Argonne NATIONAL LABORATORY

Parameter Studies of Polarized Positron Production and Capturing*

W. Gai, W. Liu, H. Wang and K. Kim

*Working with SLAC, DESY

THE UNIVERSITY OF CHICAGO
Office of Science U.S. DEPARTMENT OF ENERGY
A U.S. Department of Energy laboratory managed by The University of Chicago

Goal of the Argonne Positron Studies

- Develop a complete start-to-end model (from undulator to damping ring)
- Performing start-to-end simulation numerical studies on ILC e+ source for the collaboration.

Outline

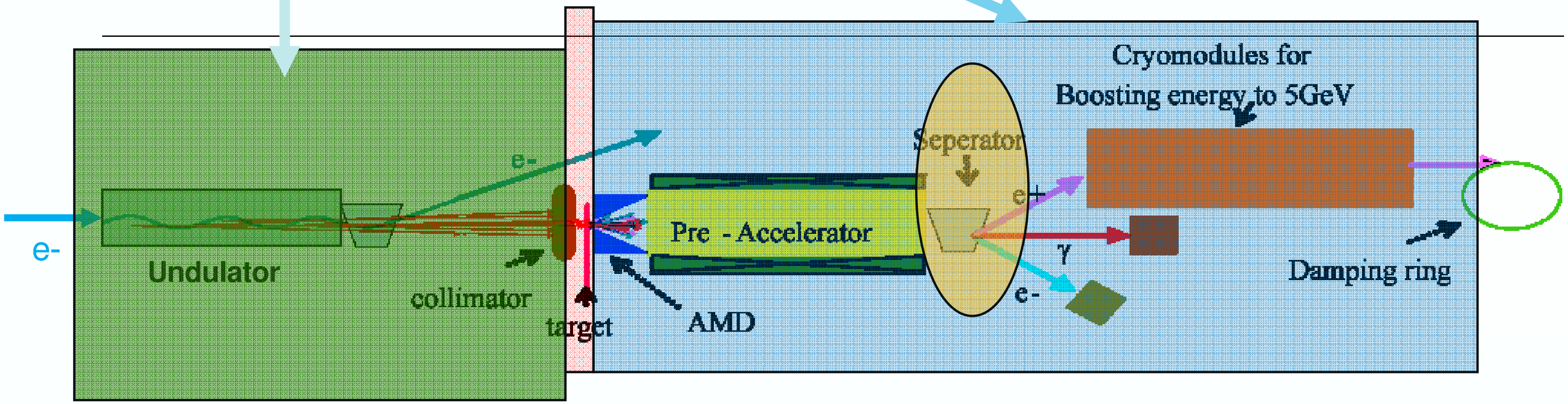
1. Start-to-end numerical modeling of undulator-based positron source
   - Description of Model
   - Optimization of Yield using Model
2. Positron separation optics
3. Keep alive positron source

Start-to-end Model of the Positron Source

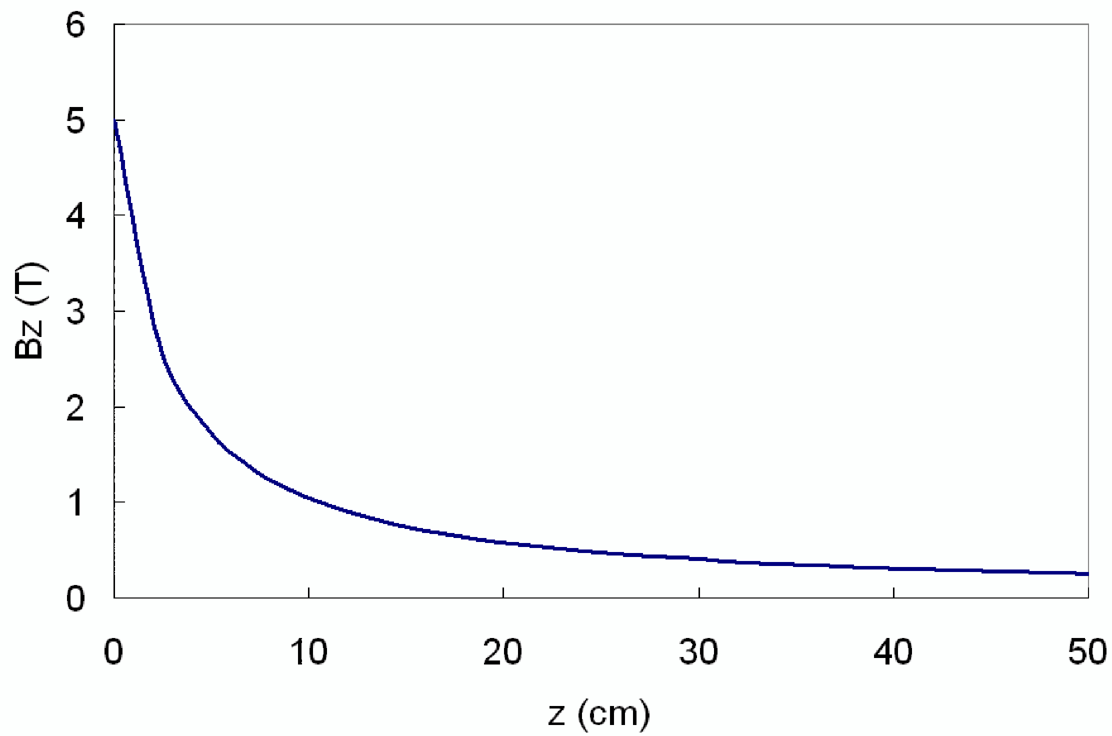
Electron Gamma
Shower code: EGSnrc

Analytical + Monte carlo

Particle dynamic code:
PARMELA

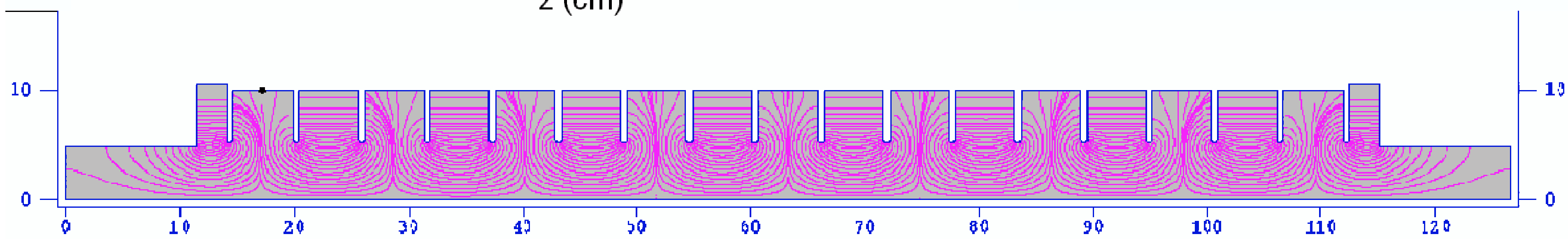


AMD profile and PreAccelerator Filed Map

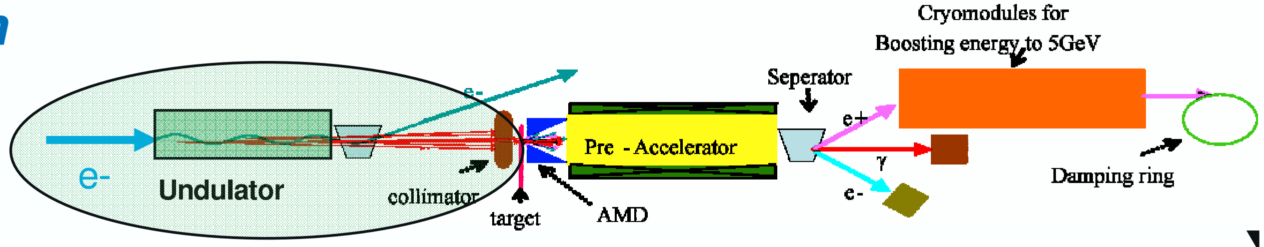


AMD field:5T-0.25T in 50cm

Accelerating gradient in preaccelerator: 12MV/m



Photon number spectrum and distribution functions



- The spectrum of photon generated by helical undulator is known as

$$\frac{dNph}{dE}\left[\frac{1}{mMeV}\right] = \frac{10^6 e^2}{4\pi\varepsilon_0 c^2 h^2}\frac{K^2}{\gamma^2}\sum_{1}^{\infty}\left(J_n'(x)^2 + \left[\frac{\alpha_n}{K} - \frac{n}{x}\right]^2 J_n(x)^2\right) \quad (1)$$

$$\alpha_n^2 = \left[n\frac{\omega_1(1+K^2)}{\omega} - 1 - K^2\right] \geq 0$$

$$x = 2K\frac{\omega}{\omega_1(1+K^2)}\alpha_n$$

$J_n = Bessel\ functions$

$$K = 0.934 * B[T] * \lambda_u[cm]$$

$$E_1 = \hbar\omega_1 = \hbar\frac{4\pi\gamma^2 c}{(1+K^2)\lambda_u}$$

$$E_n = nE_1$$

Photon number spectrum in terms of harmonics

$$\left.\frac{dNph}{dE}\right|_n = \frac{10^6 e^2}{4\pi\varepsilon_0 c^2 h^2}\frac{K^2}{\gamma^2}\left(J_n'(x)^2 + \left[\frac{\alpha_n}{K} - \frac{n}{x}\right]^2 J_n(x)^2\right) \quad (2)$$

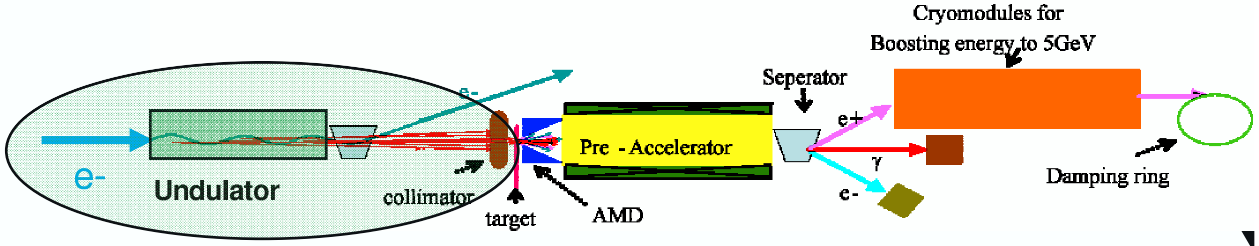
Harmonics distribution function

$$D(n) = \sum_{i=1}^{n}\int_0^{\infty}\left.\frac{dNph}{dE}\right|_i dE \Big/ \sum_{i=1}^{\infty}\int_0^{\infty}\left.\frac{dNph}{dE}\right|_i dE \quad (3)$$

Energy distribution function

$$D_n(E) = \int_0^{E}\left.\frac{dNph}{dE}\right|_n dE \Big/ \int_0^{E_n}\left.\frac{dNph}{dE}\right|_n dE \quad (4)$$

Photons from Helical Undulator– polarization and radiation angle



•The amplitude of radiation from helical undulator in terms of harmonic can be obtained as

$$Ix(E,n) = \sqrt{\frac{10^6 e^3}{4\pi\varepsilon_0 \hbar^2 c^2}} \frac{K}{\gamma} [\frac{\alpha_n}{K} - \frac{n}{x}] J_n(x)$$

$$Iy(E,n) = i\sqrt{\frac{10^6 e^3}{4\pi\varepsilon_0 \hbar^2 c^2}} \frac{K}{\gamma} J_n'(x) \qquad (1)$$

From which the Stokes parameters are obtained as:

$$\xi_1 = \frac{I_x^2 - I_y^2}{I_x^2 + I_y^2}, \quad \xi_2 = 0, \quad \xi_3 = \frac{2 I_x I_y}{I_x^2 + I_y^2} \qquad (2)$$

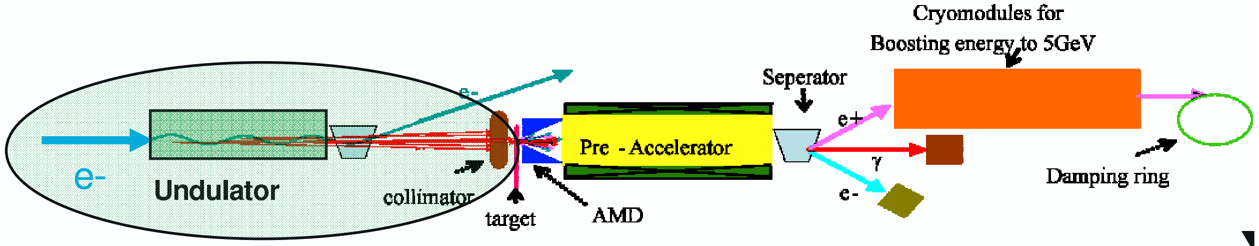
where ξ_1 describes the linear polarization, ξ_2 describes the linear polarization in coordinate system rotated by 45° with respect to the original one for ξ_1, ξ_3 describes the circular polarization.

After knowing its energy and originating harmonic, the radiation angle of photon is also determined as:

$$\Theta = \frac{1}{\gamma}[n\frac{\omega_1(1+K^2)}{\omega} - 1 - K^2]^{1/2} \qquad (3)$$

An uniform distribution on azimuthal direction is assumed

Photons from helical undualtor– originating point and collimating



In addition to distribution functions in previous slides:

- **Uniform distribution along the length of undulator is assumed**
- **Temporal and transverse distribution is inherited from drive e- beam**

Collimating:

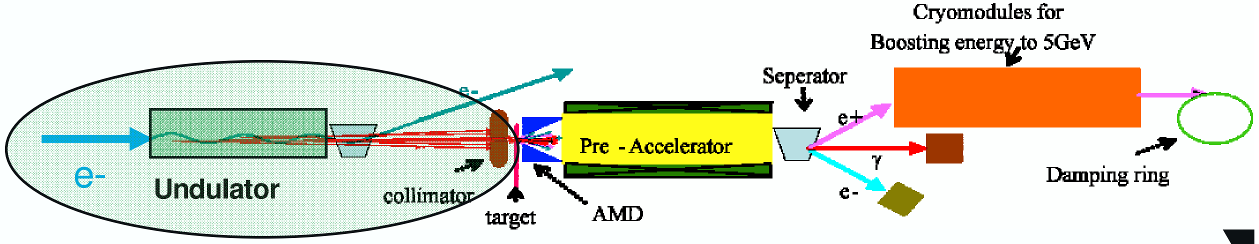
With the originating point (x_0 , y_0 , z_0) and direction vector (dx, dy, dz) assigned, the state of a photon after collimator is determined by its position on the collimator screen as:

$$r = \sqrt{[x_0 + (z_c - z_0)dx/dz]^2 + [y_0 + (z_c - z_0)dy/dz]^2} \quad (1)$$

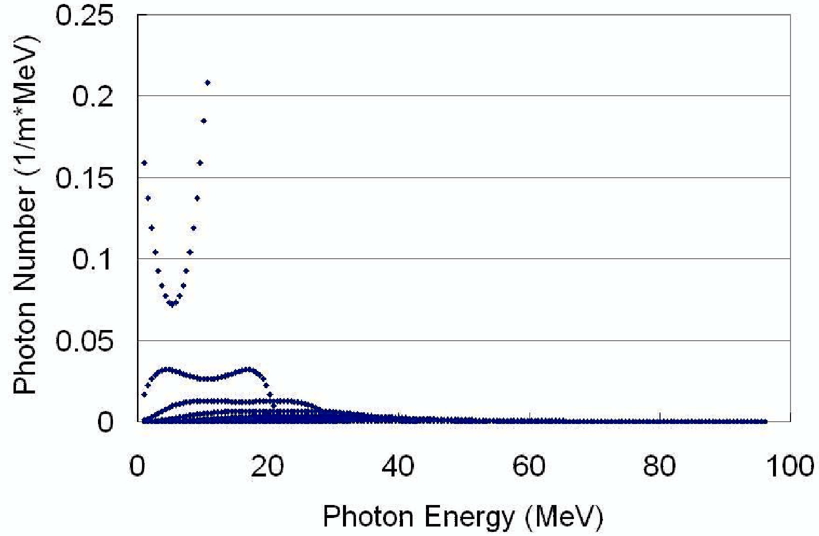
Where z_c is the location of collimator.

If r is greater than the collimator iris, the photon is then ignored and will not allowed to strike the target to produce positrons

Photon Spectrum and Polarization of ILC baseline undulator



Results of photon number spectrum and polarization characteristic of ILC undulator are given here as examples. The parameter of ILC undulator is K=1, λu=1cm and the energy of electron beam is 150GeV.



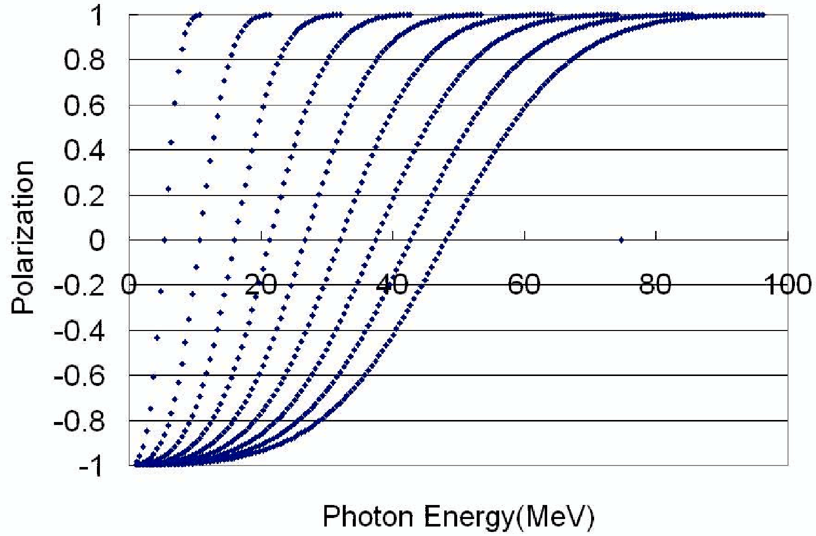
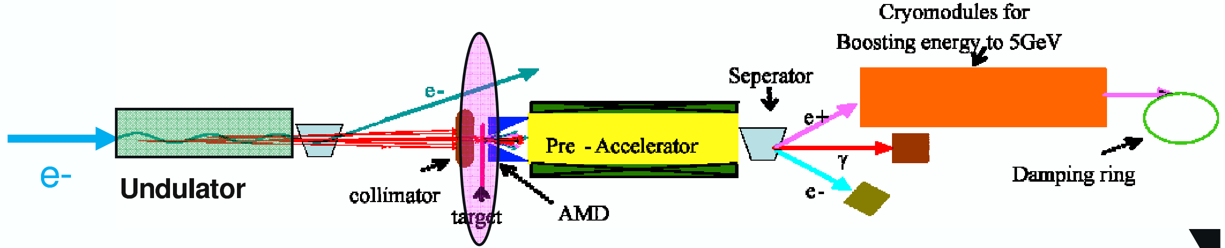


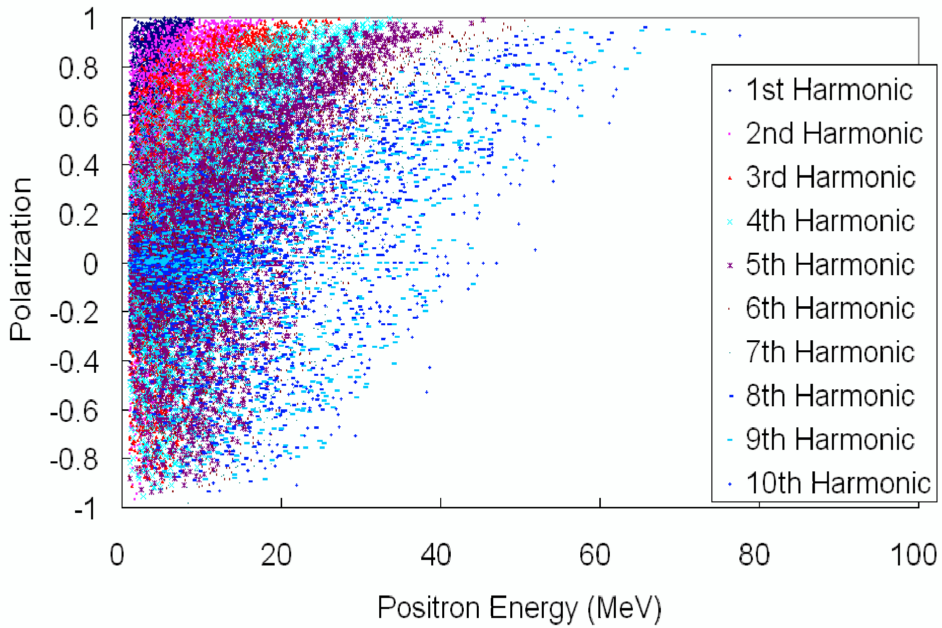
Figure1. Photon Number spectrum and polarization characteristics of ILC undulator up to the 9th harmonic

Comparison of the generated positron polarization spectrum: with/without collimator.

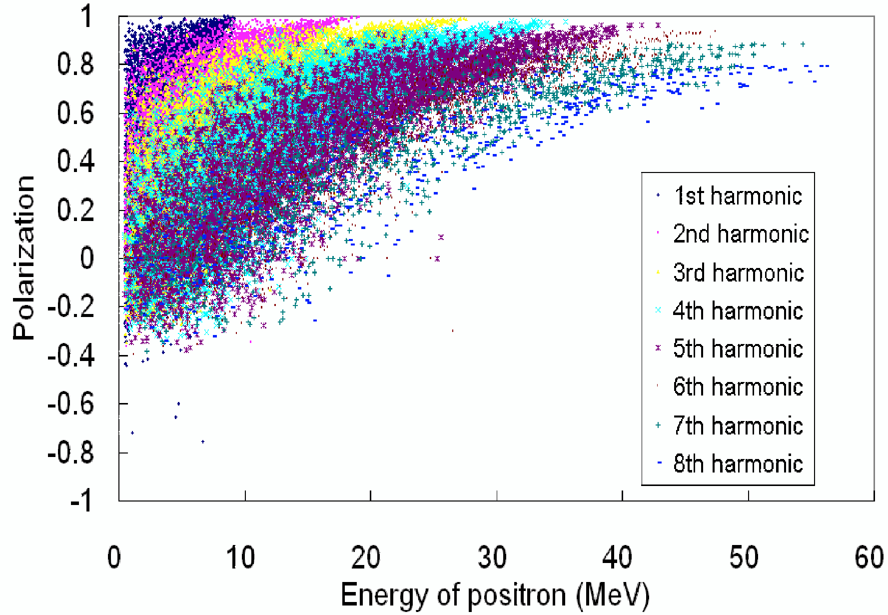


Initial distribution of polarization of positrons

without collimator

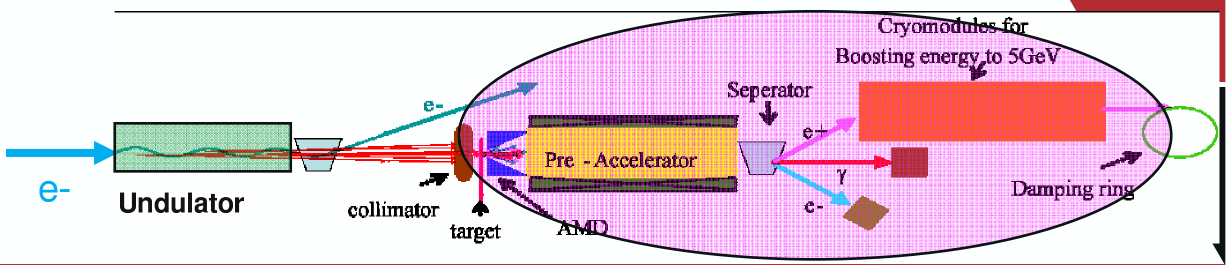


with collimator

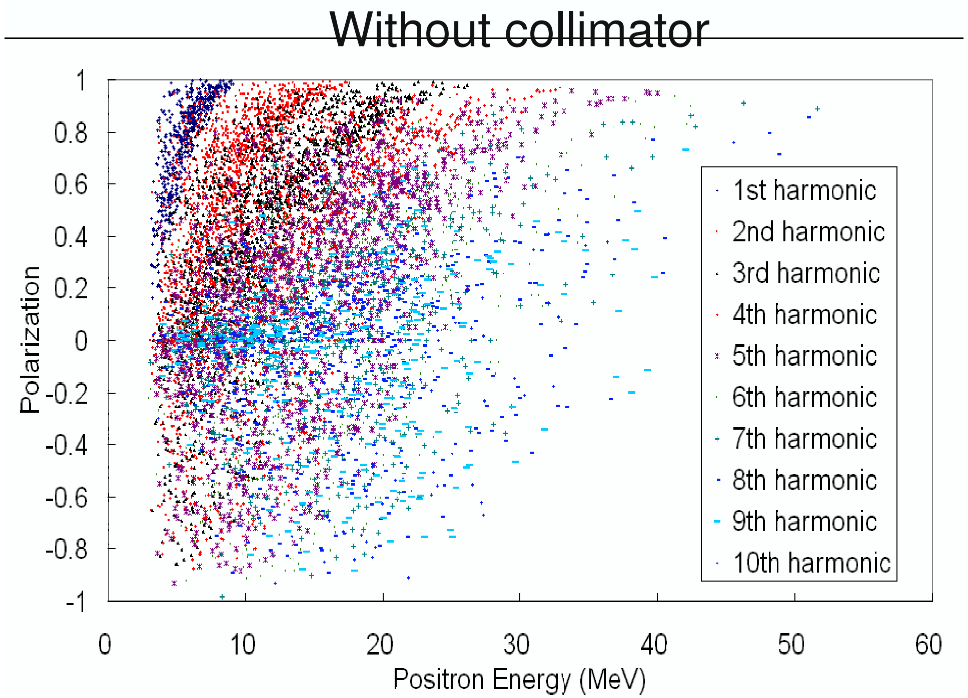


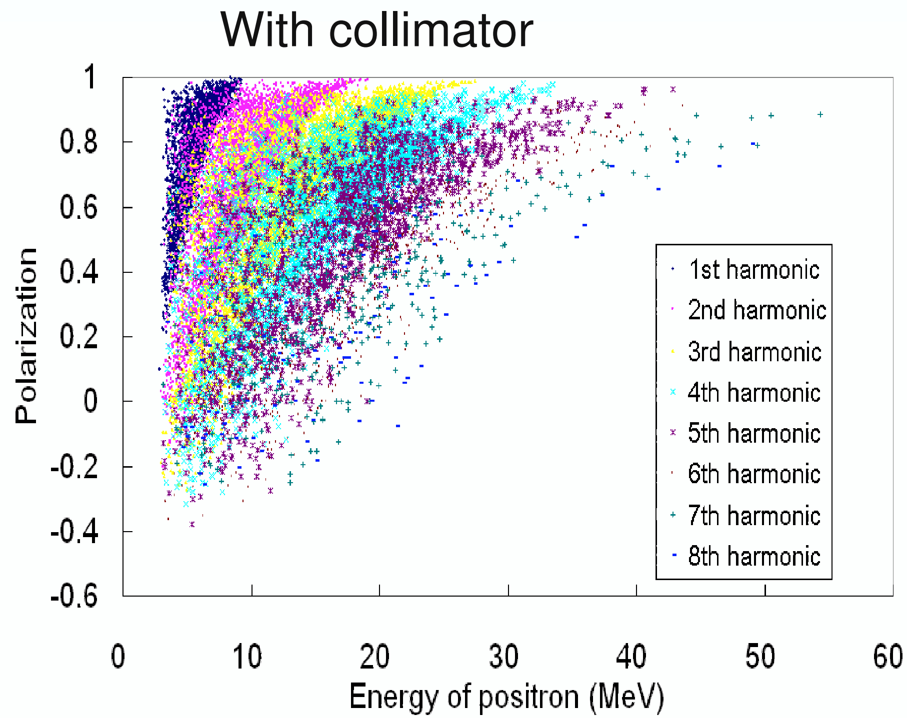
The collimator is 2.5mm in radius and is 700m away from the end of a 100m long undulator. Photons are radiated uniformly along the undulator. For the case without collimator, the photon source is treated as a point source. The collimator screened out those photon with lower polarization and thus improved the positron polarization.

Comparison of the captured positron polarization spectrum: with/without collimator.



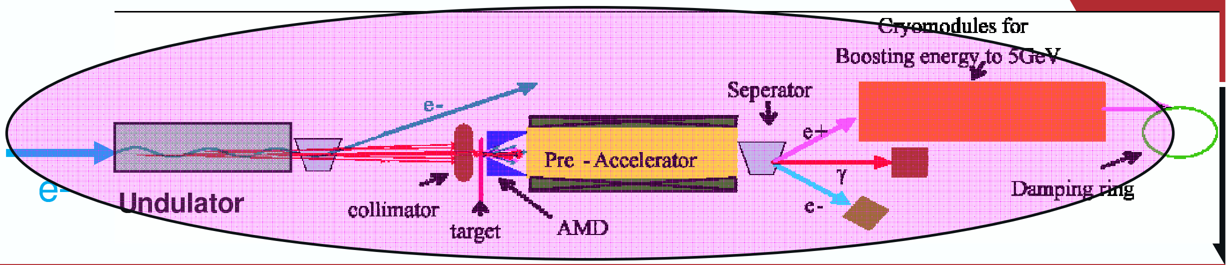
Initial Polarization vs energy of those captured positrons



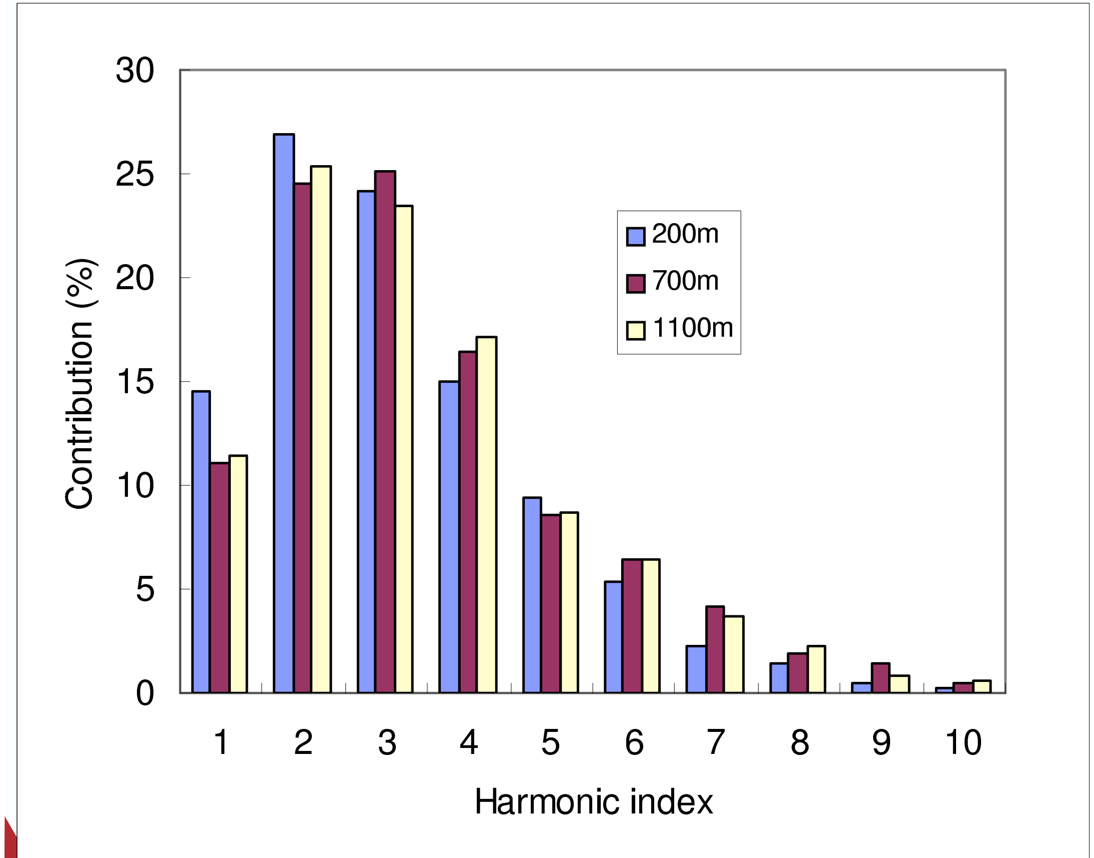


The capturing optics are the same for both with and without collimator. The collimator screened out those photons with lower polarization and thus improved the polarization of resulting positron beam. The polarization of captured positron beam is about 30% without collimator and 63% with the collimator setting used here.

Yield contribution from different harmonics.

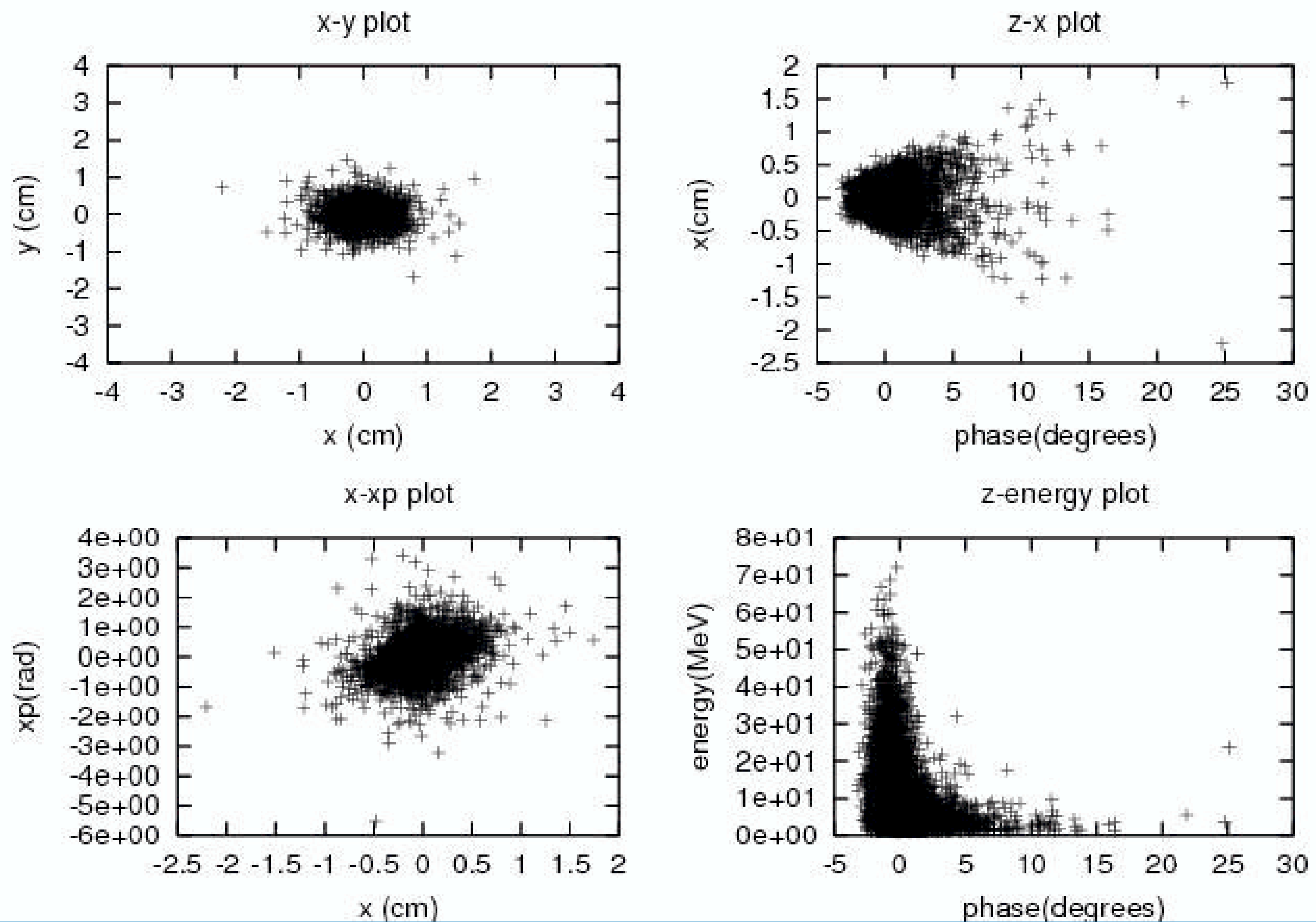


The cutting angle of collimator is fixed at 3.85μrad

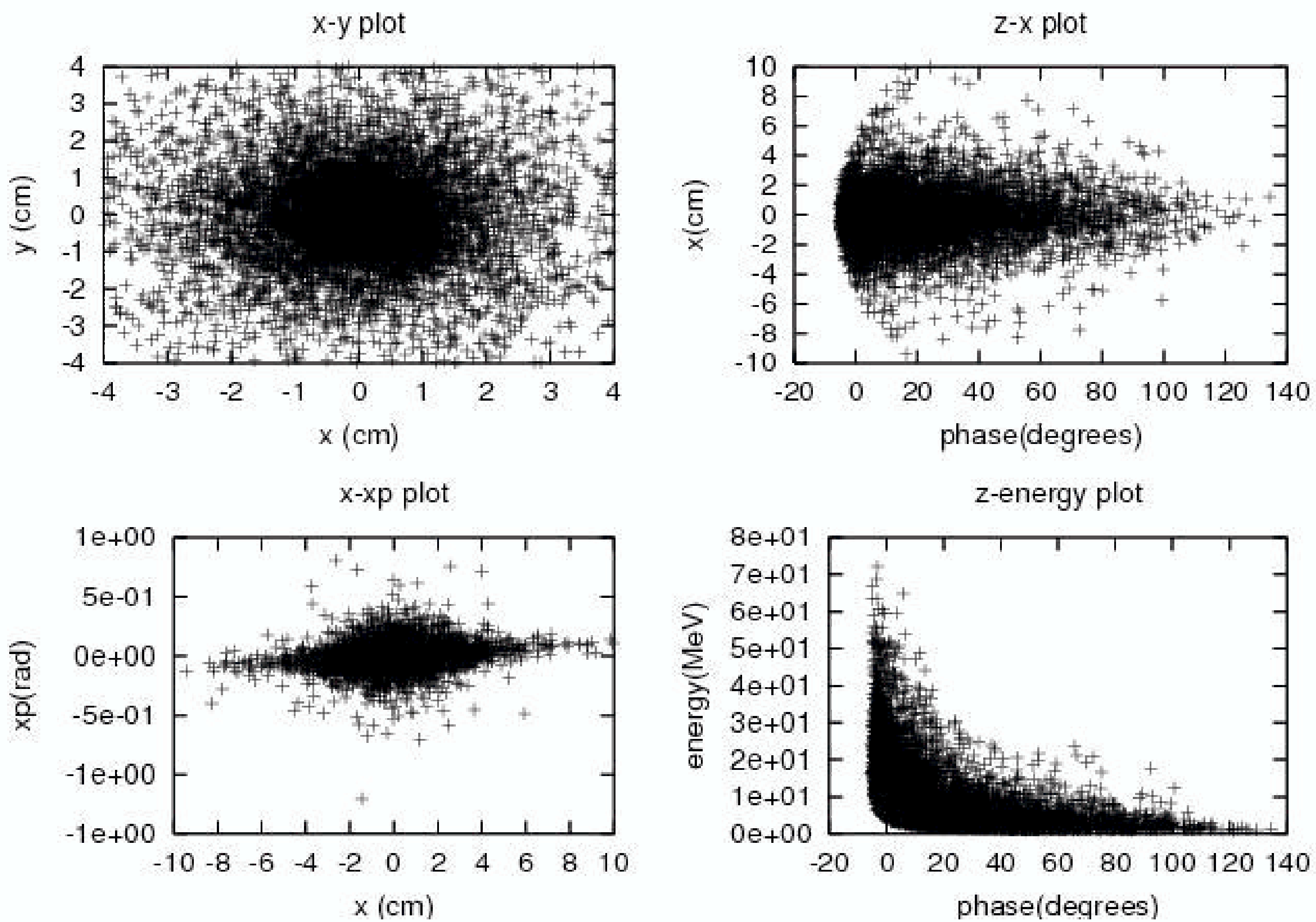


- 1st harmonic contributed <15% to the positron yield
- 2nd and 3rd harmonic together contributed >45%
- Contributions from 4th and 5th harmonic are comparable to 1st harmonic
- Positron yield is mostly contributed by high order harmonics

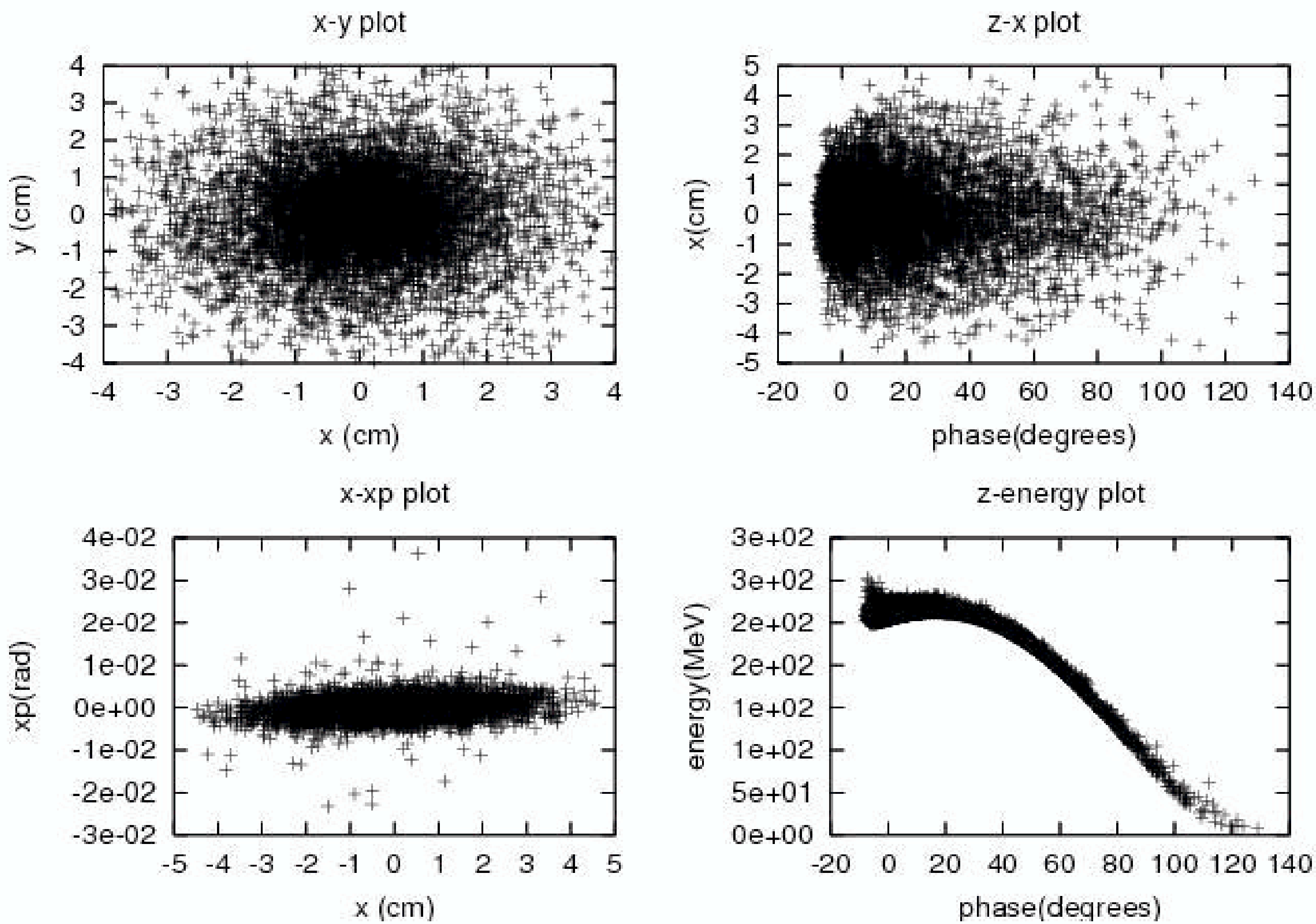
Phase space distribution of Positron coming out of the target



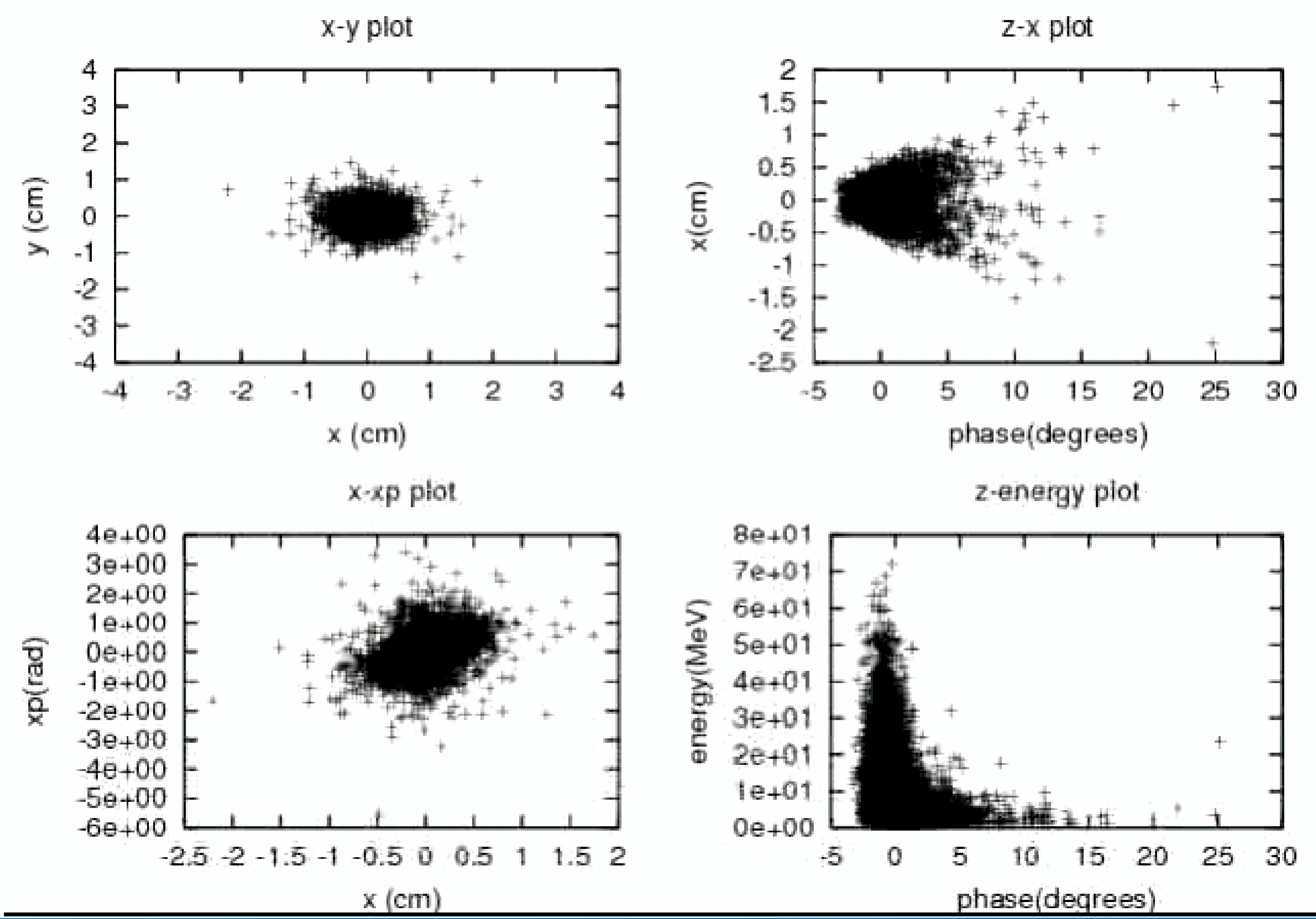
Phase Space Distribution of Positron at the End of AMD



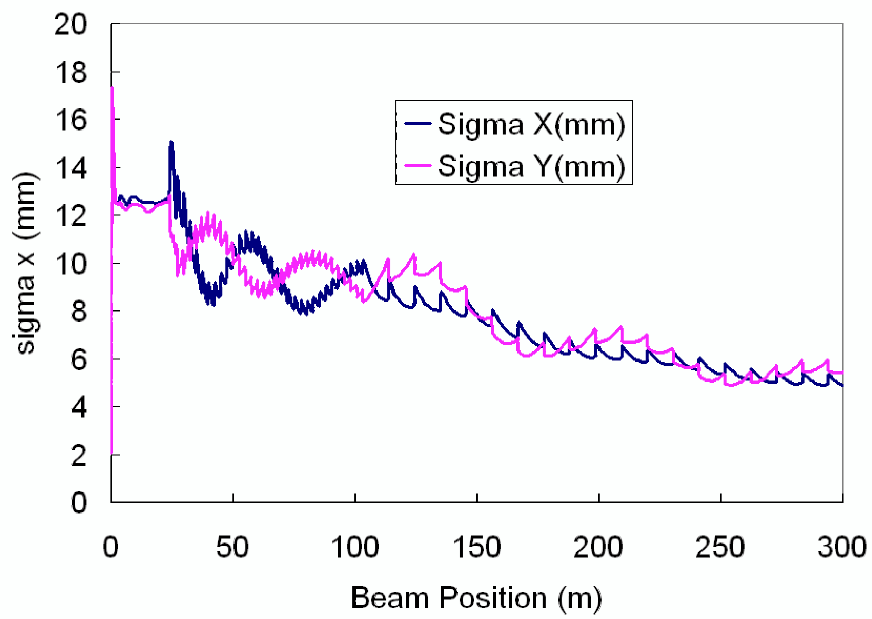
Phase Space Distribution of Positron at the end of PreAccelerator

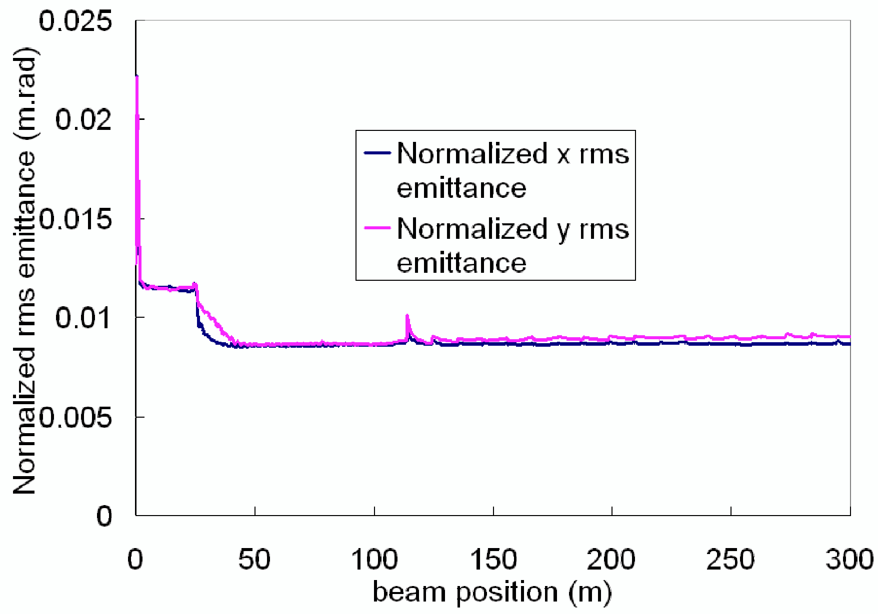


Phase Space Distribution of Positron Beam Along Beamline

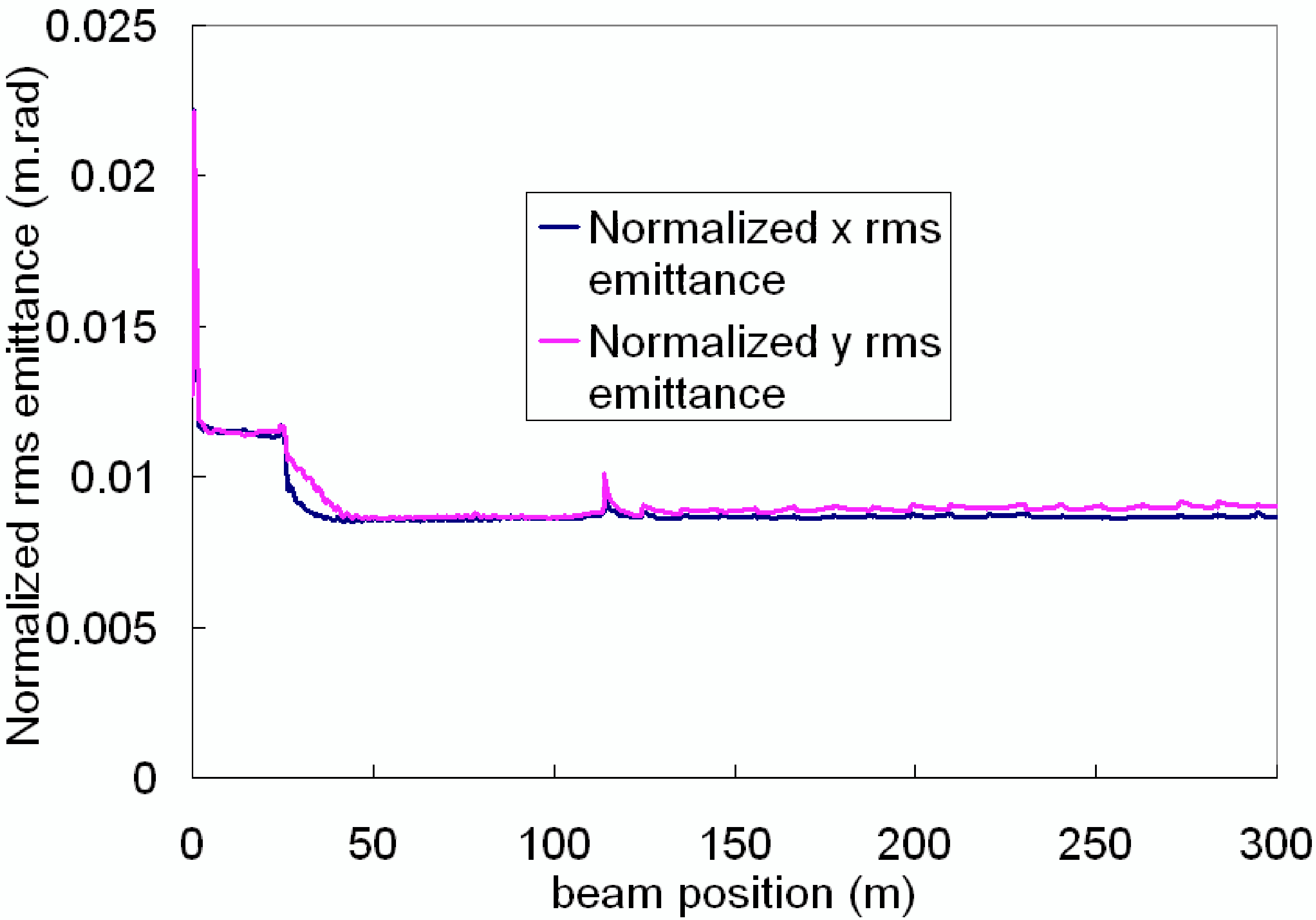


rms e+ Beam envelop and emittance evolution





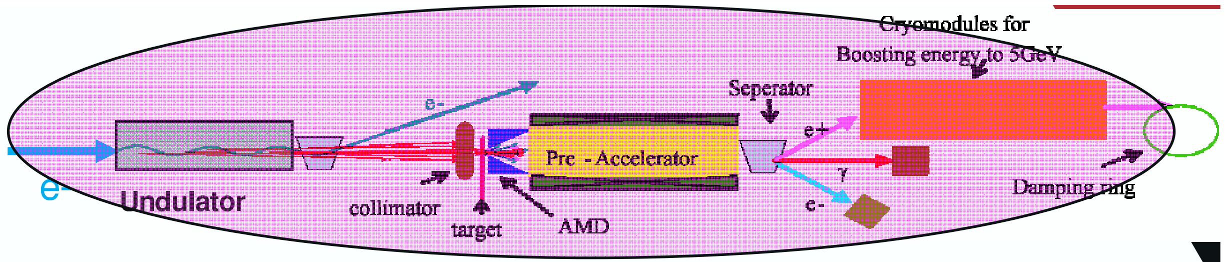
Evolution of the beam emittances

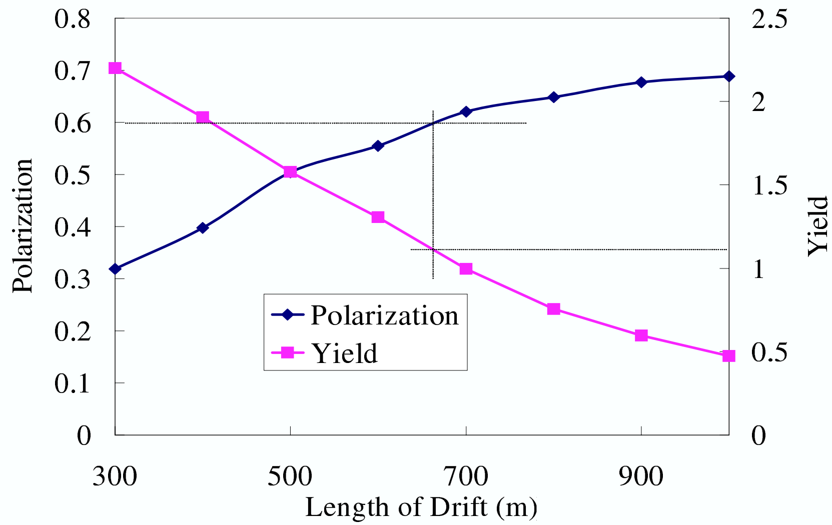


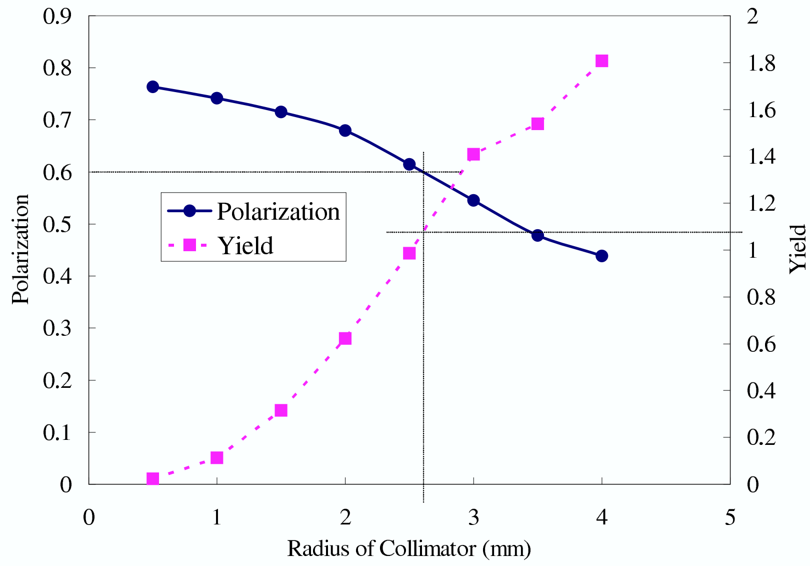
Multivariate Optimization

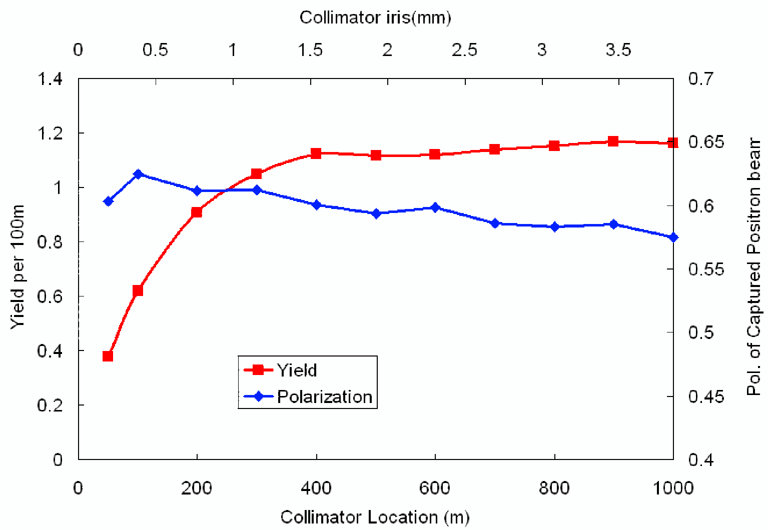
- Use Start-to-End Model to maximize positron yield delivered to the Damping Ring
  - Drive beam energy (ILC Baseline:150 GeV)
  - Collimator Angle (Drift Length and Collimator Radius)
  - Target Material and Thickness (ILC Baseline: 0.4 rl, Ti)
  - AMD profile (5T-0.25T in 50cm)
  - Accelerating gradient:
    - *12MV/m in pre-accelerator*
    - *25MV/m in super conducting linac*
  - Damping ring acceptance:
    - $\varepsilon_x+\varepsilon_y<=0.09$*m.rad.*
    - $\Delta E/E < 1\%$

Polarizations and Yield

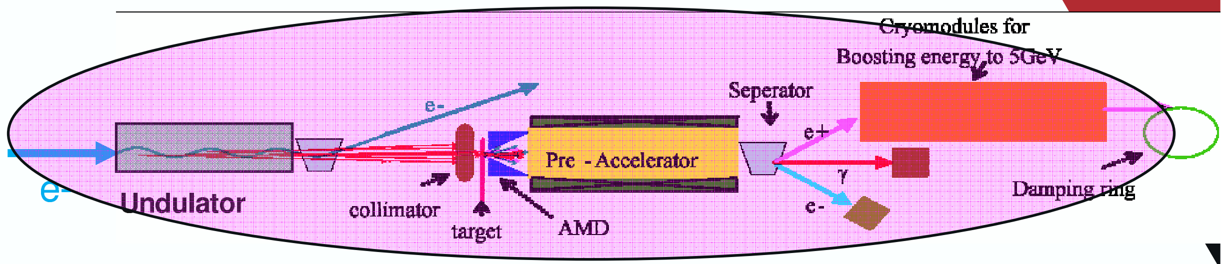


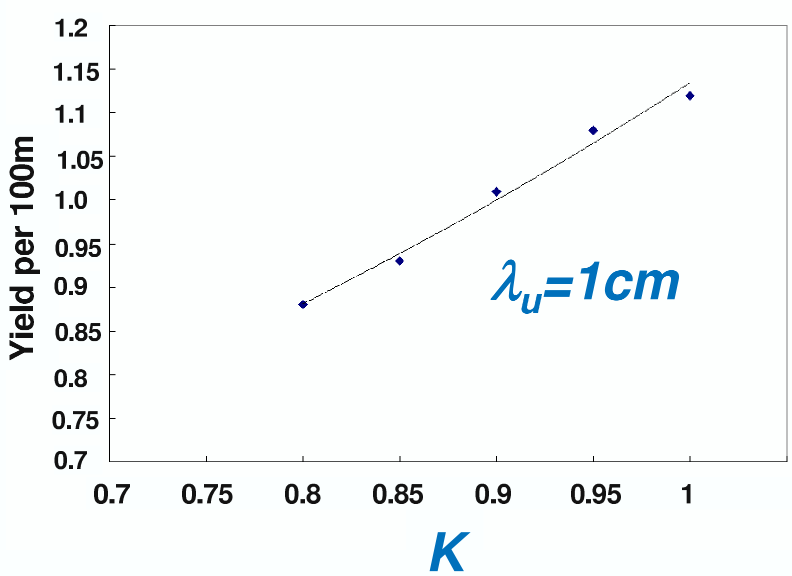


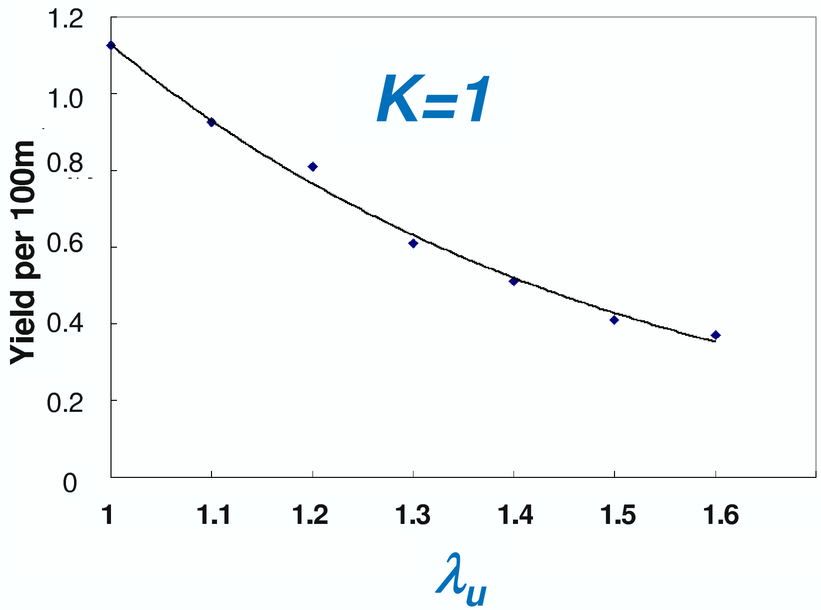




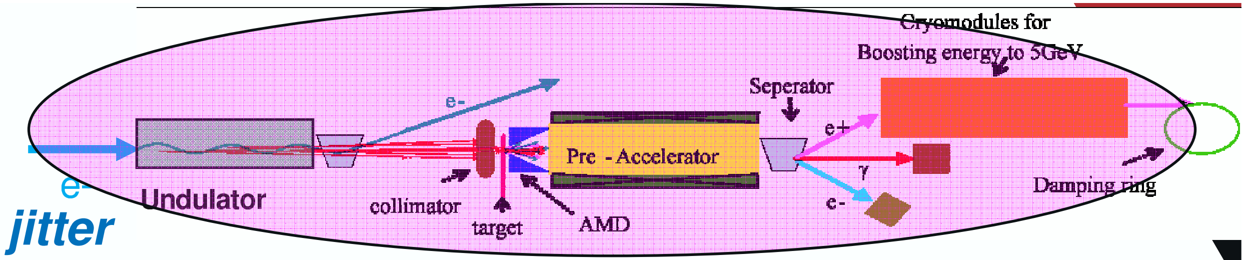
Optimum yield at Polarization=60%

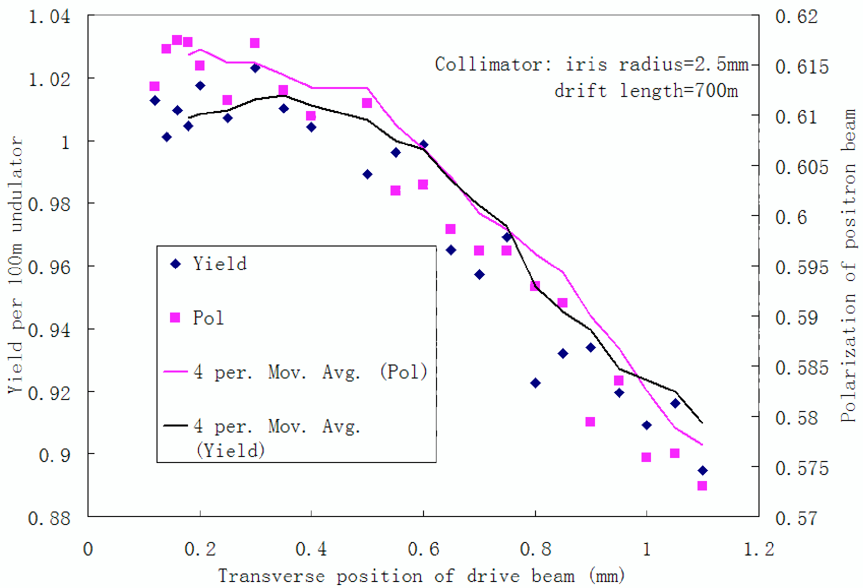


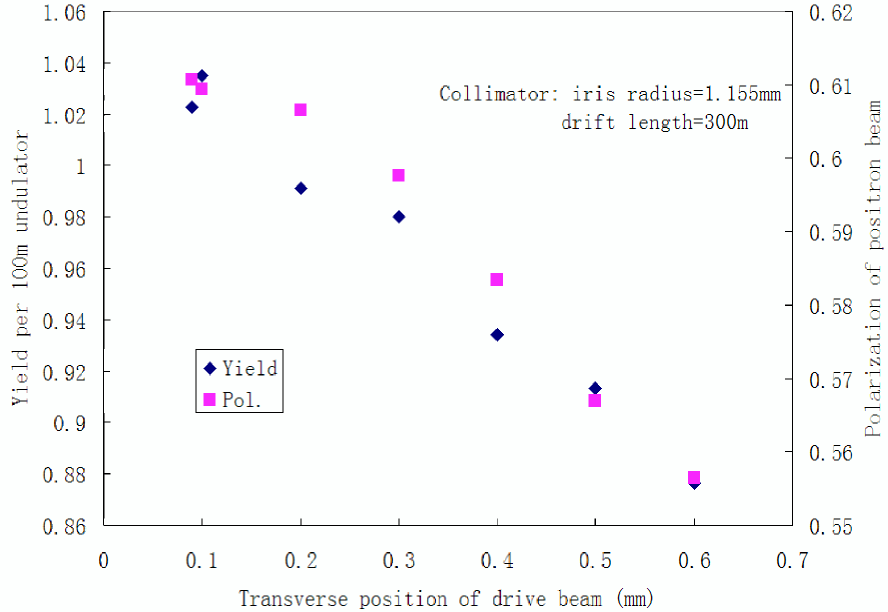




Error Analysis →
Sensitivity of Yield to beam jitter







Yield and polarization as a function of drive beam transverse position

-collimator: location 700m, iris radius 2.5mm

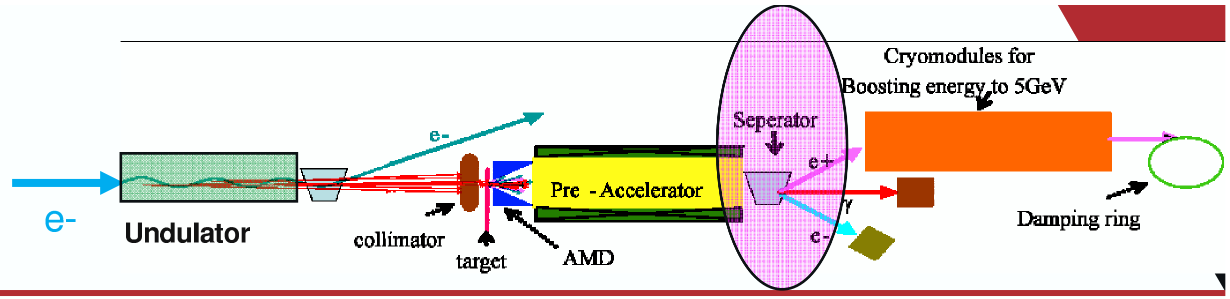
Yield and polarization as a function of drive beam transverse position

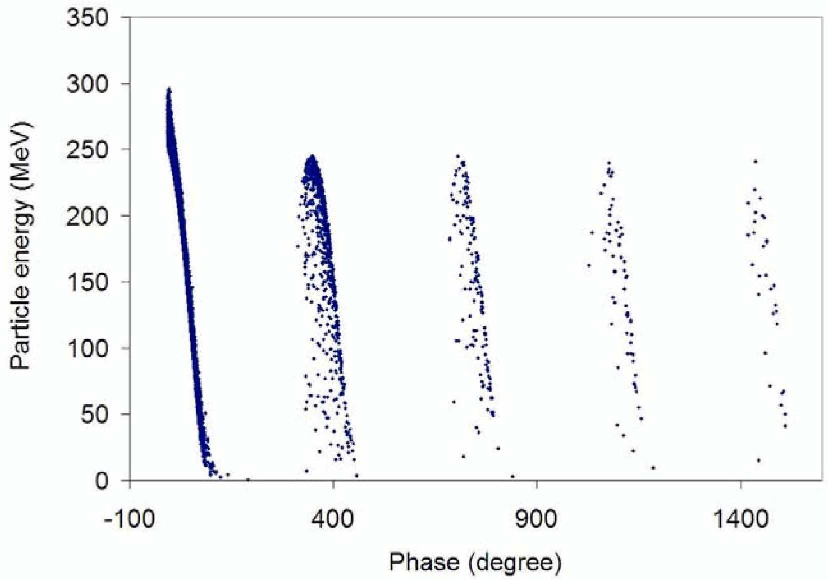
-collimator: location is 300m, iris radius= 1.155mm

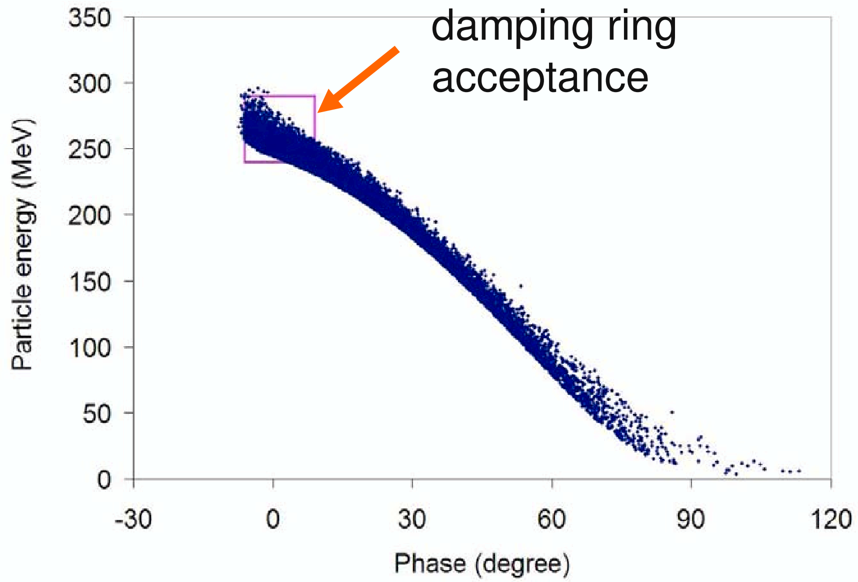
Summary on numerical modeling of helical undulator photon source

- A complete numerical model of helical undualtor photon source is established with correlations between drive beam profile, undulator length, collimator location and iris included.
- Using this model, we find that the majority of captured positrons are produced by photons from high order harmonics. 1^{st} harmonic contributed only less than 15% of the yield.
- By comparing the yield and polarization of resulted positron beam, we noticed that the optimum yield decreasing more quickly with undulator period λu than with K.
- For the effect of transverse position jittering of drive electron beam, it depends on the location of collimator. The simulation results shows that for collimator with 5mm iris aperture and located at 700m, the yield change is not significant until the offset of the drive beam reaches 0.6mm. But for collimator with aperture of 2.31mm and located at 300m, the yield is decreasing immediately after the offset of drive beam transverse position is over 0.1mm and the polarization of positron beam goes below 0.6 when the offset is over 0.3mm. But in either case, transverse jittering of drive beam is not a problem as long as the collimator is not too close to the undulator

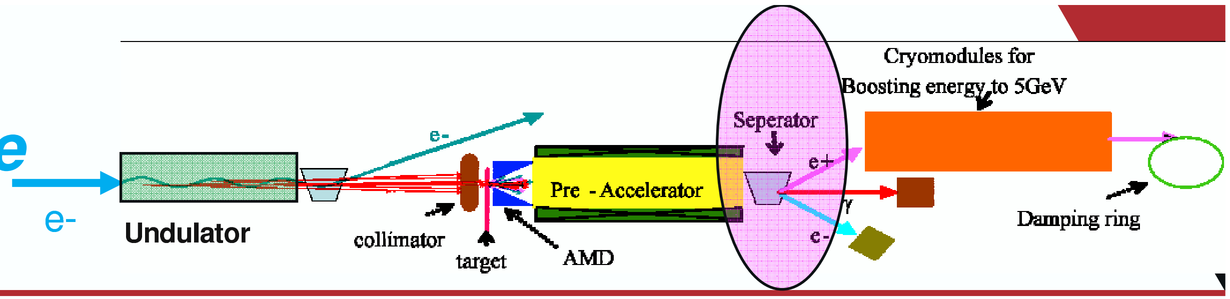
Longitudinal phase space distribution at exit of pre-accelerator



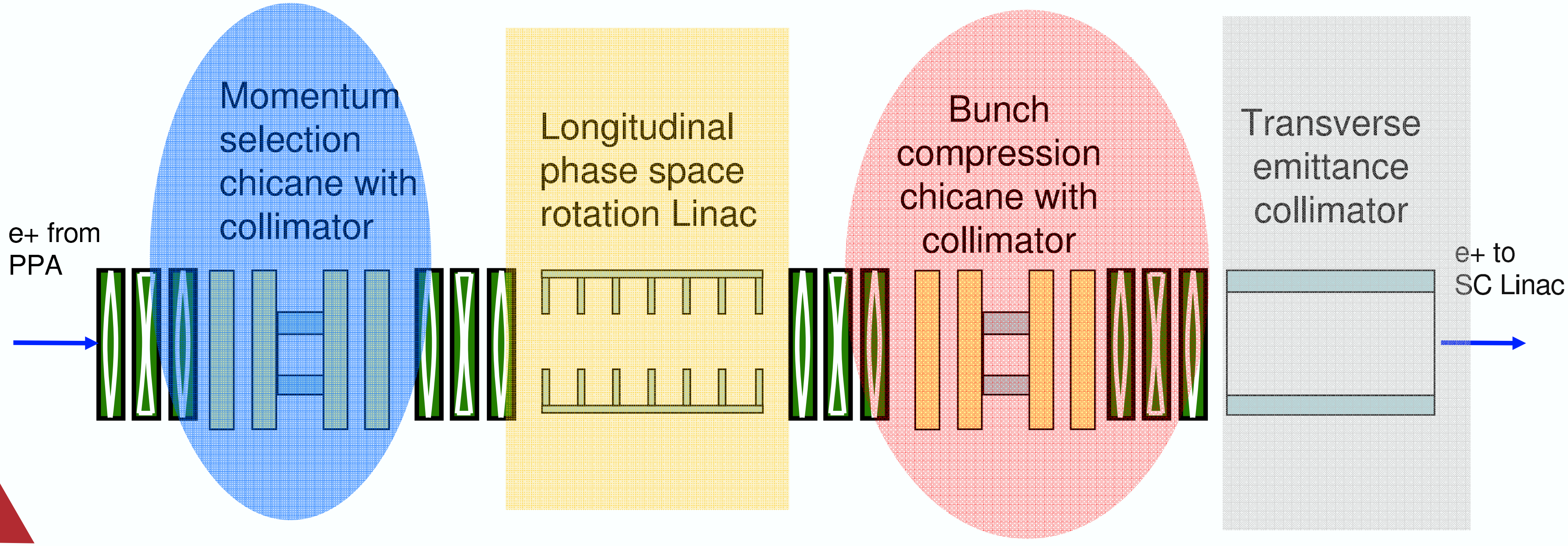




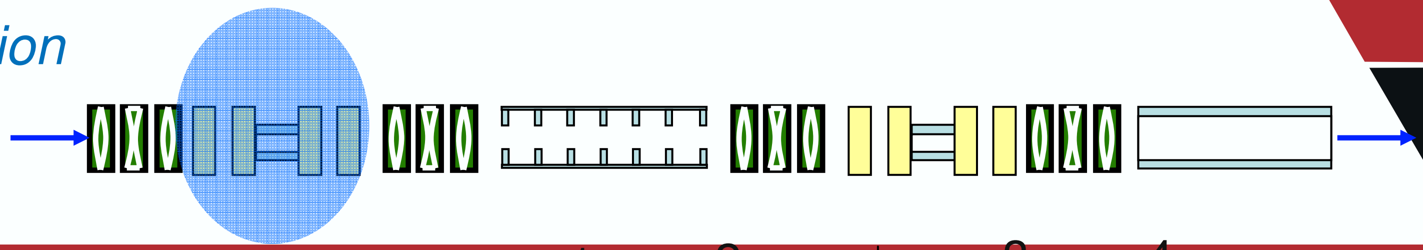
Layout of positron separation beam line

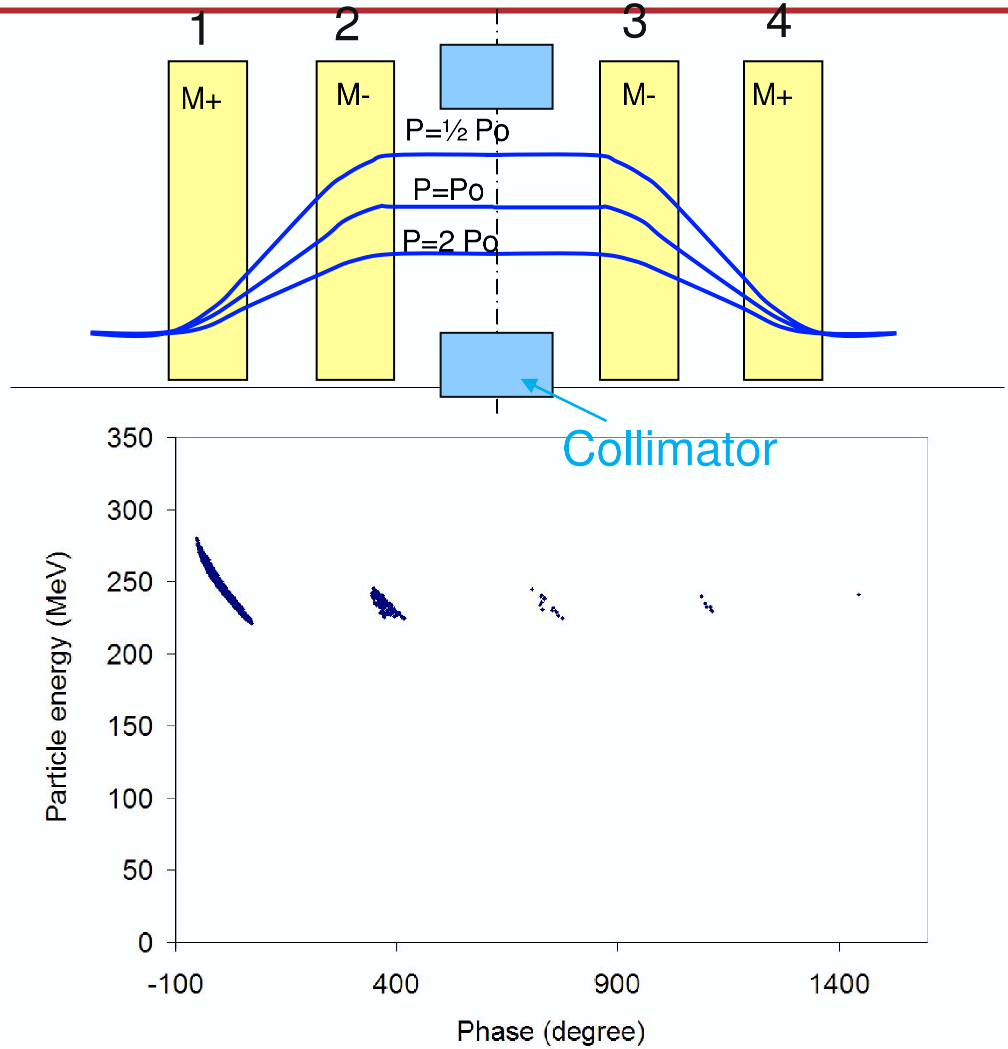


- Momentum selection
- Longitudinal phase space rotation
- Bunch compression
- Transverse collimation



Momentum selection





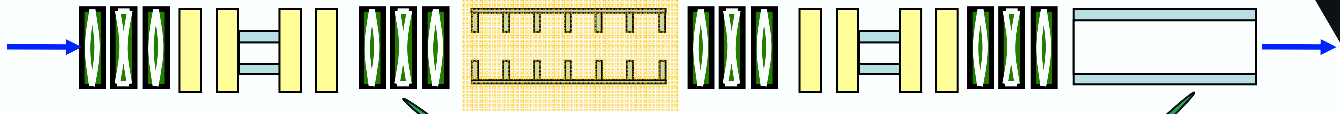
Momentum selection chicane consists of four identical rectangular bending magnets.

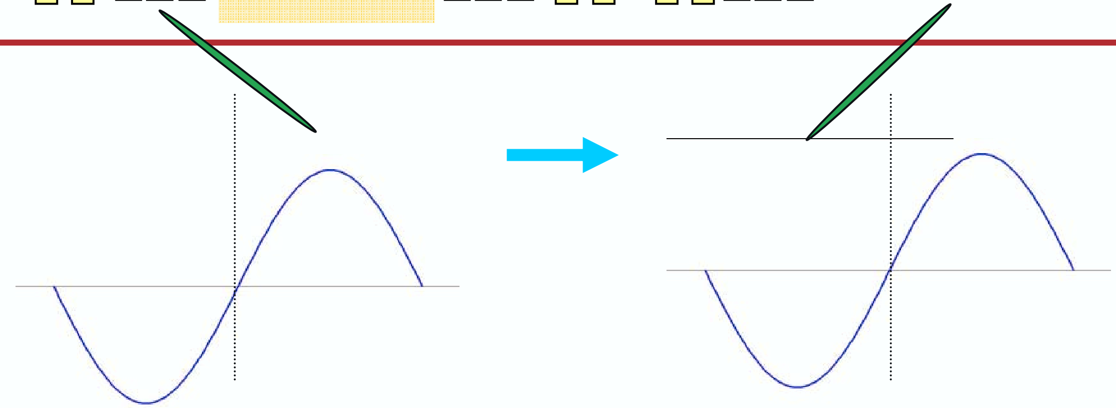
Positrons with different energy have different bending angle, which result in large transverse beam size.

Collimator is placed between 2nd and 3rd magnets to select the positrons in the desired energy range.

Beam bunch is elongated due to positron longitudinal distribution at the entrance.

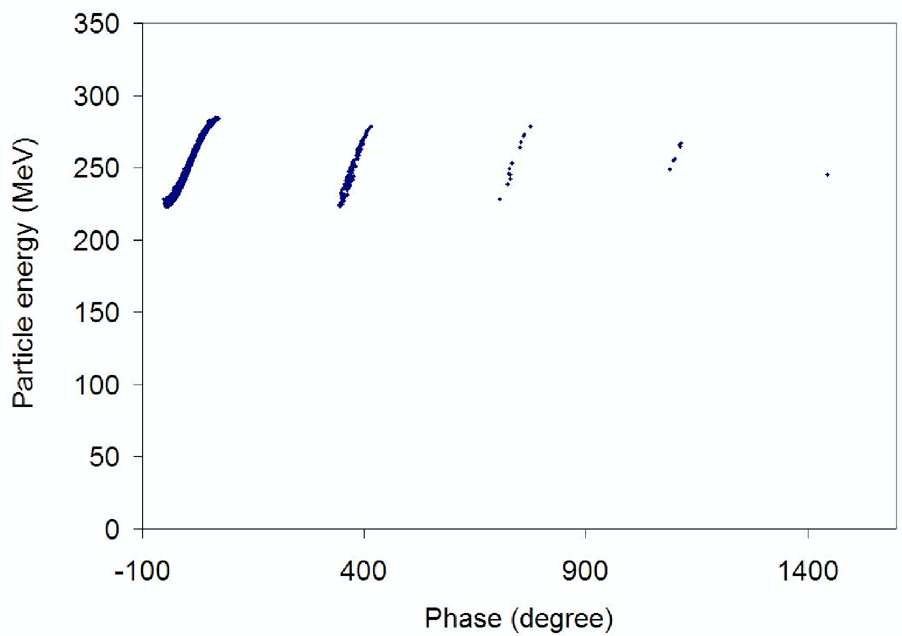
Phase Space Rotation



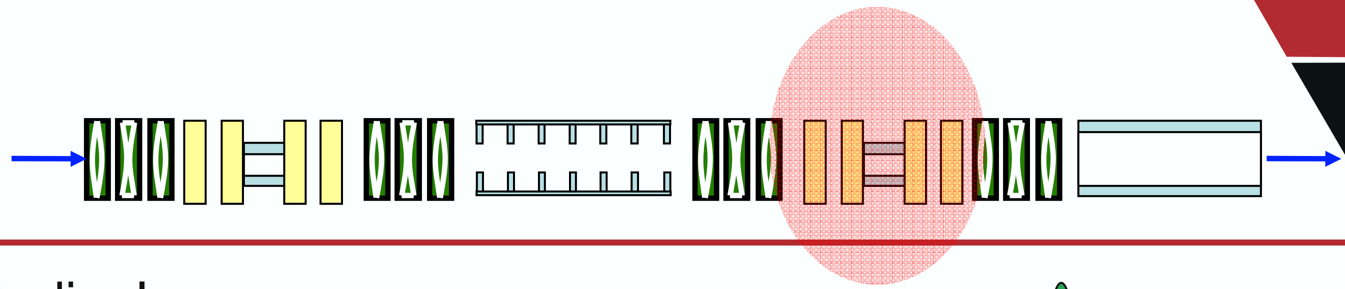


Before positrons enter bunch compressing chicane, a set of L-band Linacs are used to rotate positron longitudinal phase space.

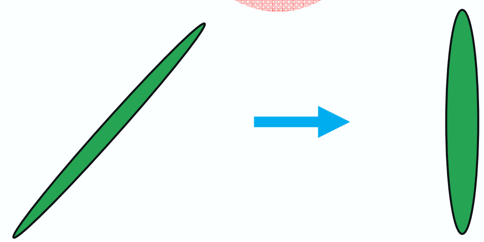
The bunch center passes through the zero crossing of the voltage of a RF cavity without acceleration, the particles ahead of the reference particle are de-accelerated, and the particles behind the reference particle are accelerated.

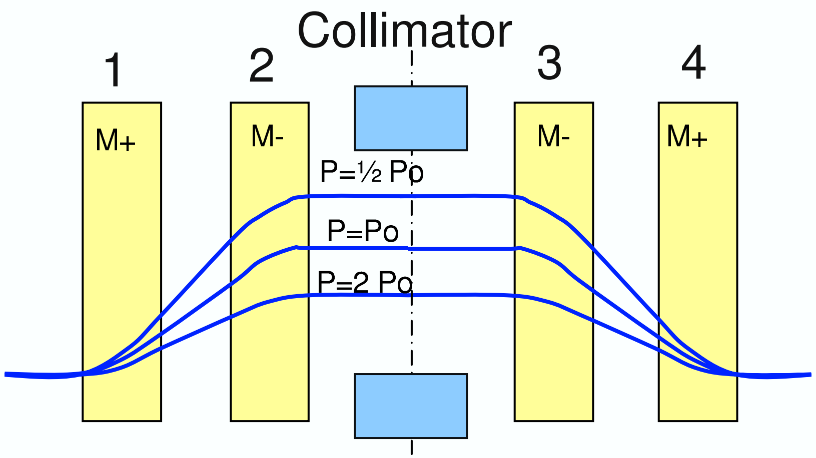


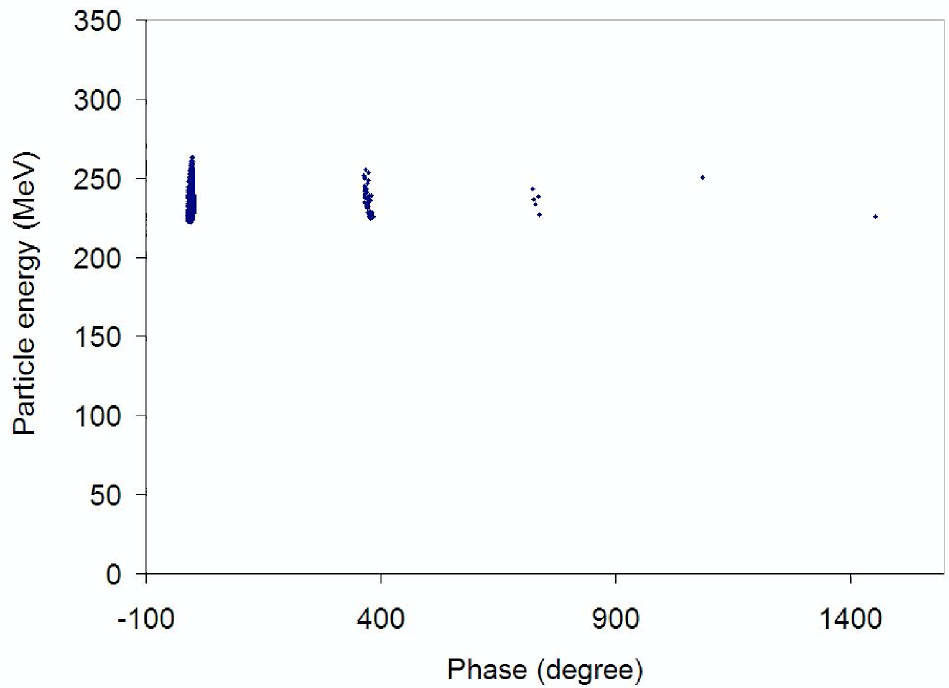
Bunch compression



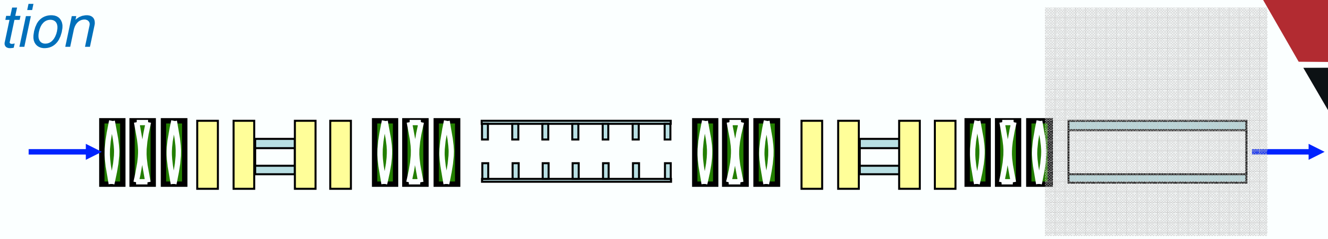
After rotating longitudinal phase space, we use another magnetic chicane to compress beam bunch.







Transverse collimation

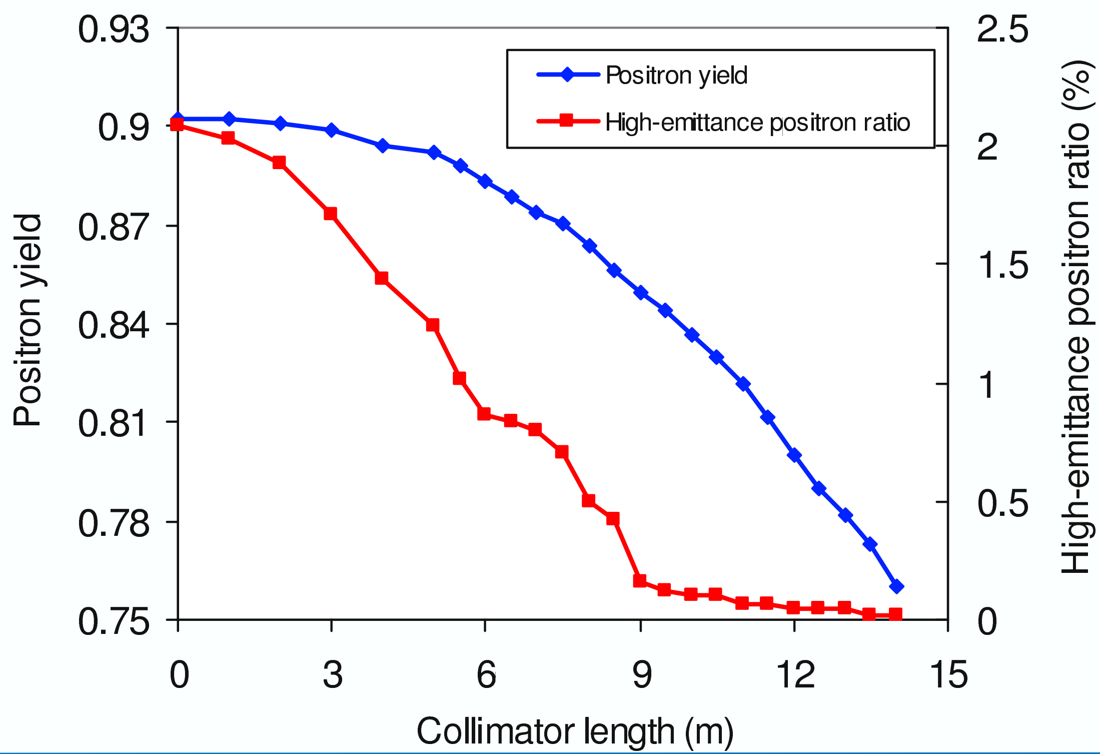


At the end of bunch compressing chicane, norm. transverse emittance of about 2% positrons among the 1st RF bucket is larger than 0.09m·rad. A transverse collimator is used to remove these high-emittance positrons.

PARMELA simulation showed increasing collimator length, both high-emittance positron ratio and positron yield decrease. With collimator length equal to 9 meters, high-emittance positron ratio is close to zero (0.16%), and positron yield is 0.85.

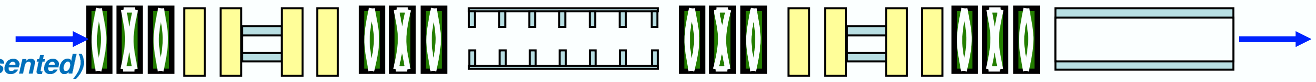
High-emittance positron ratio: the ratio of number of positrons with norm. transverse emittance larger than 0.09m·rad to the total number of positrons in the 1st RF bucket.

Positron yield: Number of positrons satisfying damping ring acceptance yielded by one electron passing through undulator with 100m in length.

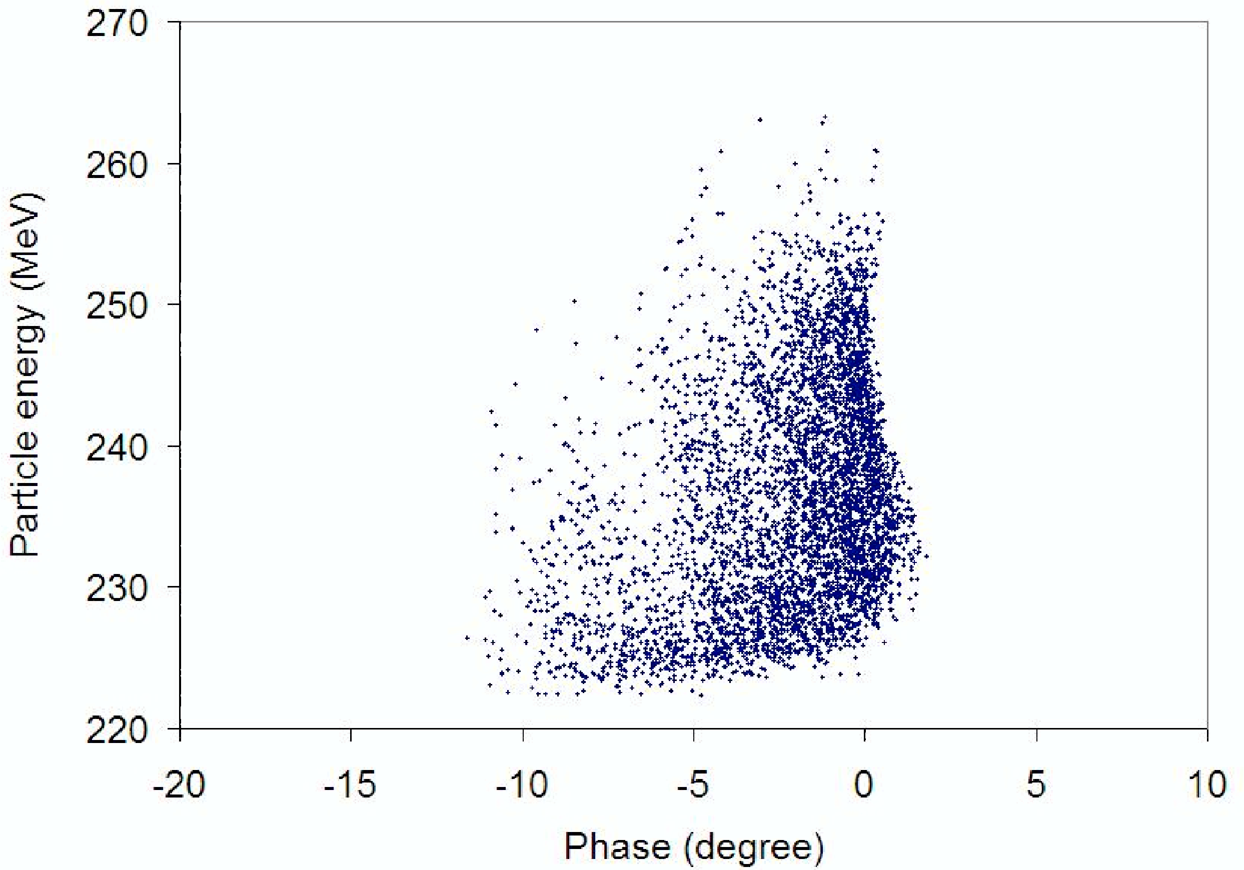


Positron longitudinal distribution at the end of positron separation optics

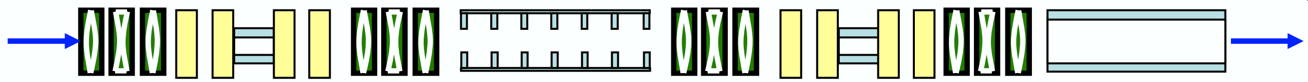
(only particles in 1st RF bucket is presented)



Positron yield: 0.85, polarization: 60%.
Compared to numerical separation, positron yield reduce about 25%.



Settings of positron separation optics



Momentum selection chicane:	
bending angle (degree)	25
Bend radius of curvature (cm)	177.5
collimator radius (cm)	4
Longitudinal phase space rotation Linac	
Linac type	5-cell L-band π -mode standing wave
frequency (GHz)	1.3
Accelerating gradient (MV/m)	12
Number of Linacs	8
Bunch compressing chicane:	
bending angle (degree)	21
Bend radius of curvature (cm)	261
collimator radius (cm)	3
Transverse emittance collimator:	
Aperture radius (cm)	4
Length (m)	9

Keep alive positron source -- In collaborating with SLAC

- From GDE: a 0.3 nC e+ beam keep alive source from a conventional target with drive beam energy of ~ 500 MeV and maximum intensity of ~ 4×10^{10} e-
- Identical beam line for polarized positron source is used. When AMD is off, the AMD field is replaced by a uniform Bz field of 0.25T.
- Electron energy deposition on the target is calculated with the assumption of 0.3nC positrons in the captured positron beam.
- Damping ring acceptance: 1% energy spread and $\gamma Ax+\gamma Ay<0.09$m-rad.
- The positron yield is normalized to per incident electron.

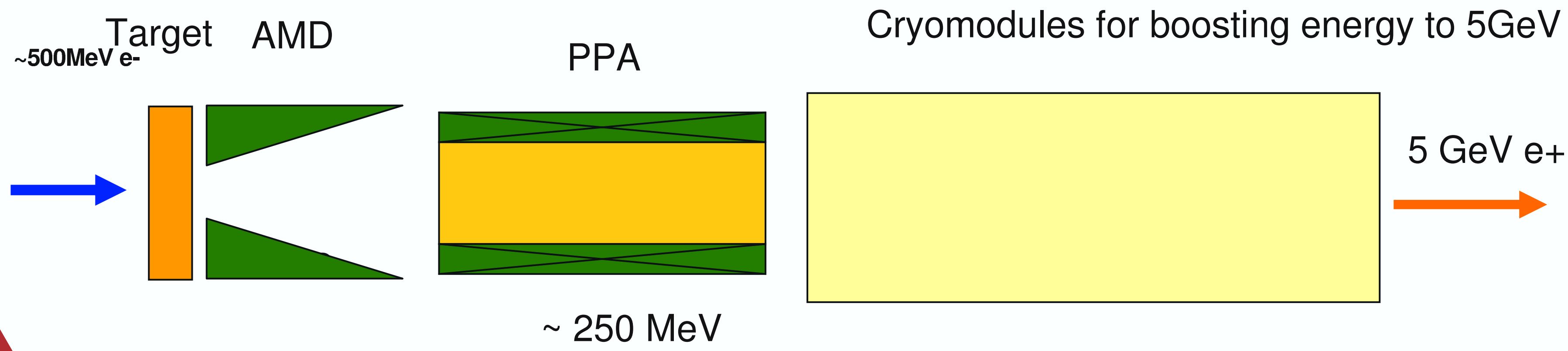


Table requested by GDE (John Sheppard)

Target	e- Beam size	e- Energy	Raw Yield	Emittance	Capture Yield	AMD
0.2 r.l. Ti	1mm	500MeV	0.0375	0.007	0.011	ON
0.4 r.l. Ti	1mm	500MeV	0.126	0.011	0.031	ON
4.0 r.l. W	1mm	500MeV	1.327	0.021	0.216	ON
0.2 r.l. Ti	1mm	500MeV	0.0375	0.007	0.0034	OFF
0.4 r.l. Ti	1mm	500MeV	0.126	0.011	0.008	OFF
4.0 r.l. W	1mm	500MeV	1.327	0.021	0.029	OFF

Energy deposition for recommended e- energy(500MeV) and intensity(4e10) are:

- 0.2 rl Ti: 0.0336(J)
- 0.4 rl Ti: 0.0757(J)
- 4.0 rl W: 1.17 (J)

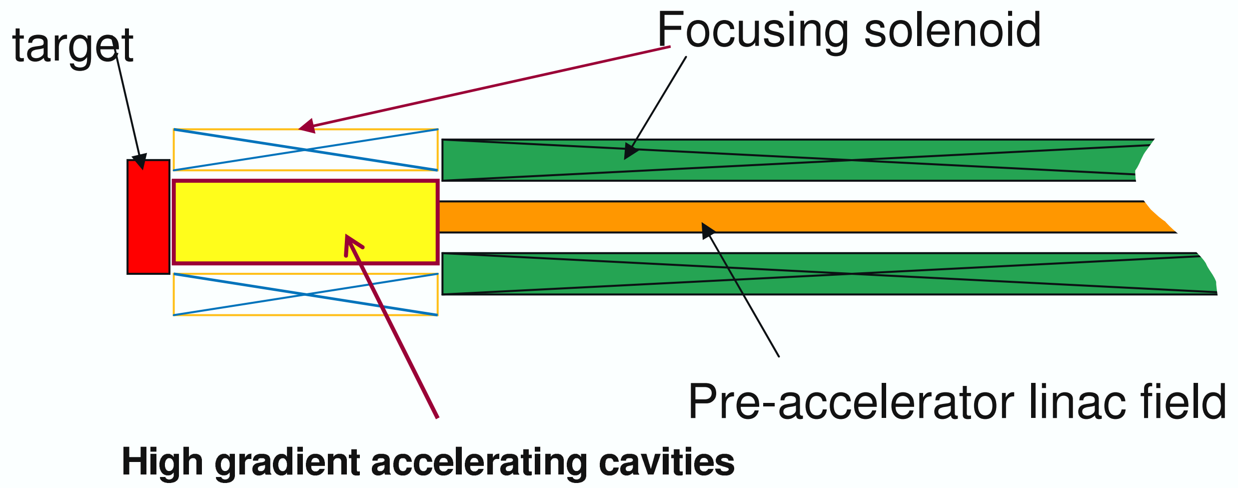
Based on our calculation, the minimal requirements are:

Target	e- Beam size	e- Energy	Raw Yield	Capture Yield	AMD
4.0 r.l. W	2mm	300MeV	0.717	0.105	ON
4.0 r.l. W	0.5mm	700MeV* Double e-	1.908	>0.05	OFF

NOTE: The captured yield for 4 rl W when AMD off is estimated with assumption of bunch compressing in beamline (it was shown by Roger, Juwen and Klauss that compression could enhance the yield by 20 – 30%). A special design would increase this number and thus lower the e-energy by employing a positron gun idea.

Summary on keep alive source

- For the keep alive source, a 4rl W target will work. 0.4rl Ti target can not produce enough e+.
- Further work will explore new ideas such as: pulse compression, high gradient, fast acceleration (positron gun).



Summary

- Developed a complete start-to-end numerical model of the ILC positron source
- An ILC positron separation optics layout was designed for select positrons to fit damping ring acceptance.
- Continue to expand our capabilities.