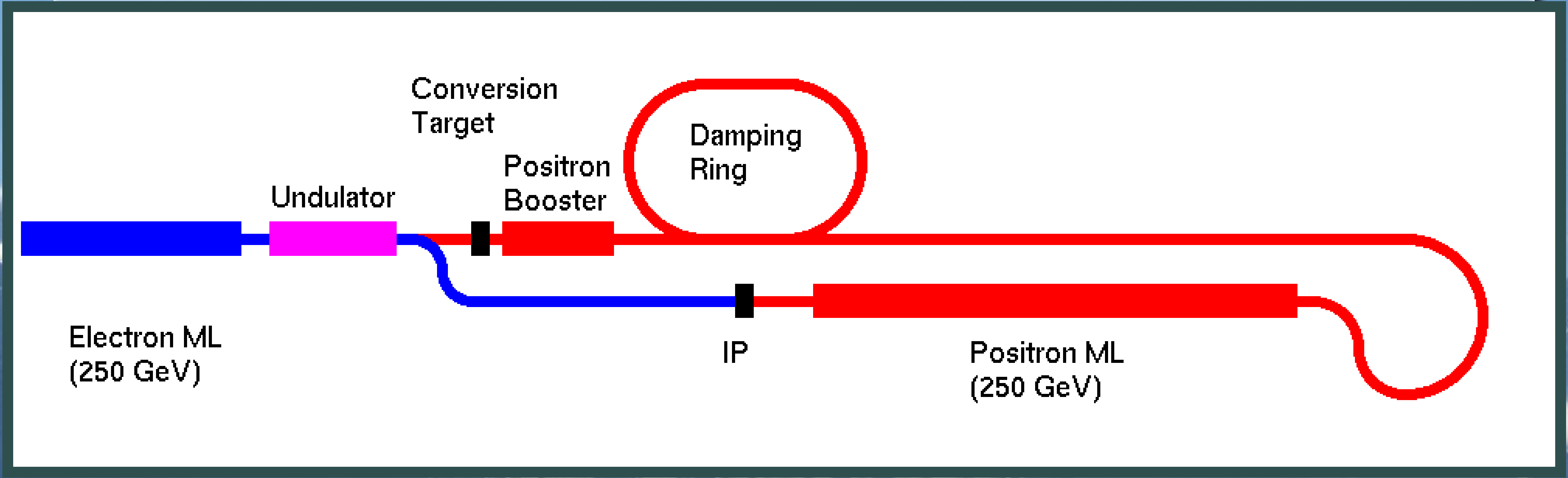
e^+ bunches from Compton Source

DR/PDR

F. Zimmermann

Positron Source
another staging approach

- Staging approach to minimize technical risks and maximize physics potential.
  - 1st stage : Unpolarized e-driven e+ source .
    (no polarizatino, but “conventional”)
  - 2nd stage: Undulator e+ source. (polarized, but totally new)



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.
  - Electron driven is a promissing technical backup.
  - Laser Compton is still challenging.
- A technical demonstration of the undulator system is not practically difficult.
- To maximize the technical feasibility and minimize the possible risks, a staging approach is desireable.