Helical Undulator Based Positron Source for LC

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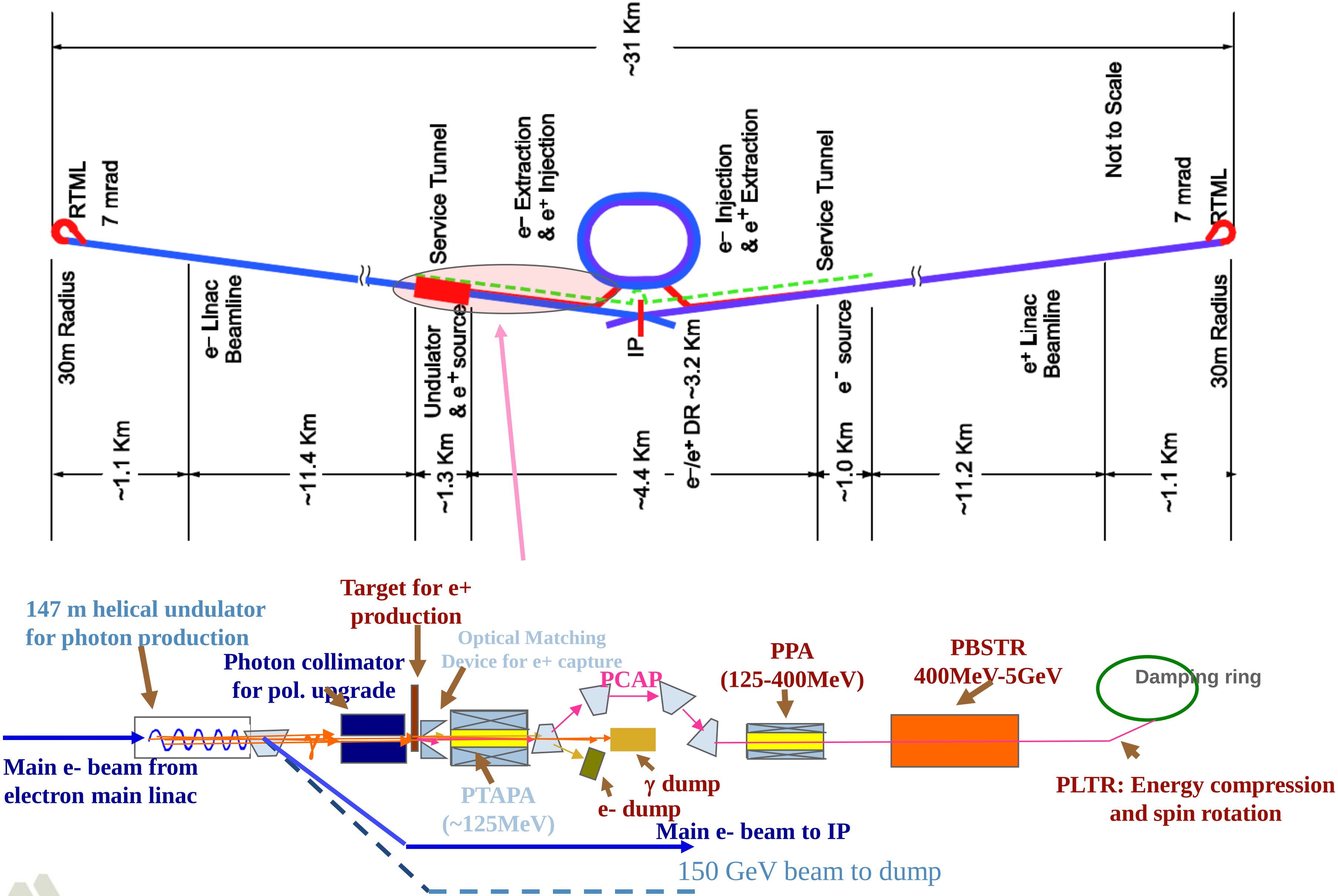
05/29/2013

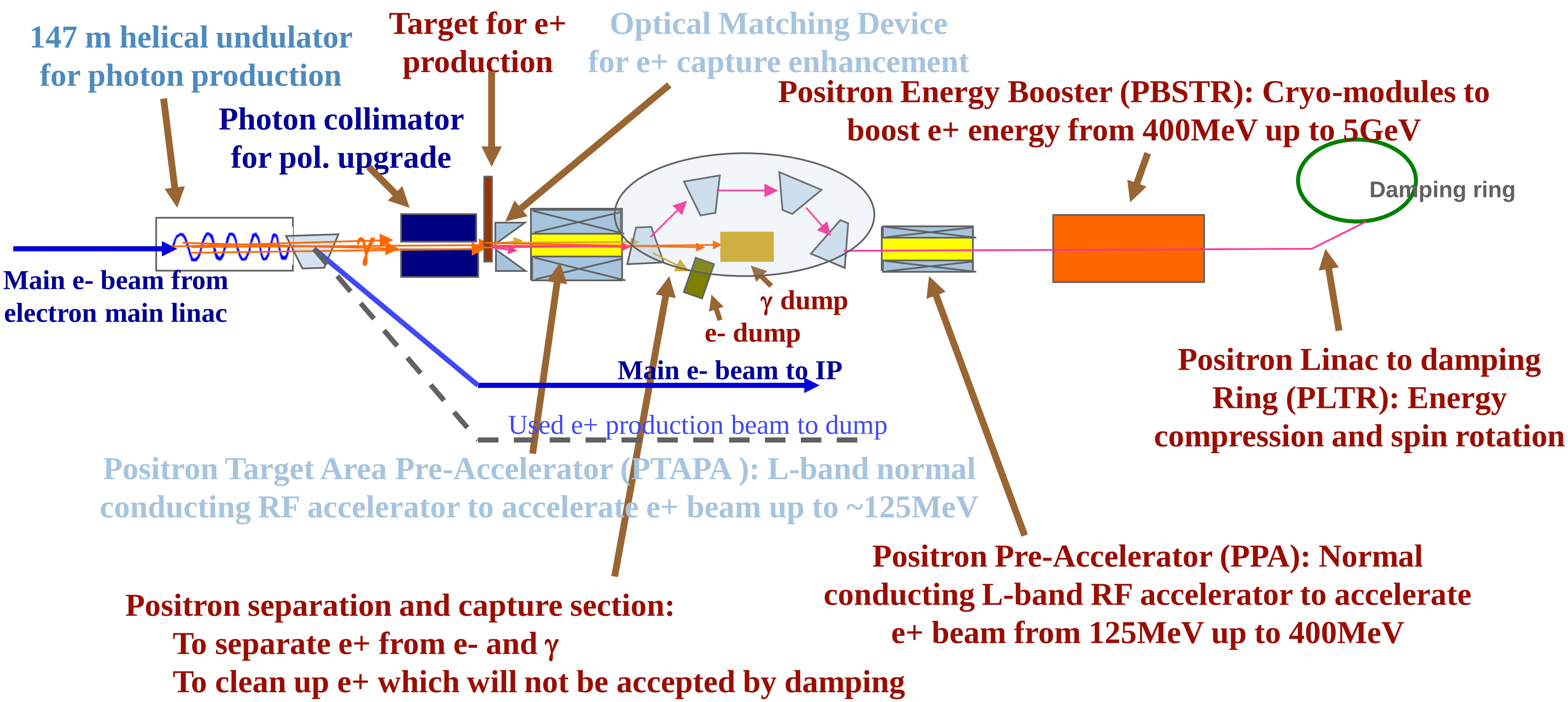
Outline

- Undulator based positron source for ILC
- Photon beam from helical undulator
  - Effects from undulator
  - Effects from drive beam
- Polarization of positron beam under different conditions
- Practical issues

ILC TDR positron source location

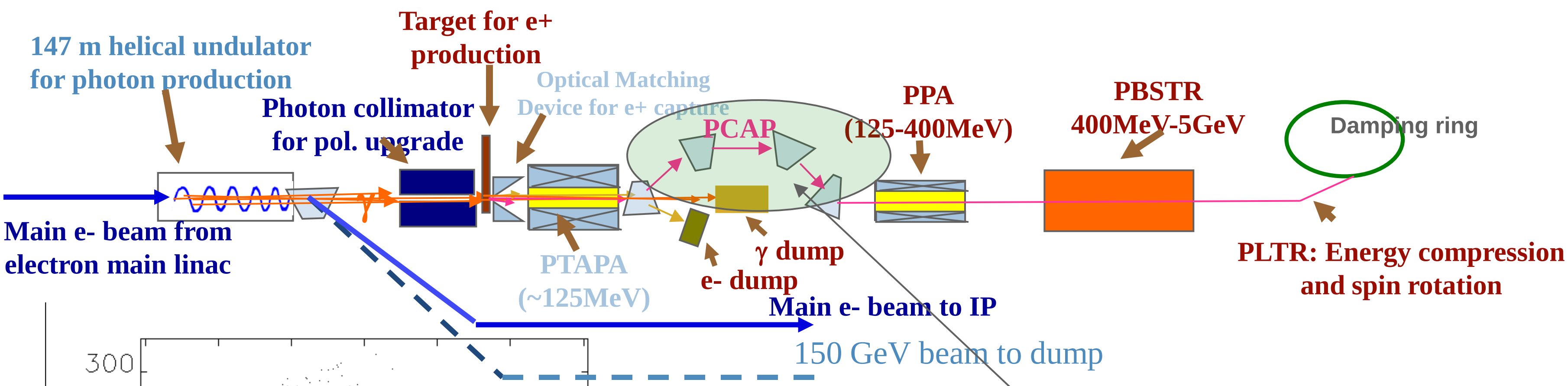


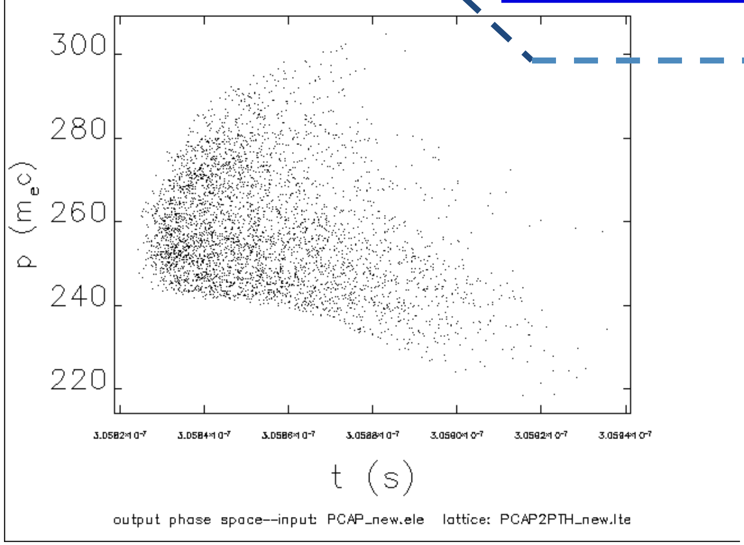
ILC Positron source schematic with key components



- When Ecm is bellow 300GeV, the machine will be working in 10Hz mode where a dedicated 5Hz 150GeV positron production beam will be interlaced with 5Hz luminosity production beam

Positron separation



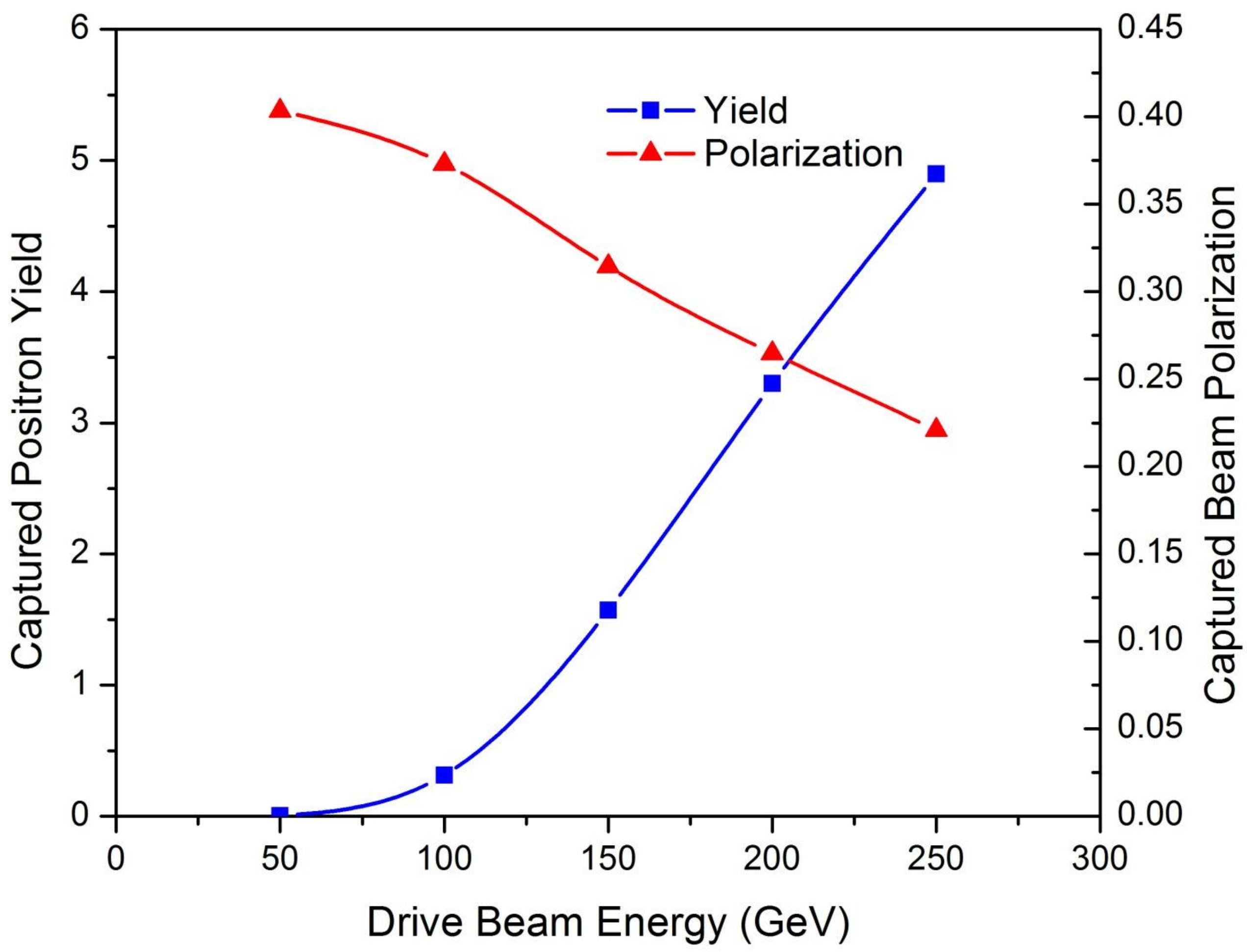


Positron separation beamline

Typical longitudinal distribution after PCAP

- Positron separation beamline (PCAP section) is used to separate positrons beam from electrons and γ beam.
- The electron beam and γ beam will be dumped into the e- dump and γ dump.
- The positrons with energy too low and too high will be cleaned up in this chicane using collimators.
- The length of this section is 74m

Drive beam energy dependence study (no collimation)



Nominal parameters of ILC positron source

Parameter	Symbol	Value	Units
Positrons per bunch at IP	n_b	2×10^{10}	number
Bunches per pulse	N_b	1312	number
Pulse Repetition Rate	f_{rep}	5	Hz
Positron Energy (DR injection)	E_0	5	GeV
DR Dynamic Aperture	$\gamma(A_x + A_y)$	<0.07	m rad
DR Energy Acceptance	Δ	0.75	%
DR Longitudinal Acceptance	A_l	3.4 x 37.5	cm-MeV
Electron Drive Beam Energy[a]	E_e	150/175/250	GeV
Undulator Period	λ	1.15	cm
Undulator Strength[b]	K	0.92/0.75/0.45	-
Undulator Type	-	Helical	-
Undulator Length	L_u	147	m
Photon Energy (1^{st} harm cutoff)	E_{c10}	10.1/16.2/42.8	MeV
Photon Beam Power	P_γ	63.1/54.7/41.7	kW
Target Material	-	Ti-6%Al-4%V	-
Target Thickness	L_t	0.4 / 1.4	r.l. / cm
Target Absorption	-	7	%
Incident Spot Size on Target	σ_i	1.4/1.2/0.8	mm, rms
Positron Polarisation	P	31/30/29	%

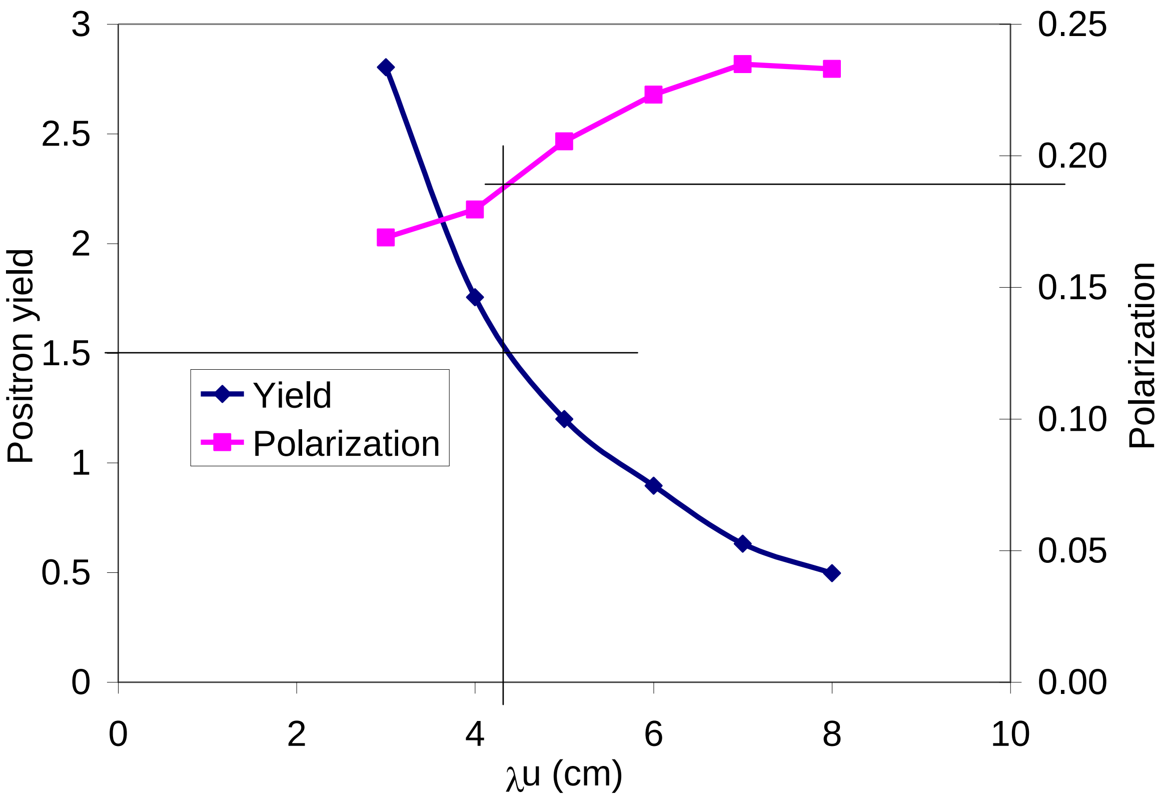
[a] For centre-of-mass energy below 300 GeV, the machine operates in 10 Hz mode where a 5 Hz 150 GeV beam with parameters as shown in the table is a dedicated drive beam positron source.

[b] K is lowered for beam energies above 150 GeV to bring the polarisation back to 30 % without adding a photon collimator before the target.

TeV upgrade

- High drive beam energy, 500GeV which doubles the 250GeV TDR maximum
  - photon beam energy increases by factor of 4 results in a larger energy spread and more positrons with unwanted polarization
  - Smaller radiation angle results in smaller beam spot on target and thus higher energy deposition density
- Solution
  - New undulator, challenges exist in finding the parameter set with photon number spectrum similar to RDR undulator with 150GeV drive beam

With Fixed K=1 and different undulator period length



Based on the above plot, λu=4.3 is used for a more detail simulation to evaluate the energy deposition and impact on drive beam

Photon collimator for Polarization upgrade

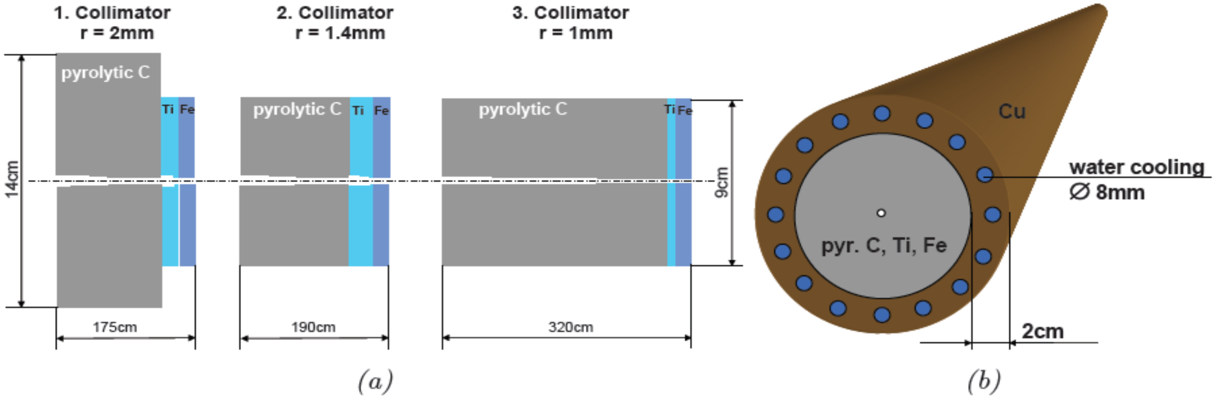


Figure 4.12. Basic layout of the multi-stage photon collimator at the positron source: (a) longitudinal section; (b) three-dimensional CAD model showing copper lading and water-cooling channels.

Parameter	Unit					L upgrade
Centre-of-mass energy	GeV	200-250	350	500	500	500
Drive-electron-beam energy	GeV	150	175	250	250	250
Undulator K value				0.92		
Undulator period	cm			1.15		
Positron polarisation	%	55	59	50	59	50
Collimator-iris radius	mm	2.0	1.4	1.0	0.7	1.0
Active undulator length	m	231	196	70	144	70
Photon beam power	kW	98.5	113.8	83	173	166
Power absorbed in collimator	kW	48.1	68.7	43.4	121	86.8
Power absorbed in collimator	%	48.8	60.4	52.3	70.1	52.3

- A photon collimator is not required for the TDR baseline
- As part of positron source upgrade study, DESY team developed a photon collimator design. With the designed photon collimator, positron source polarization can be increased from ~30% up to 50-60% depending on the colliding beam energy

Photon Number and Polarization of Radiation from Undulator

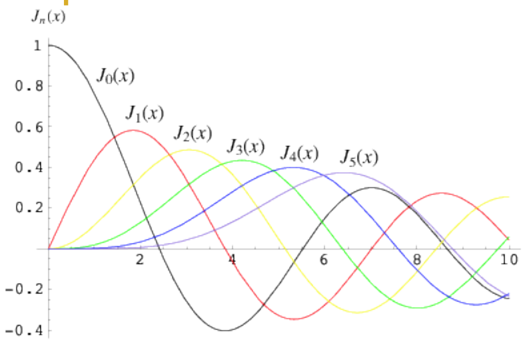
Helical undulator:

Can produce circularly polarized photon, good for polarized e+ source.

$$\frac{dN_{ph}}{dE} = \frac{10^6 e^3}{4\pi\varepsilon_0 c^2\hbar^2} \cdot \frac{K^2}{\gamma^2} \sum_{n=1}^{\infty} (J_n^{'}(x)^2 + [\frac{\alpha_n}{K} - \frac{n}{x}]^2 J_n(x)^2)$$

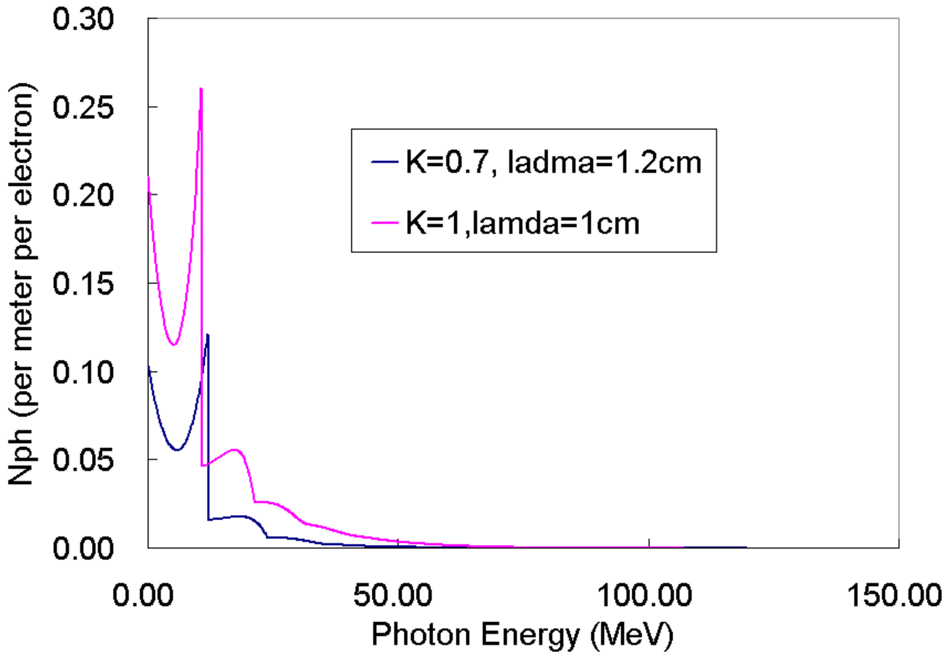
$$\alpha_n^2 = [n\frac{\omega_1(1+K^2)}{\omega} - 1 - K^2]$$

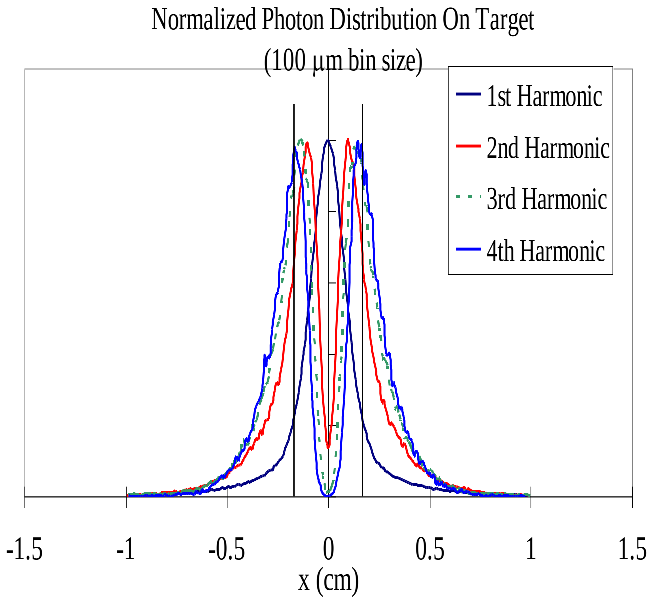
$$x = 2K\frac{\omega}{\omega_1(1+K^2)}\alpha_n \qquad E_1 = \hbar\omega_1 = \hbar\frac{4\pi\gamma^2 c}{(1+K^2)\lambda_u}$$



Higher k, more high order harmonics contents.

Smaller k, fewer high order harmonics, less photon flux, higher photon energy





Formulas about the polarization characteristics of helical undulator radiation*

- The amplitude of radiation from helical undulator can be obtained as

$$Ix(E,\Theta)=\sum_{n=1}^{\infty}\sqrt{\frac{10^6 e^3}{4\pi\varepsilon_0\hbar^2c^2}}\frac{K}{\gamma}[\frac{\alpha_n}{K}-\frac{n}{x}]J_n(x)\delta(\gamma^2\Theta^2-\alpha_n{}^2)$$

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

Where,

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

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

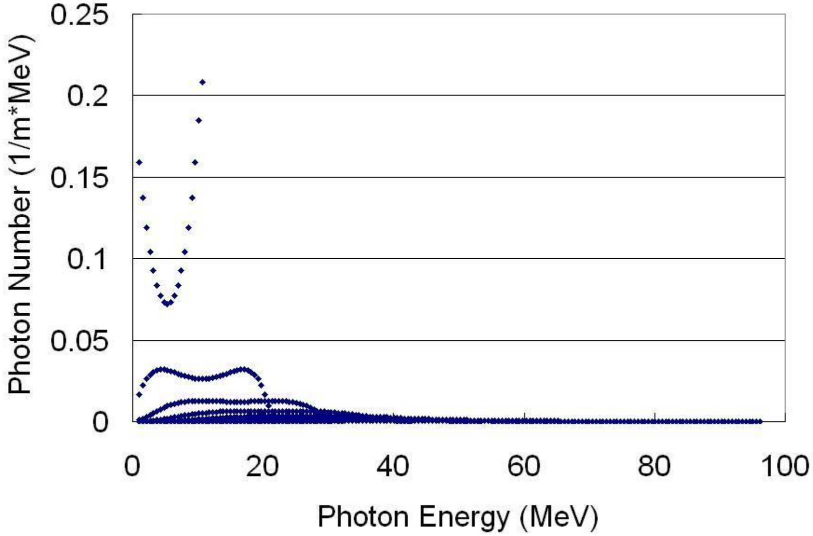
From which the Stokes parameters is obtained as:

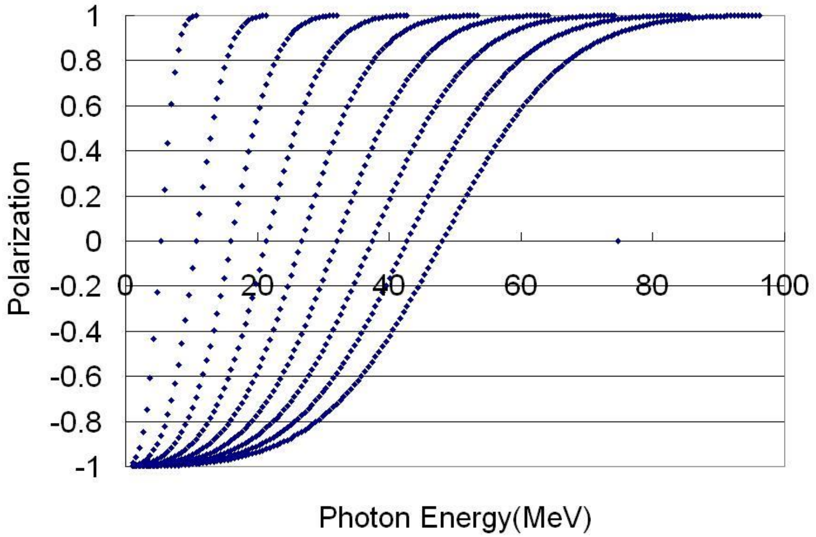
$$\xi_1=\frac{I_x{}^2-I_y{}^2}{I_x{}^2+I_y{}^2},\ \xi_2=0,\ \xi_3=\frac{2I_xI_y}{I_x{}^2+I_y{}^2} \qquad (2)$$

* Klaus Flottmann, Investigation toward the development of polarized and unpolarized high intensity positron sources for linear colliders, DESY 93-161

Results ---Photon number spectrum and polarization characteristics

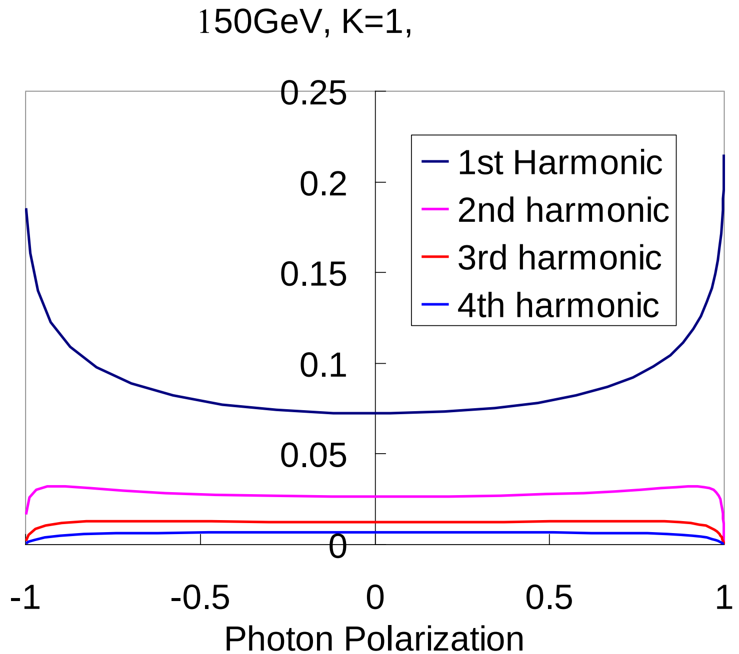
Results of photon number spectrum and polarization characteristic of ILC undulator are given here as examples. The parameter of ILC undulator is K=1, λu=1cm and the energy of electron beam is 150GeV.

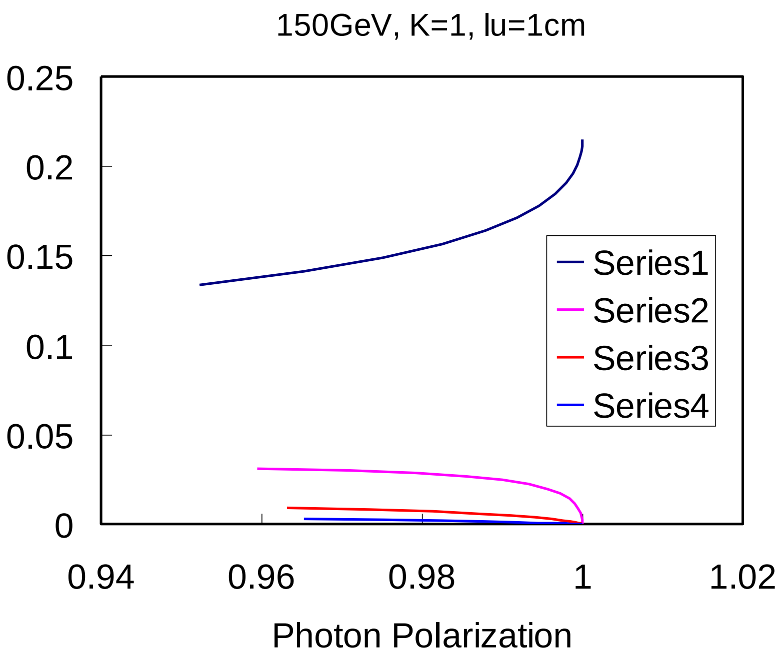




Photon Number spectrum and polarization characteristics of ILC undulator up to the 9th harmonic

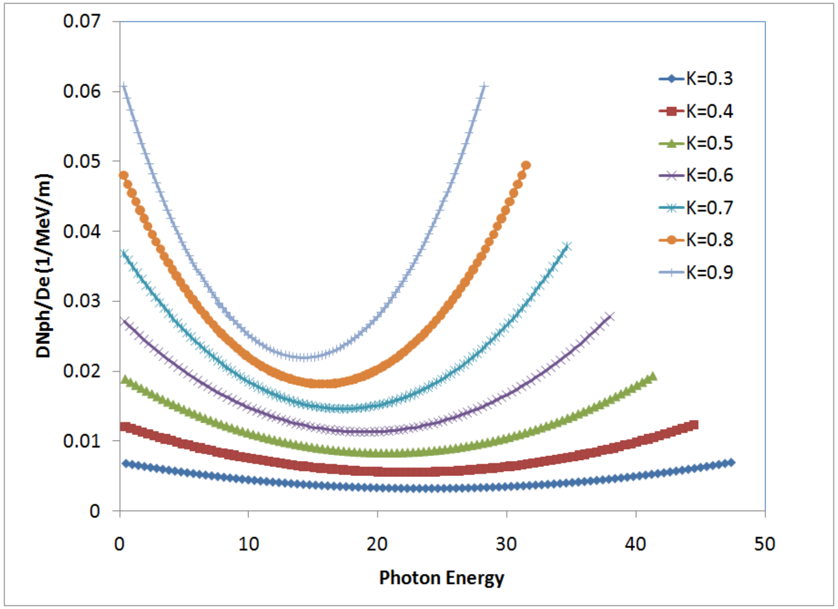
Results, photon number vs polarization before and after collimator





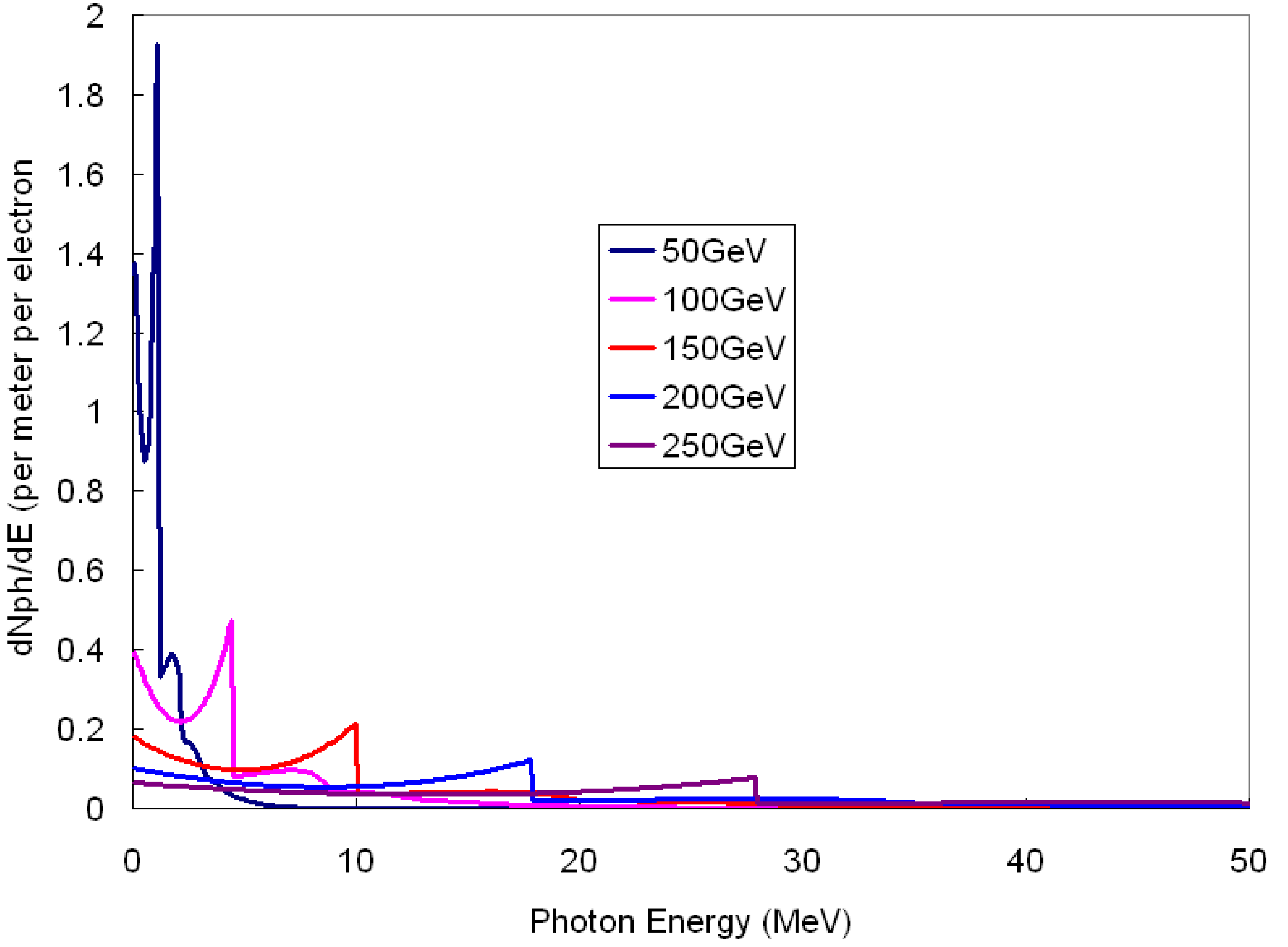
the relation between photon number and their polarization before and after collimator with acceptance angle of 2.1e-6 rad. After the collimator, only photons with polarization greater than 0.95 will survive.

Effect of K

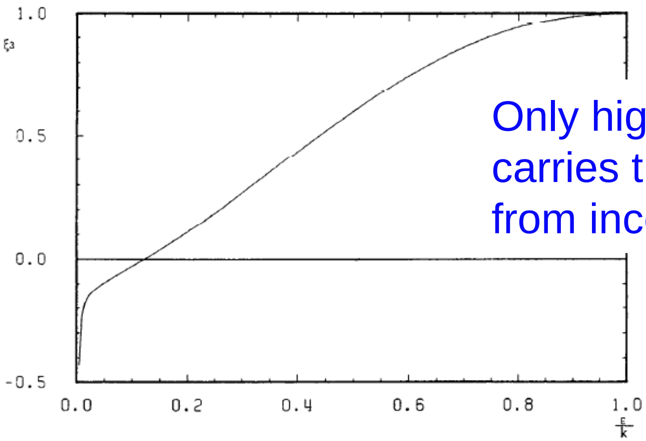


- Disadvantage of Low K: increase the critical energy of photon of helical undlator radiations and lower the number of photon produced for a given length of undulator.
- Advantage of low K: lower high order harmonic radiation

photon number spectrum for different drive beam energy



Some facts about pair production



Longitudinal polarization of e+ or e- as function of its fractional energy

Only high energy e+ carries the polarization from incoming photon

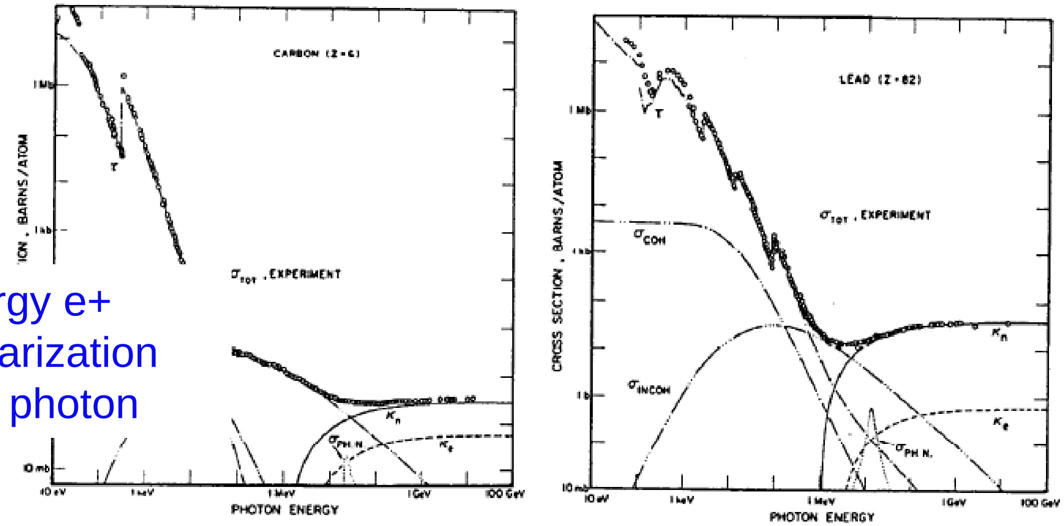
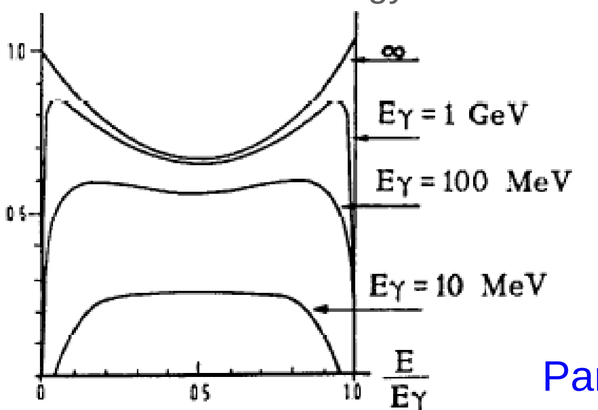


Fig. 1.1 Photon total cross section as a function of energy in Carbon and Lead [ref. 58]

τ	=	atomic photo-effect
σ_{COH}	=	coherent scattering (Rayleigh scattering)
σ_{INCOH}	=	incoherent scattering (Compton scattering)
K_n	=	pair production, nuclear field
K_e	=	pair production, electron field
$\sigma_{PH.N.}$	=	photonuclear absorption

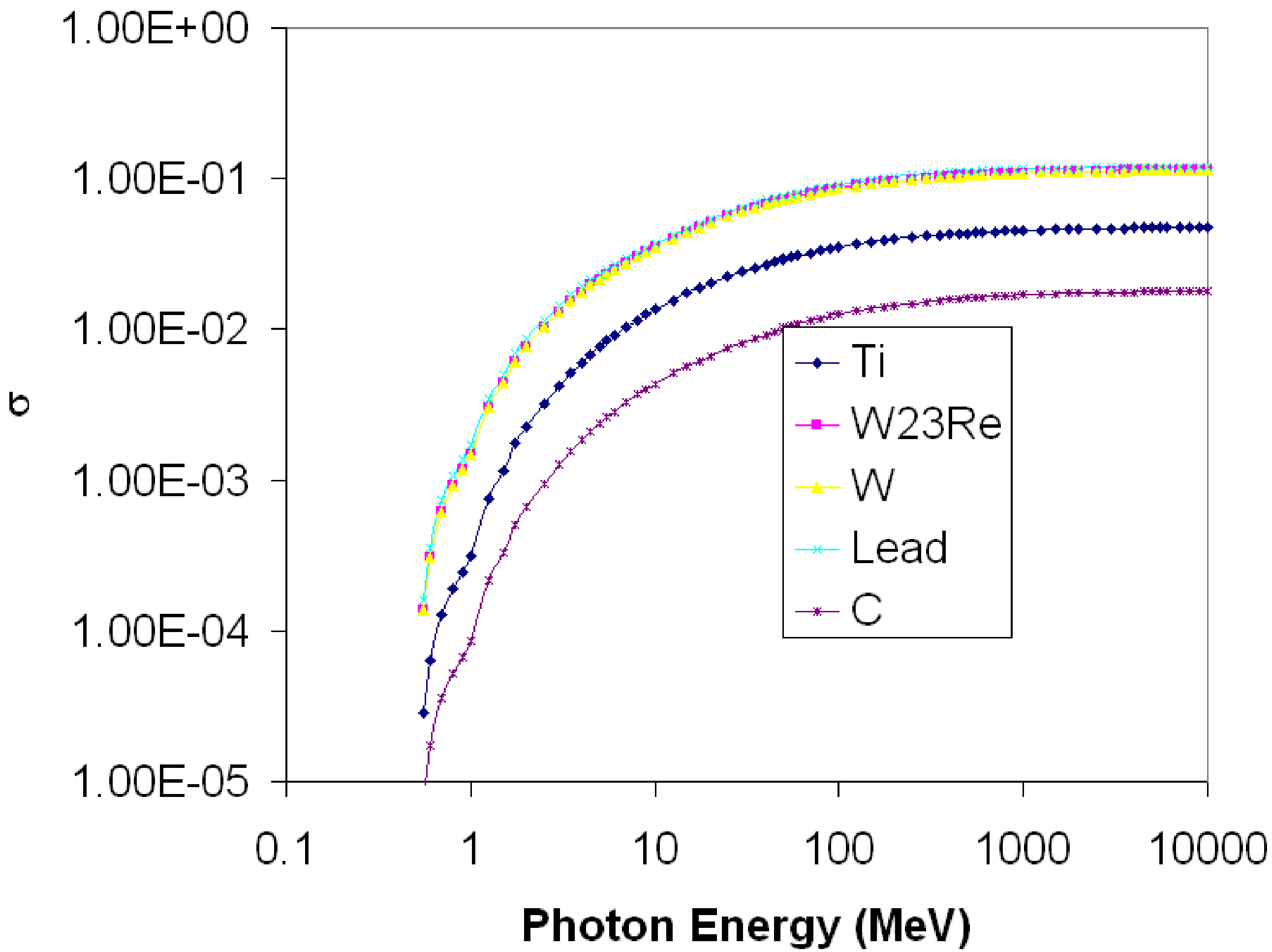
Cross section of pair production is near constant for high energy photons; high Z material tends to have a sharper leading edge for pair production cross section and higher cross section.



Particles are roughly equally distributed except for very high and very low photon energy

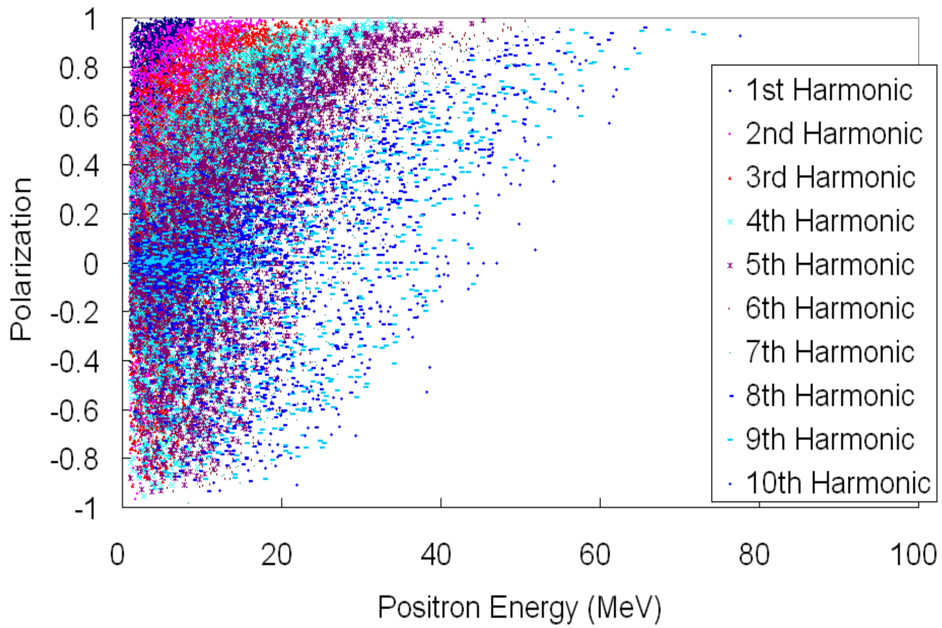
Energy distribution of e+/e- pairs as function of fractional energy

The cross section of Pair production extracted from PEGS4 (we do not use table directly)

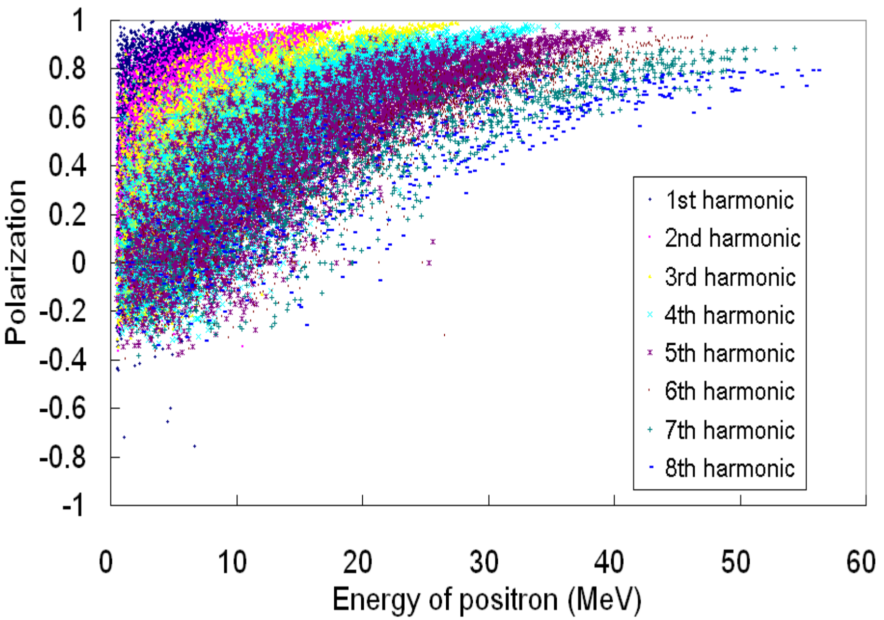


polarization vs energy of positron generated with photon from different undulator harmonics

without collimator



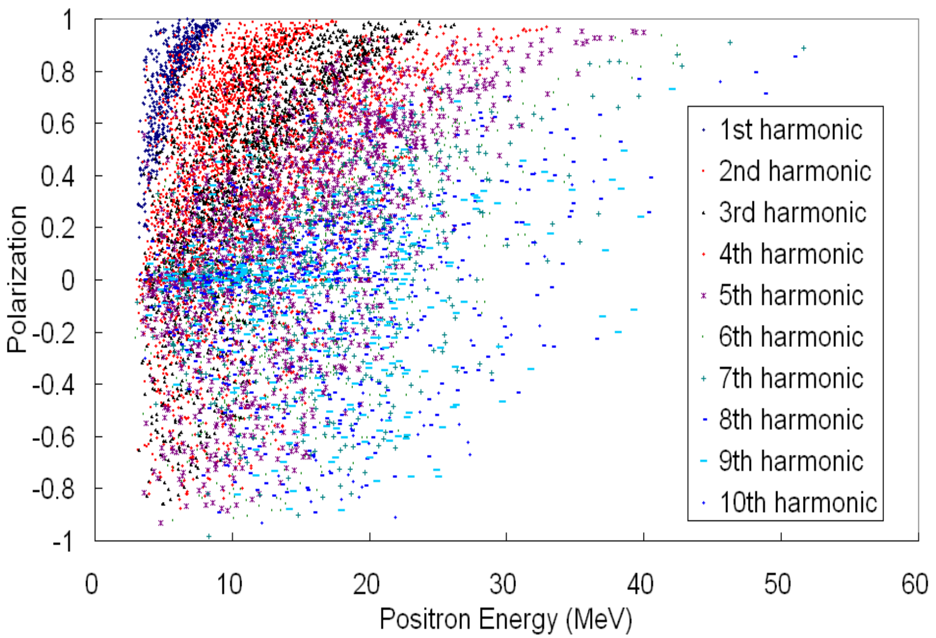
with collimator



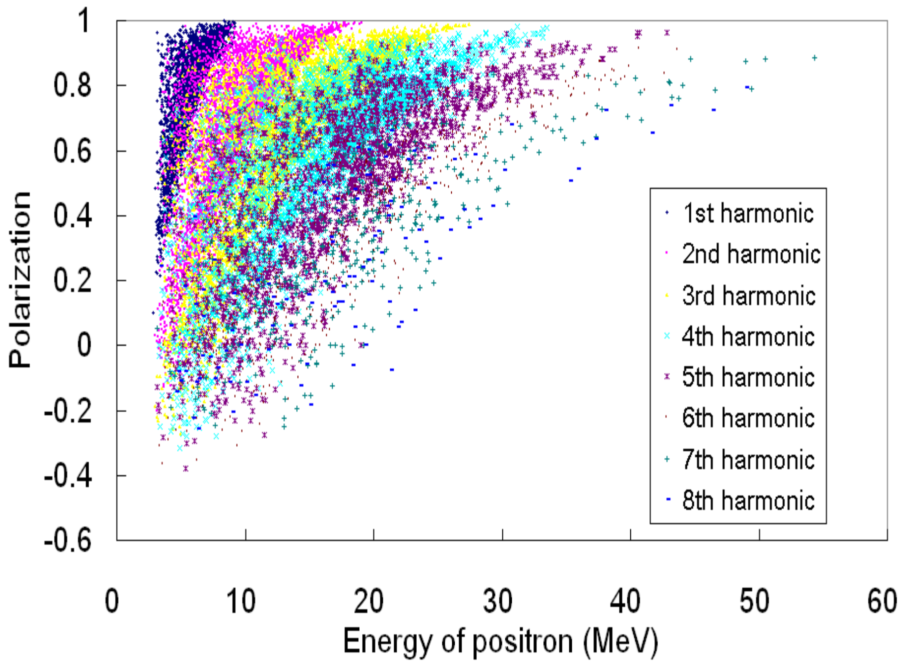
The collimator is 2.5mm in radius and is 700m away from the end of an 100m long undulator. Photons are radiated uniformly along the undulator. For the case without collimator, the photon source is treated as a point source. The collimator screened out those photon with lower polarization and thus improved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

Initial Polarization vs energy of those captured positrons

Without collimator



With collimator



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 resulting positron beam. The polarization of captured positron beam is about 30% without collimator and 63% with the collimator setting used here.

What will impact on positron polarization

- The impact on polarization of Undulator parameters
- Drive beam energy
- Photon collimator
- The capturing optics

Assumptions and conditions

- OMD: flux concentrator : 0.5T at target (z=0), 3.5T at z=2cm decrease adiabatically down to 0.5T at z=14cm.
- Target: 0.4X0 Ti
- Undulator:
  - RDR undulator and high K short period undulators
    - Length is fixed at 231m
    - Drive beam energy varies from 100GeV to 250GeV
  - RDR undulator with lower B field (Lower K)
    - K varies from 0.3 to 0.9
    - Length is fixed to 231m
    - Drive beam energy is 250GeV
- Drift between undulator end and the target: 400m long
- Photon collimator: A numerical mask with an iris at target

Undulator parameters

Photon spectrum

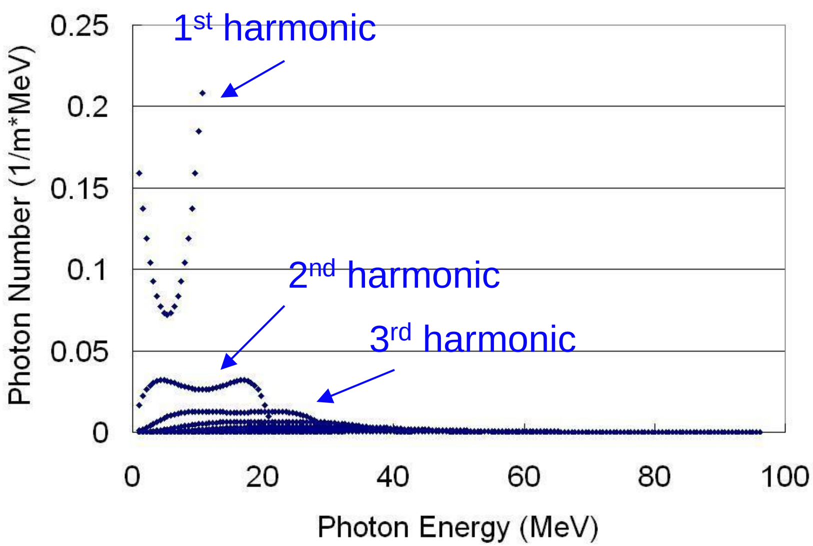
$$\frac{dNph}{dE}\left[\frac{1}{mMeV}\right] = \frac{10^6 e^2}{4\pi\varepsilon_0 c^2 h^2}\frac{K^2}{\gamma^2}\sum_1^{\infty}\left(J_n^{'}(x)^2 + \left[\frac{\alpha_n}{K} - \frac{n}{x}\right]^2 J_n(x)^2\right)$$

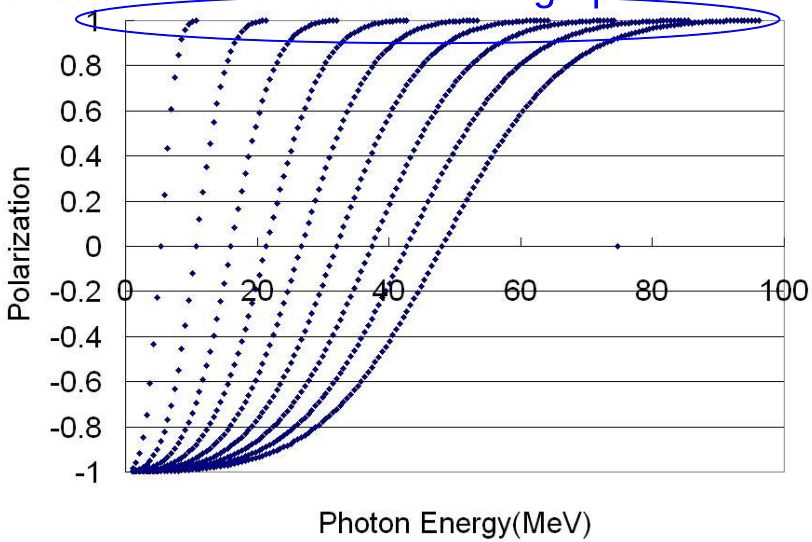
$$K = 0.934 * B[T] * \lambda_u[cm]$$

1st harmonic critical energy

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

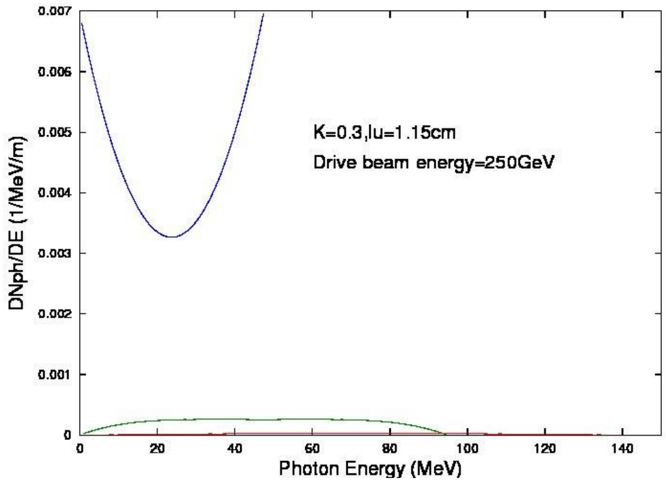
Only photons with energy near critical energy of each harmonics carries high polarization

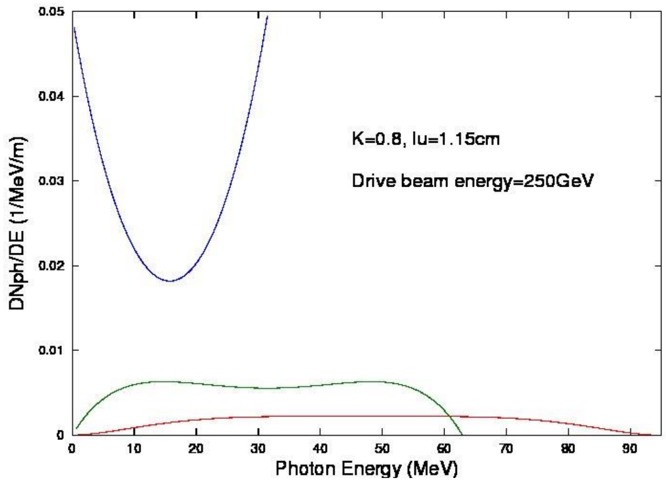




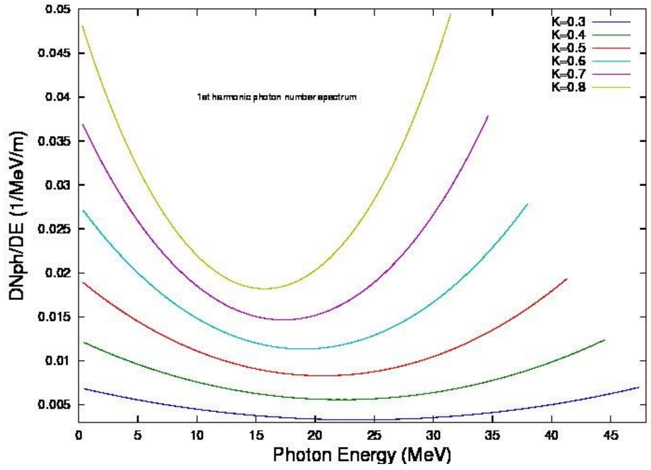
In order to have higher polarization in e+ beam, one would want to have fewer photons from higher order harmonics. 150 GeV and RDR undulator

Undulator parameters





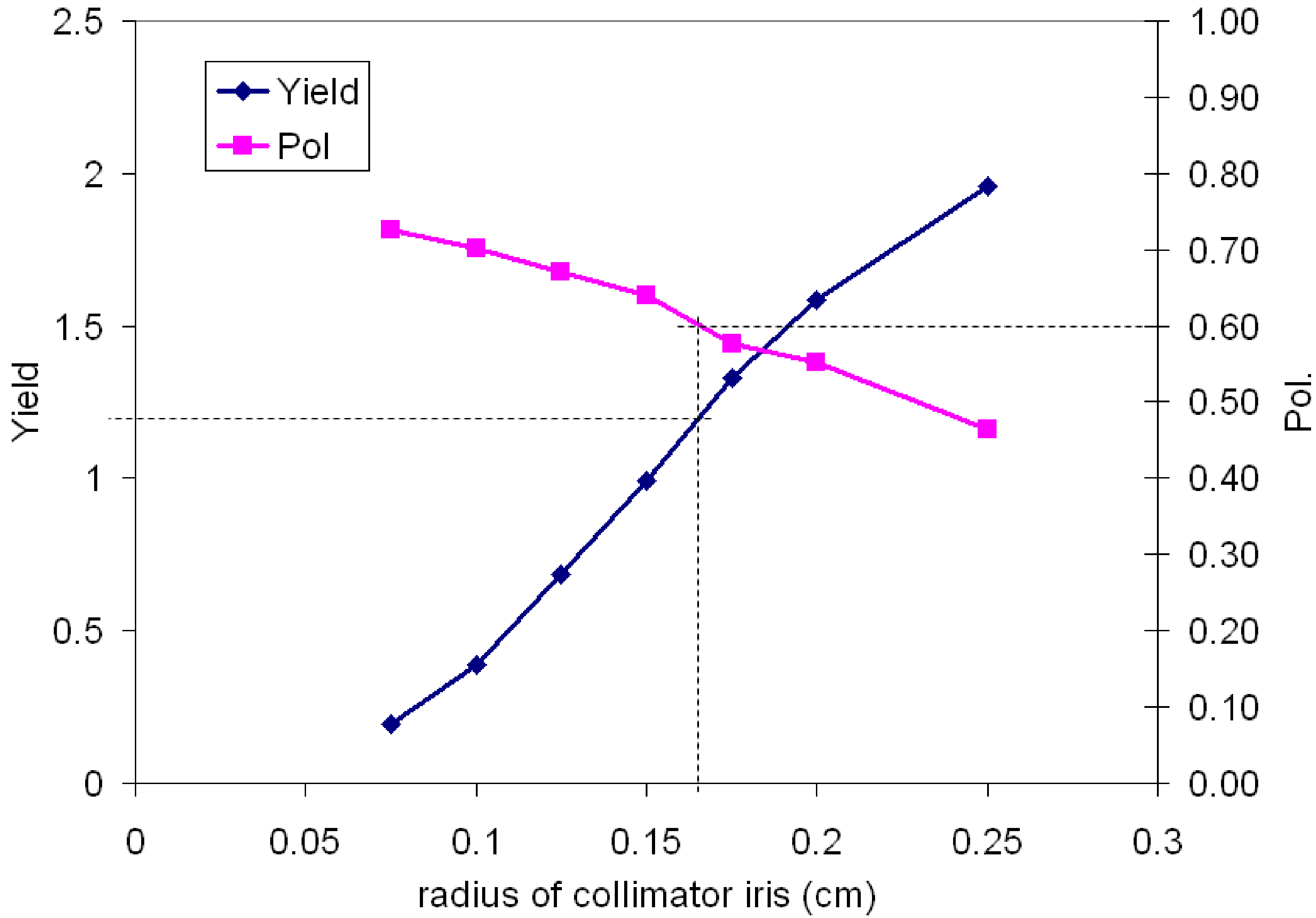
Lower K gives higher 1st harmonic radiation contents in spectrum and also higher critical energies



Lower K radiates less photons for a given length and drive beam

Lowering K can improve the polarization with a price on the e+ beam intensity

150GeV drive beam, RDR undulator (reference)

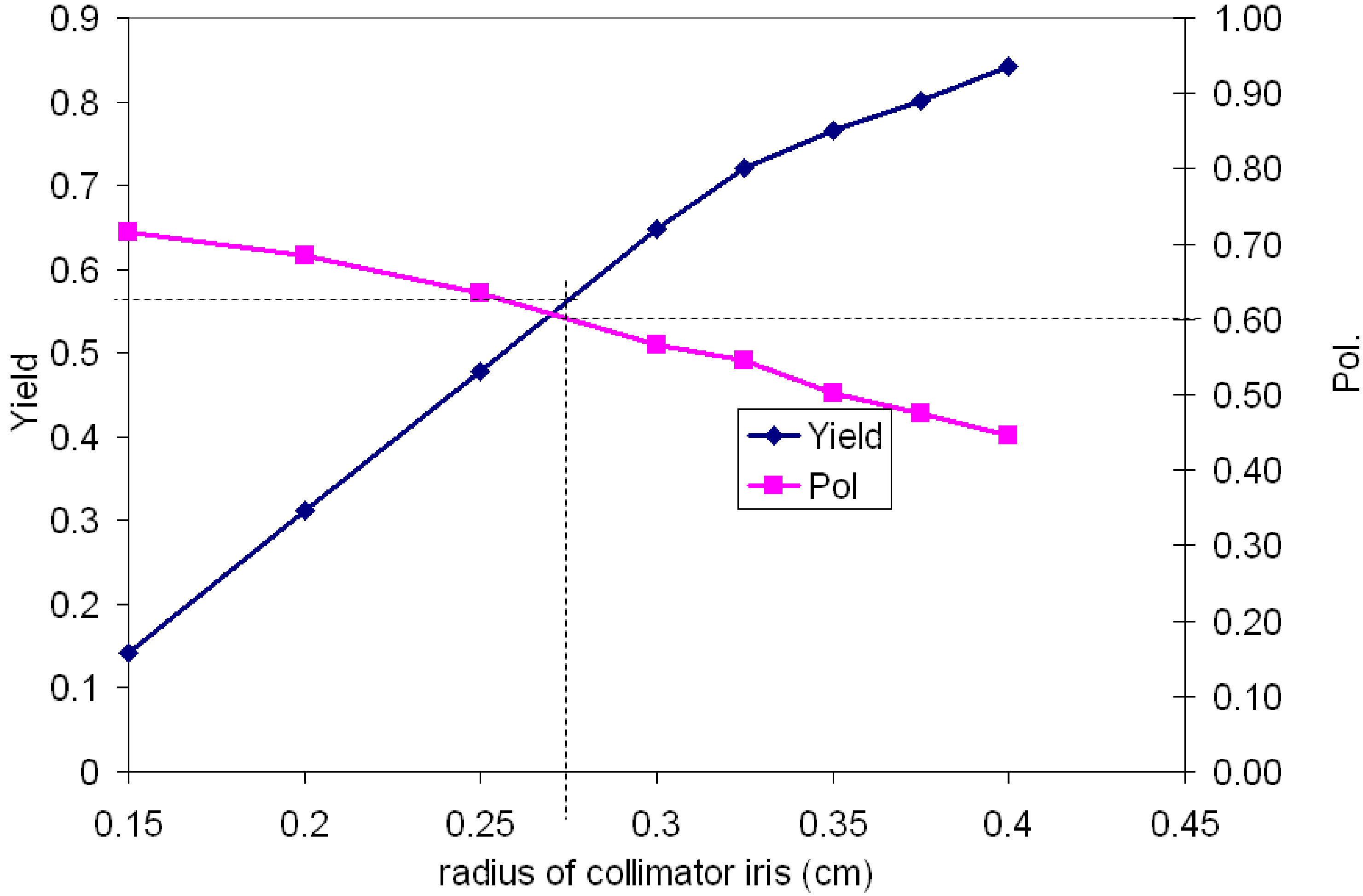


For 150GeV drive beam, 60% polarization required a photon collimator with an iris of ~1.6mm in radius. The corresponding yield is ~1.2 for 231m long RDR undulator

Examples

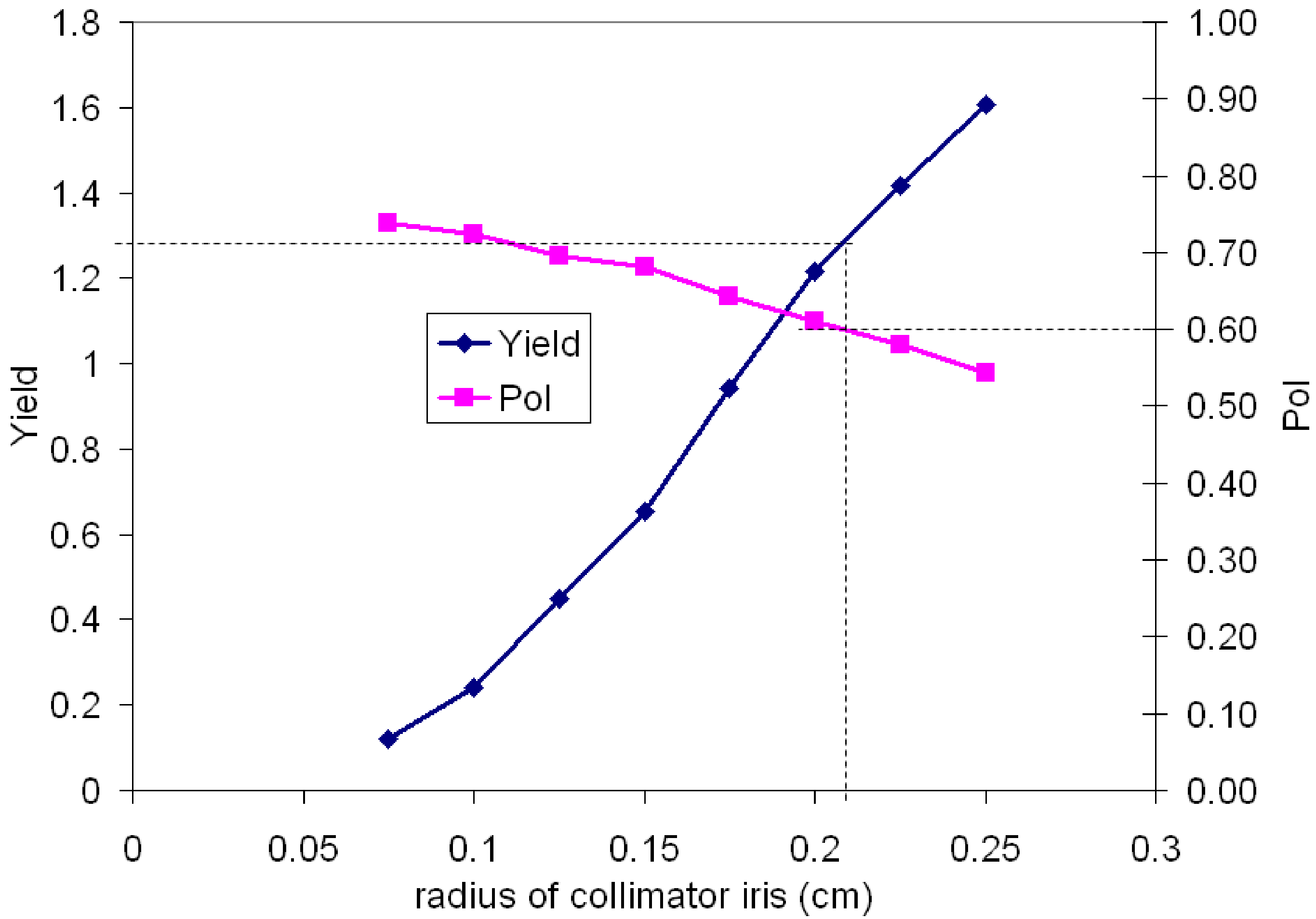
- Varying E (100 -250 GeV),
- K (0.3 – 0.9)
- Lambda (0.9 and 1.15 cm)
- Collimator radius as a variable.

Drive beam energy 100GeV, K=0.9,λu=0.9



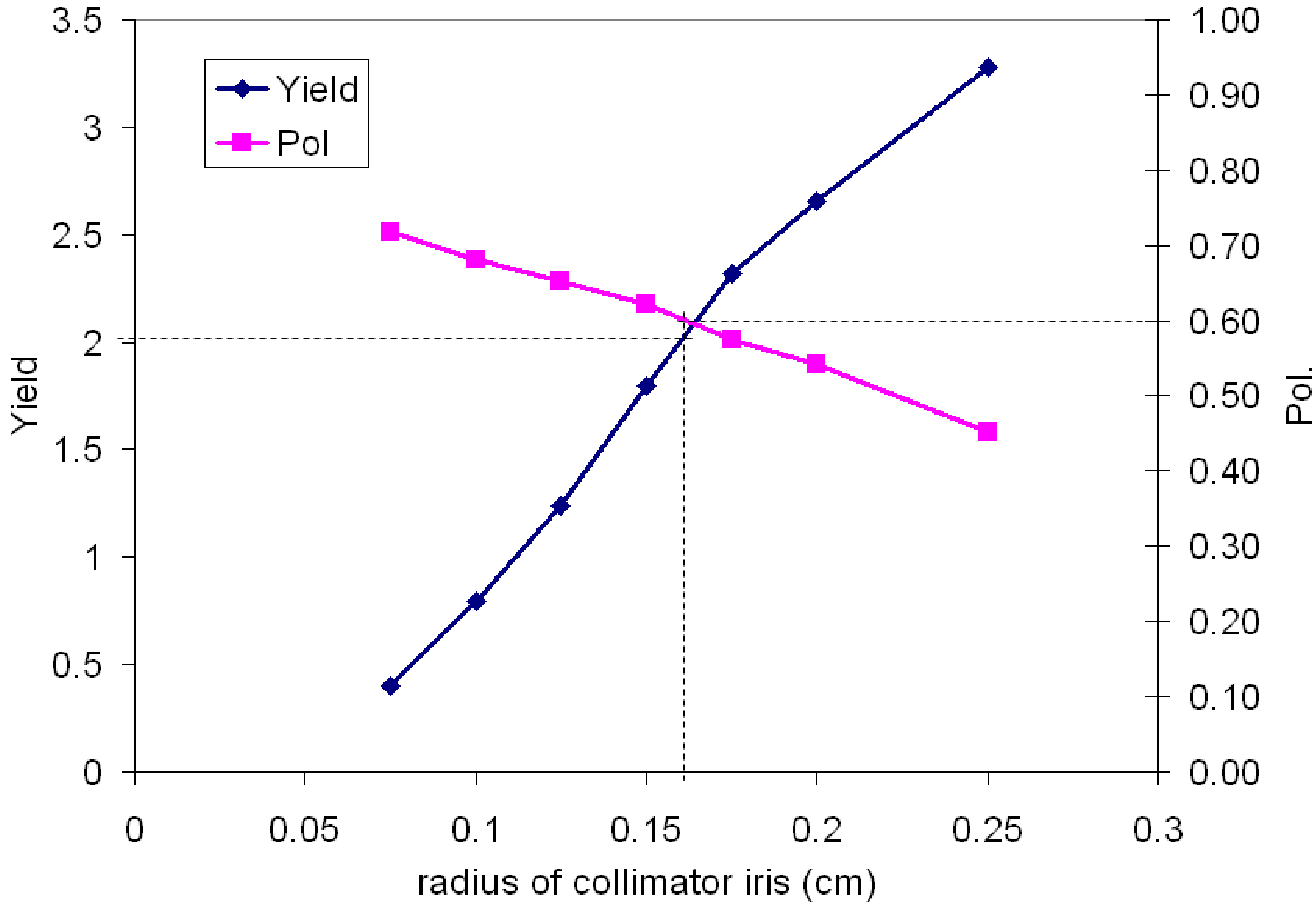
For 60% polarization, an photon collimator with iris of 2.75mm in radius is required and the corresponding yield is only ~0.57 for 231m long undulator.

Drive beam energy 125GeV, K=0.9,λu=0.9



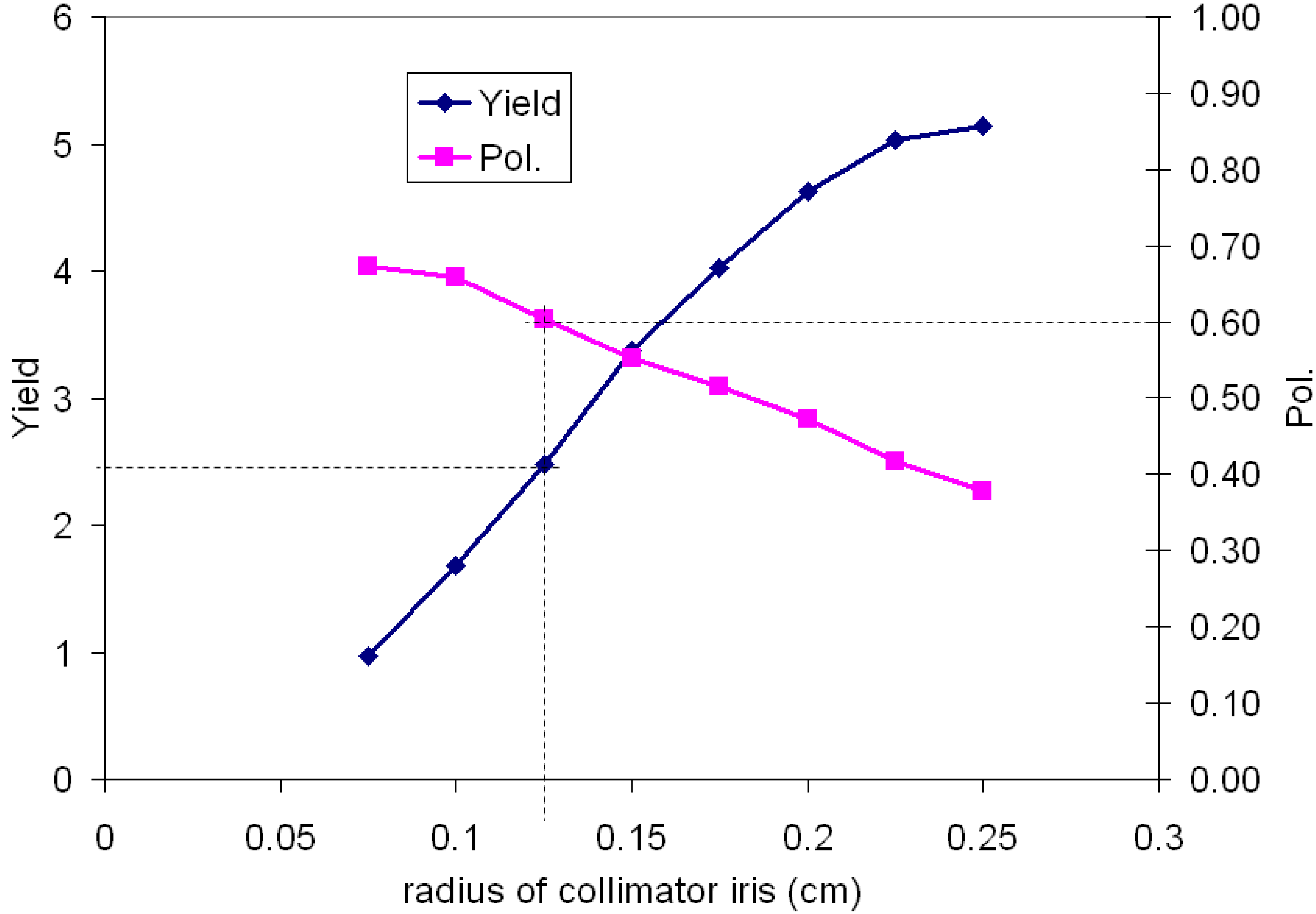
For 125GeV drive beam, the 60% polarization required a photon collimator with an iris of ~2.1mm in radius and the corresponding yield is ~1.28 for 231m long undulator

Drive beam energy 150GeV, K=0.9,λu=0.9



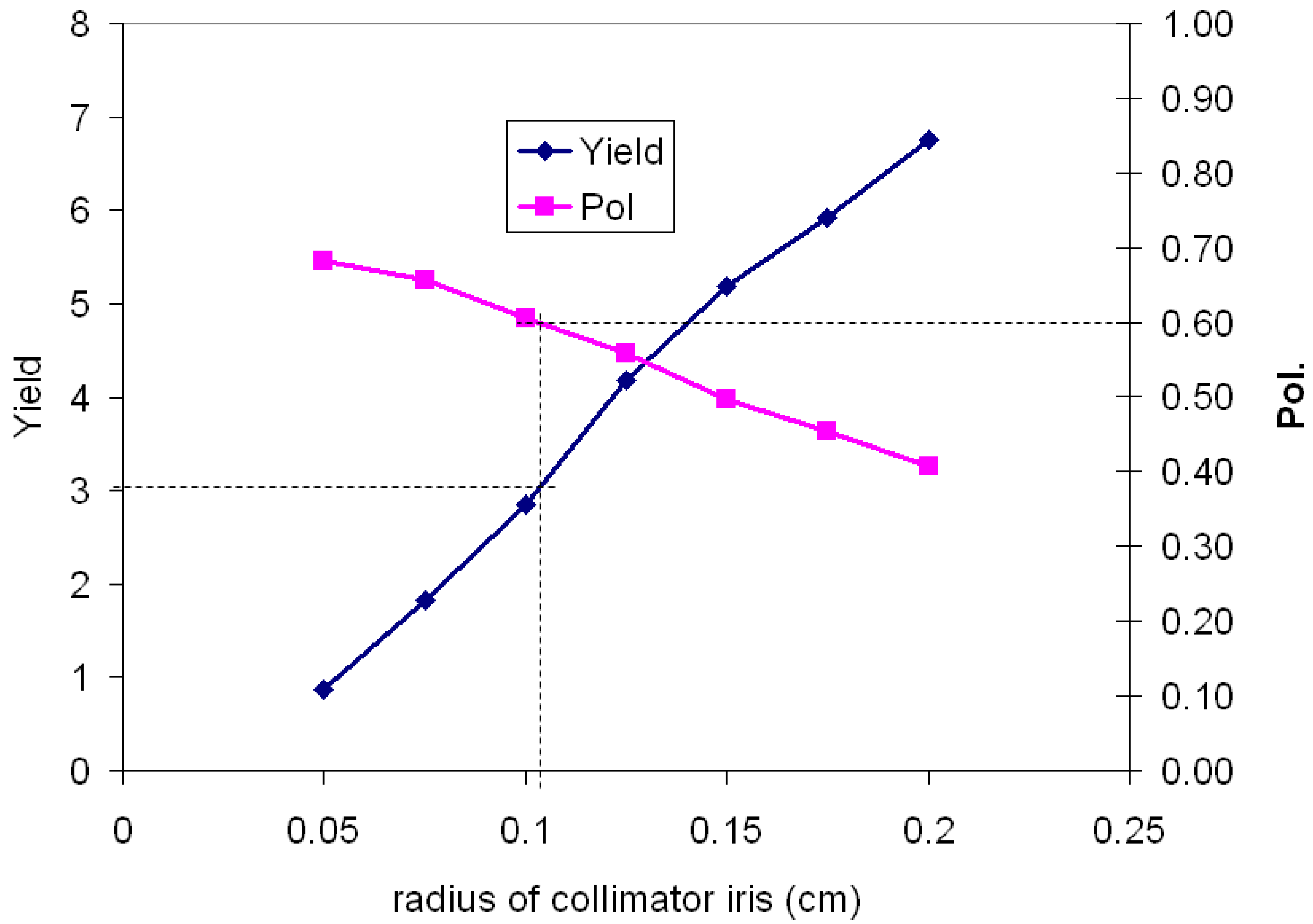
For 150GeV drive beam, 60% polarization required a photon collimator with an iris of ~1.6mm in radius. The corresponding yield is ~2 for 231m long undulator

Drive beam energy 175GeV, K=0.9,λu=0.9



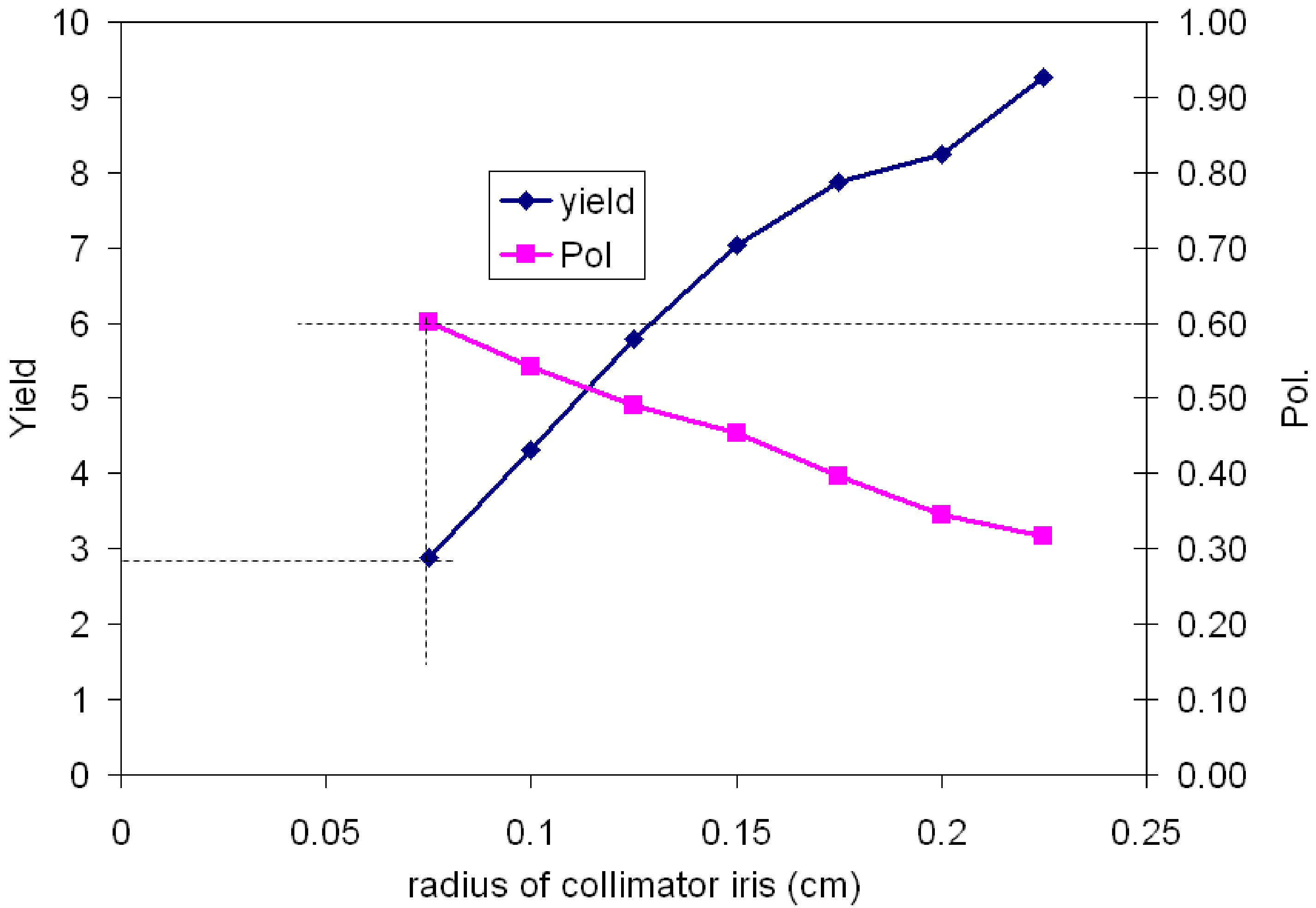
For 175GeV drive beam, 60% polarization required a photon collimator with an iris of ~1.25mm in radius. The corresponding yield is ~2.4 for 231m long undulator

Drive beam energy 200GeV, K=0.9,λu=0.9



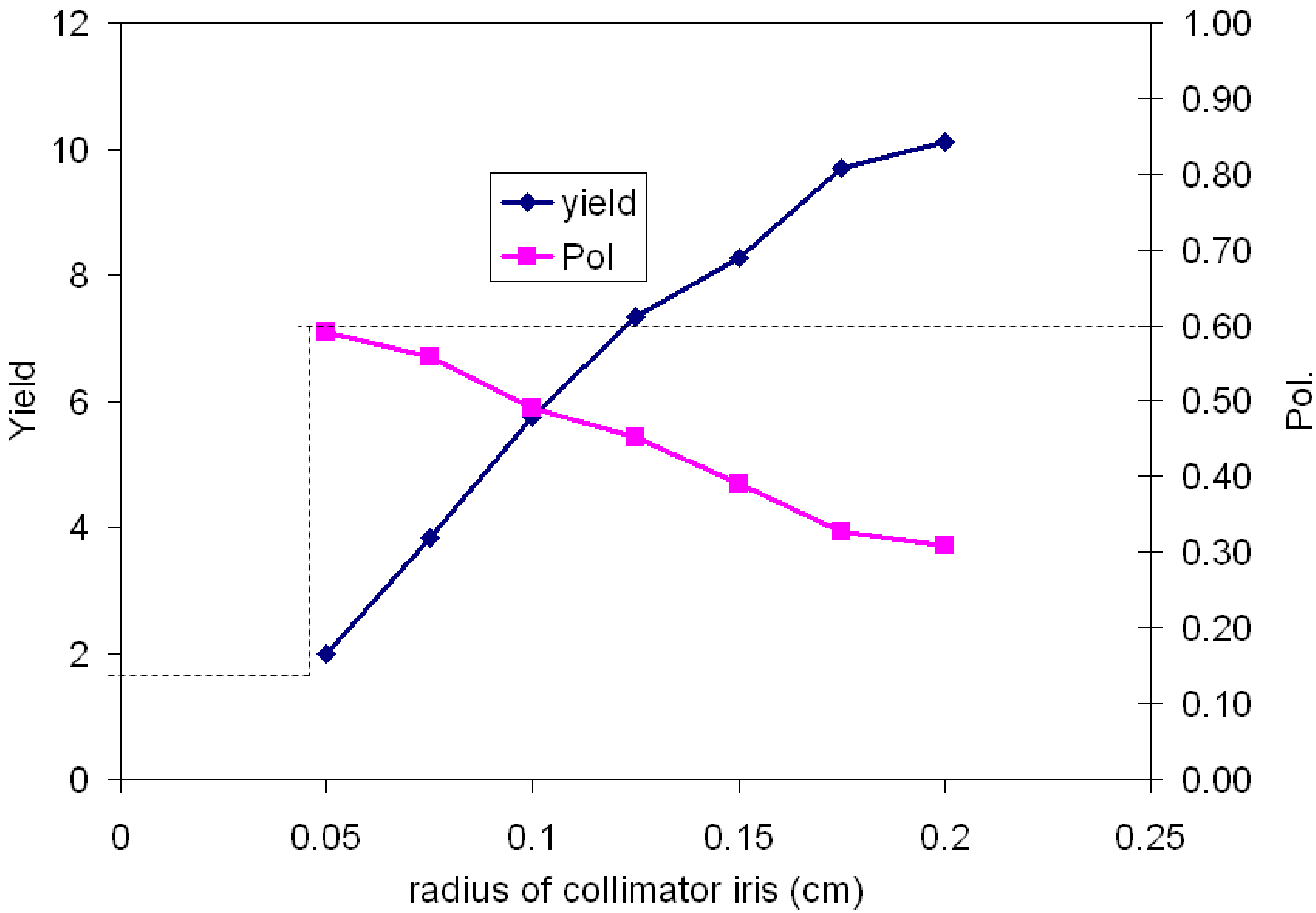
For 200GeV drive beam, 60% polarization required a photon collimator with an iris of ~1.1mm in radius. The corresponding yield is ~3 for 231m long undulator

Drive beam energy 225GeV, K=0.9,λu=0.9



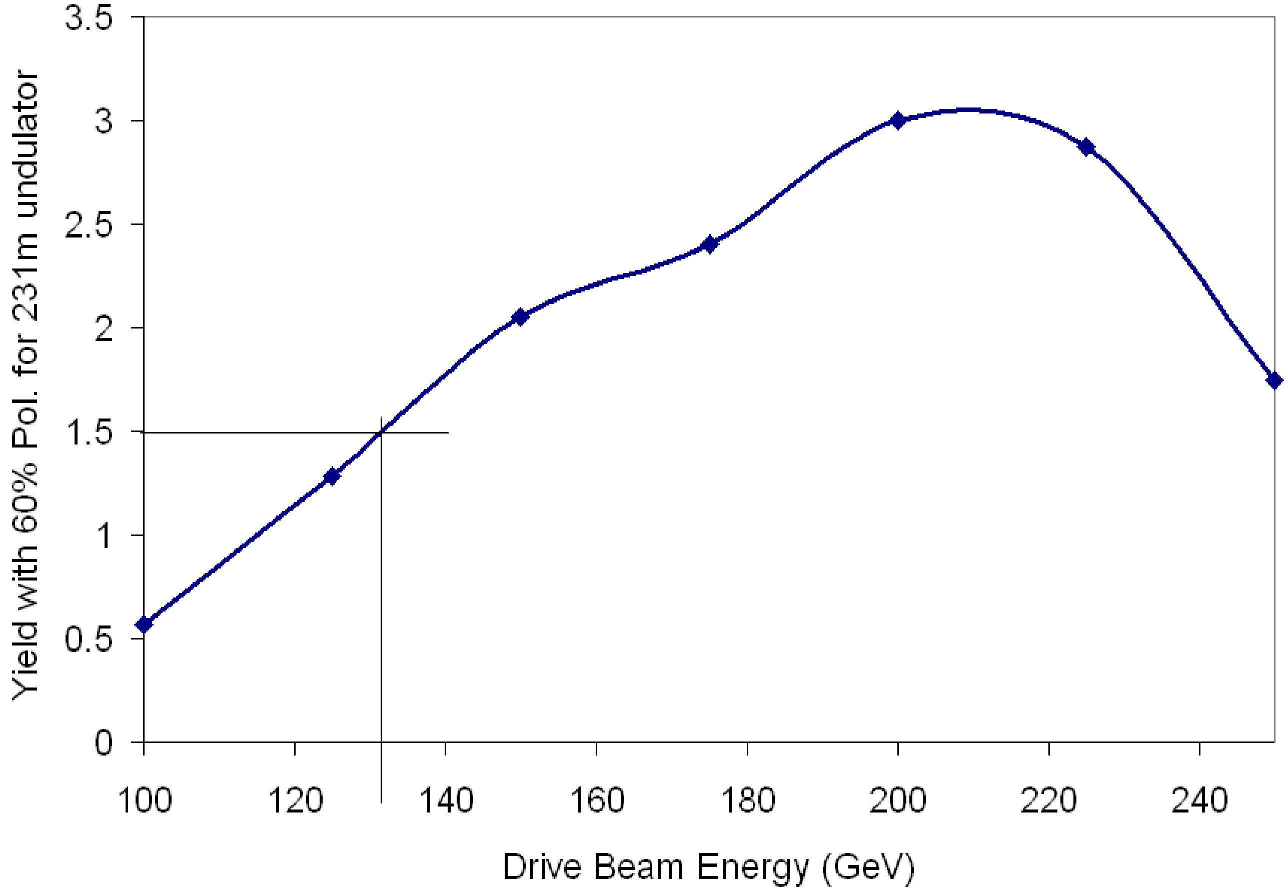
For 200GeV drive beam, 60% polarization required a photon collimator with an iris of ~0.75mm in radius. The corresponding yield is ~2.8 for 231m long undulator

Drive beam energy 250GeV, K=0.9,λu=0.9



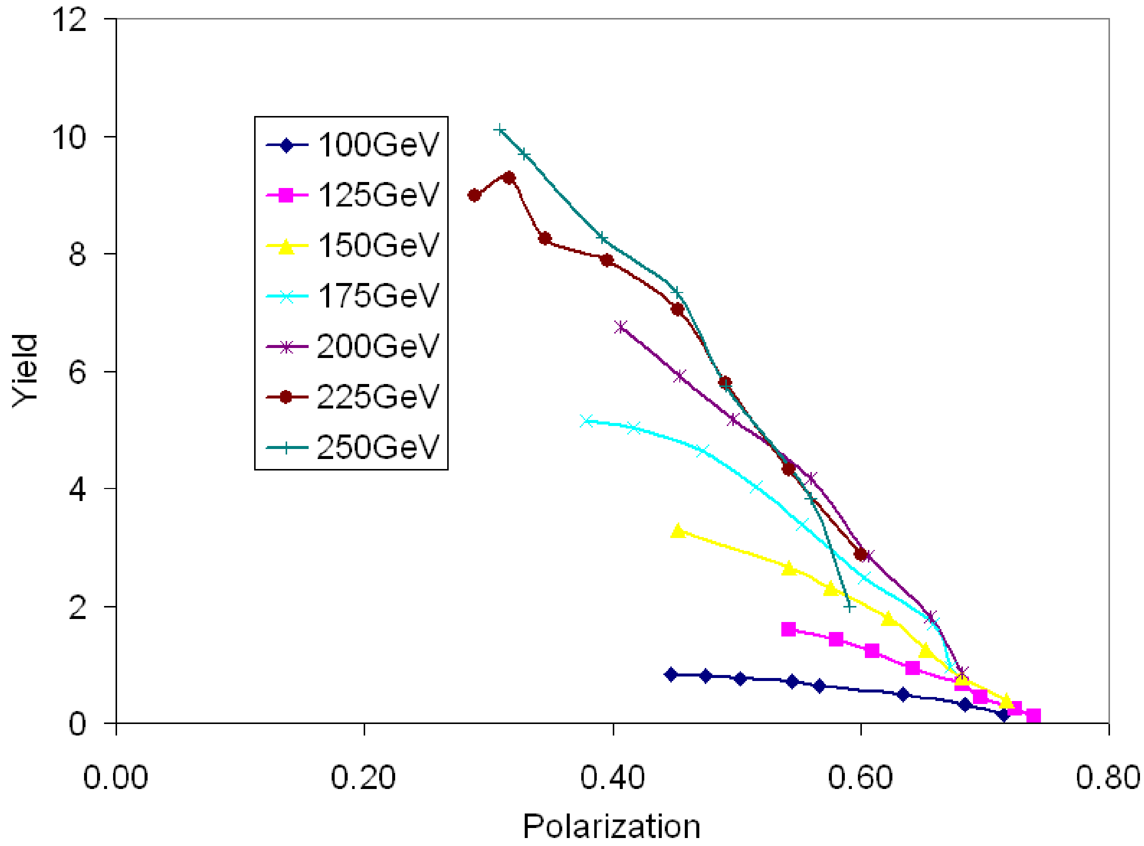
For 250GeV drive beam, 60% polarization required a photon collimator with an iris of ~0.45mm in radius. The corresponding yield is ~1.75 for 231m long undulator

Yield with 60% Pol. As function of drive beam energy



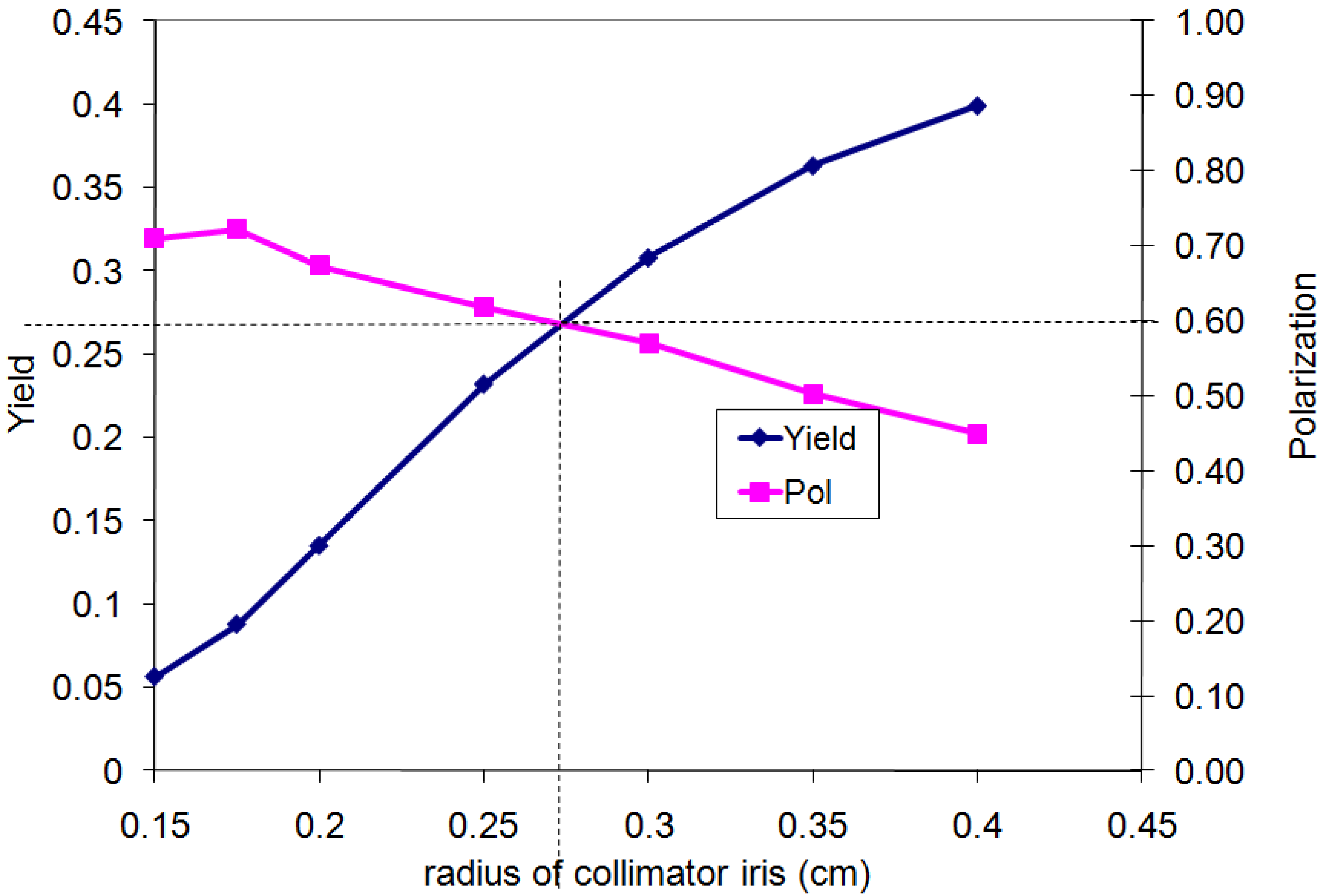
- With 231m long undulator with K=0.9, λu=0.9, 1.5 yield with 60% polarization can be achieved with drive beam energy of about 132GeV

Yield vs Pol for different drive beam Energy K=0.9,λu=0.9



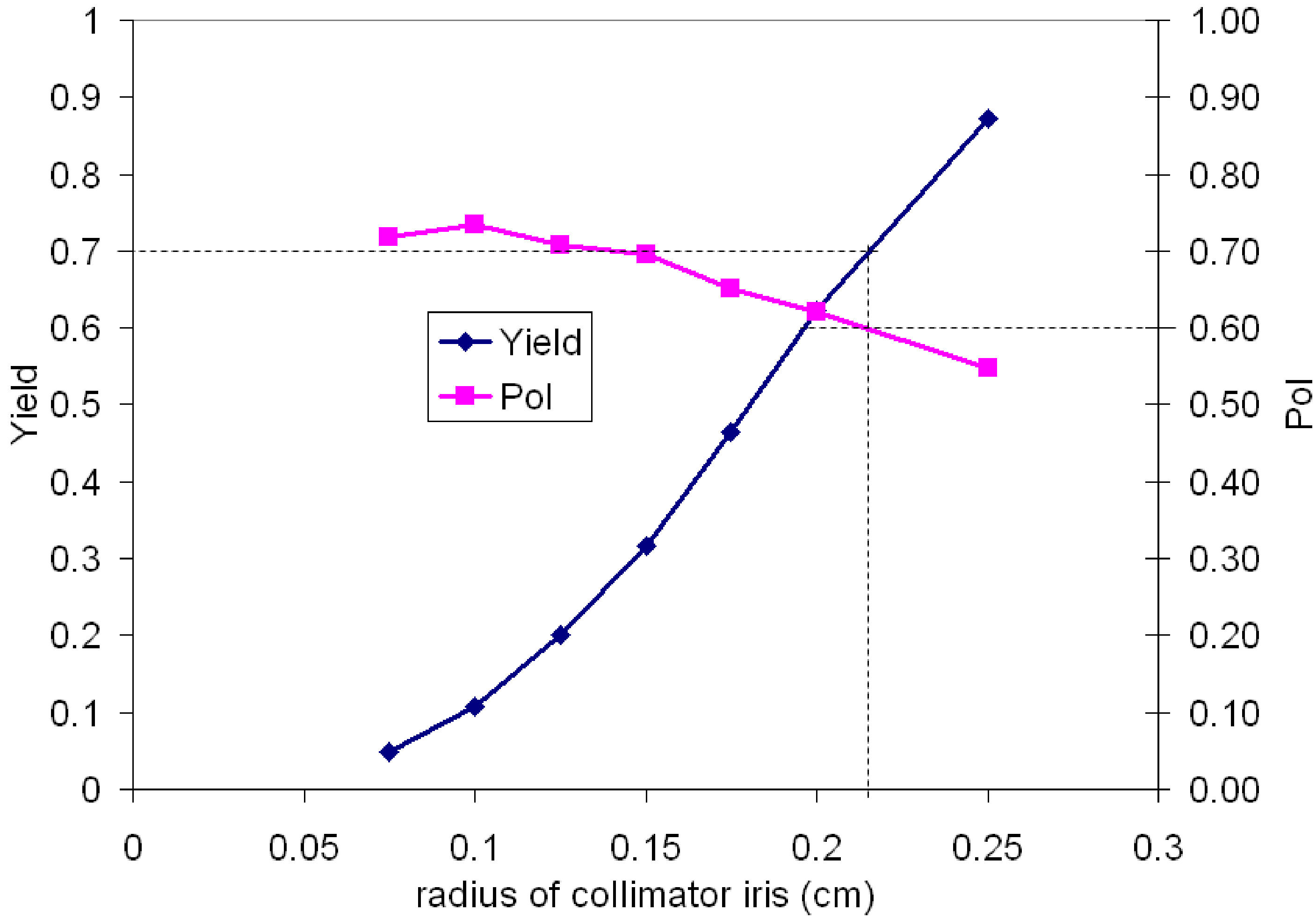
- For a given required polarization, the yield increase with drive beam energy with the penalty of more challenge to the photon collimator design
- Higher drive beam energy will have a lower achievable polarization.

100GeV drive beam, RDR undulator



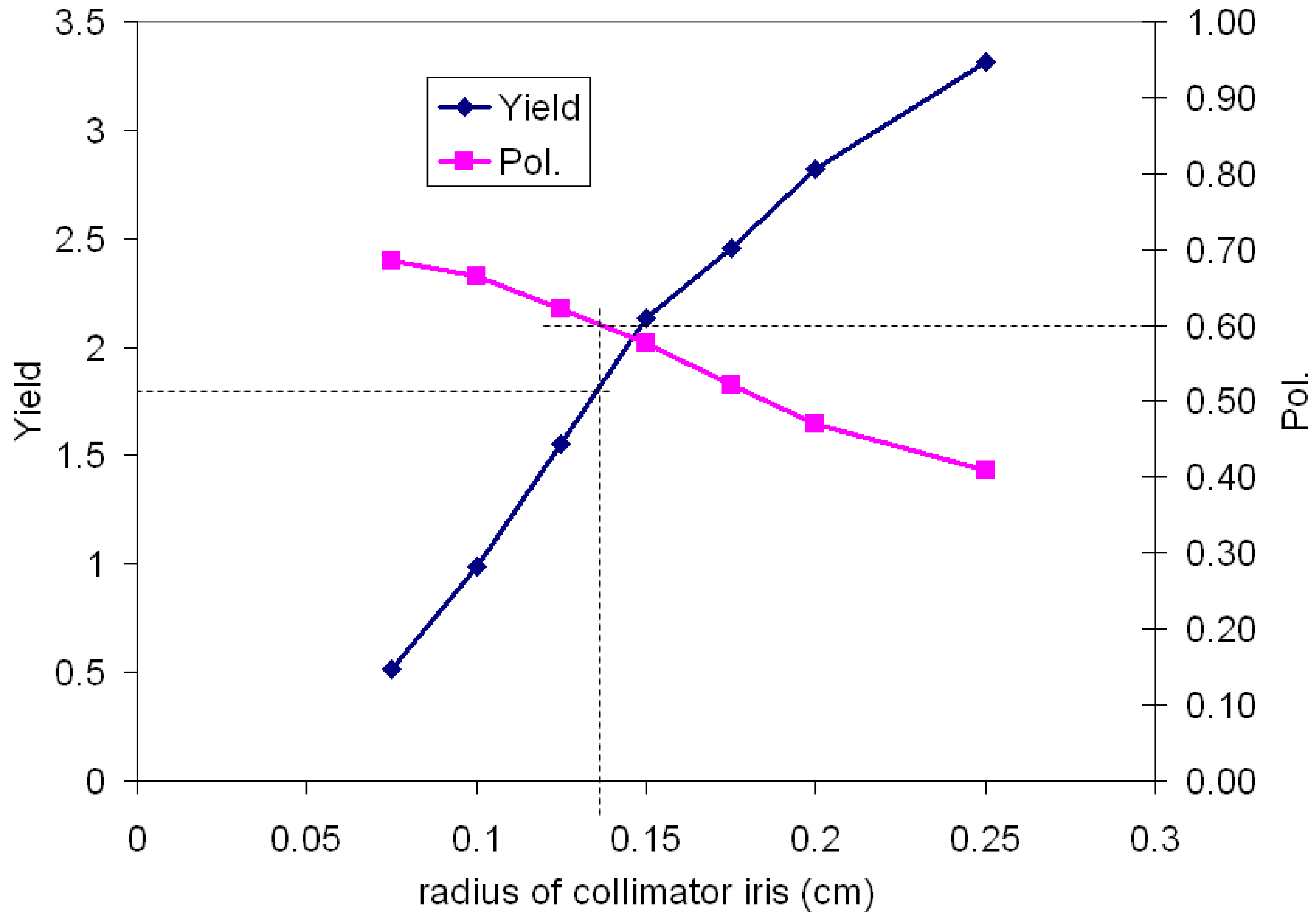
For 100GeV drive beam, 60% polarization required a photon collimator with an iris of ~2.6mm in radius. The corresponding yield is ~0.27 for 231m long RDR undulator

125GeV drive beam, RDR undulator



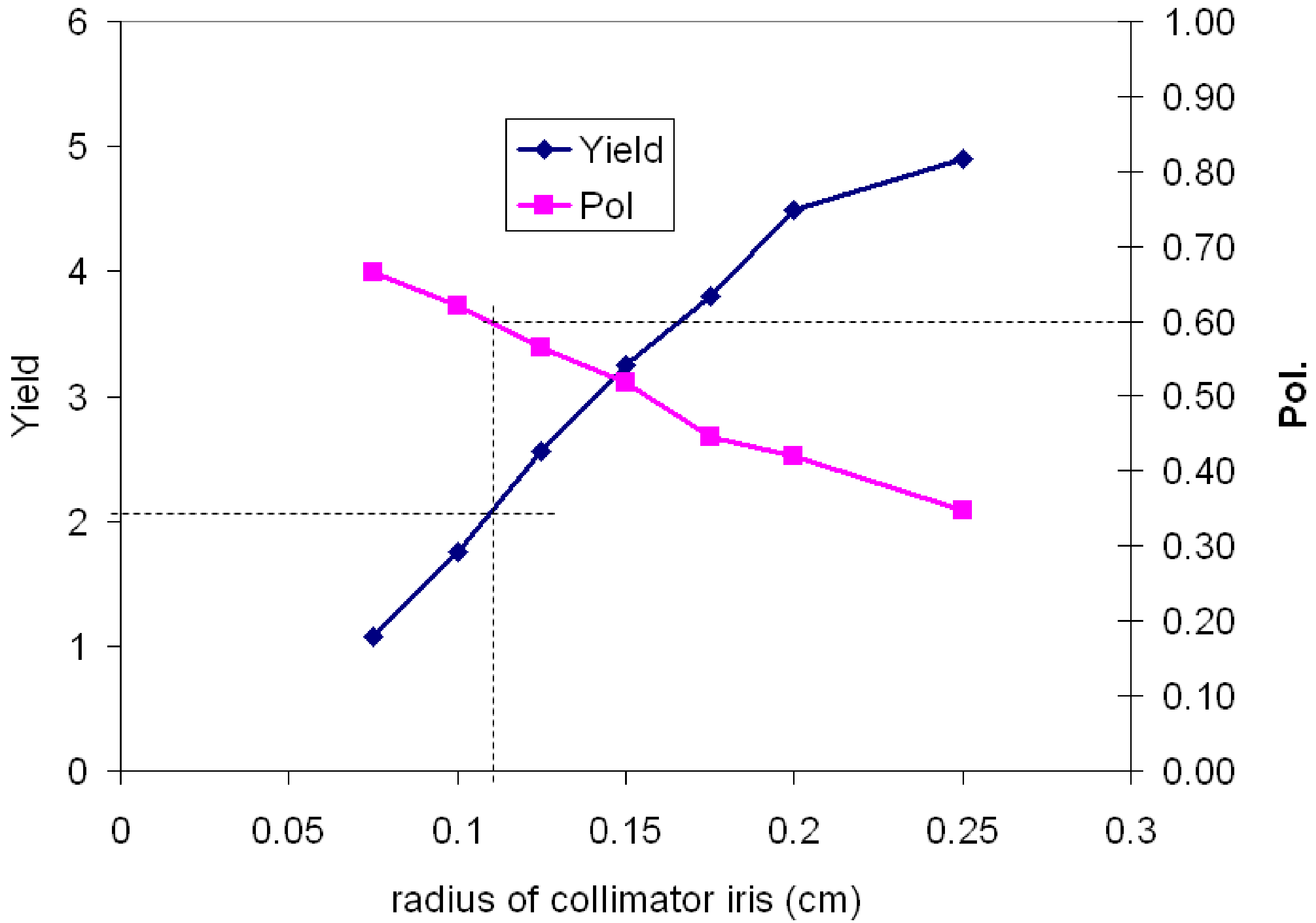
For 125GeV drive beam, 60% polarization required a photon collimator with an iris of ~2.2mm in radius. The corresponding yield is ~0.7 for 231m long RDR undulator

175GeV drive beam, RDR undulator



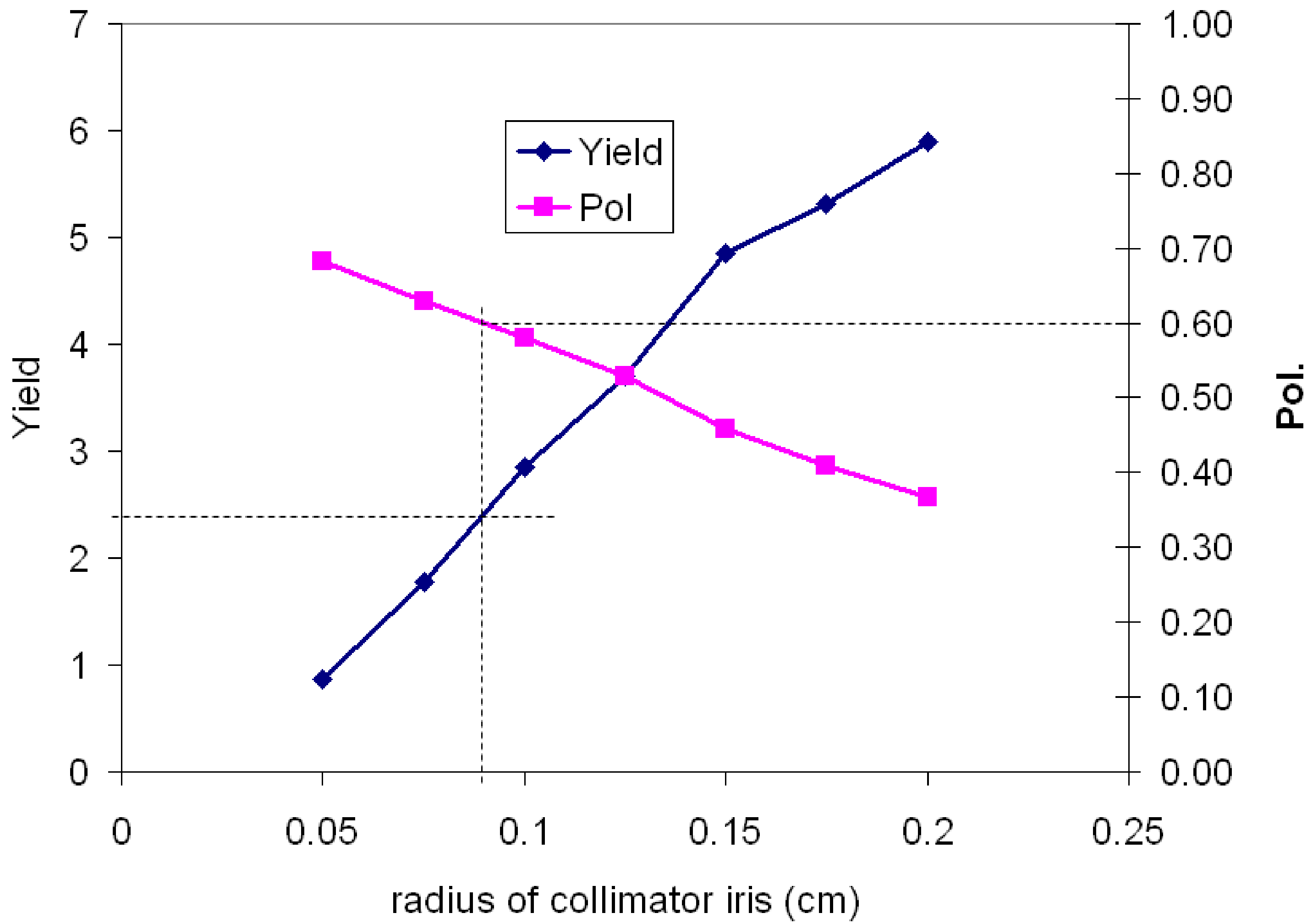
For 175GeV drive beam, 60% polarization required a photon collimator with an iris of ~1.4mm in radius. The corresponding yield is ~1.8 for 231m long RDR undulator

200GeV drive beam, RDR undulator



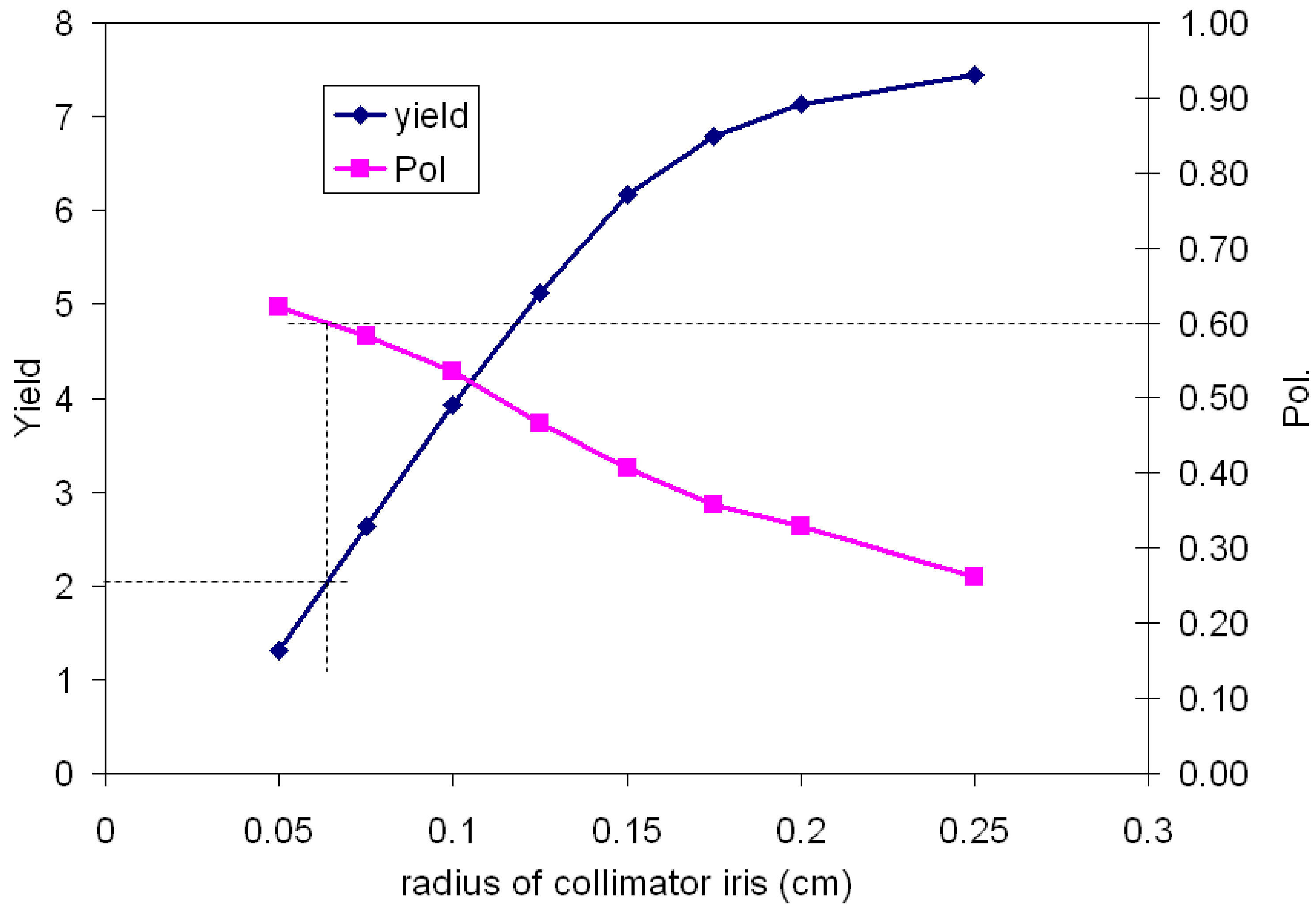
For 200GeV drive beam, 60% polarization required a photon collimator with an iris of ~1.15mm in radius. The corresponding yield is ~2.05 for 231m long RDR undulator

225GeV drive beam, RDR undulator



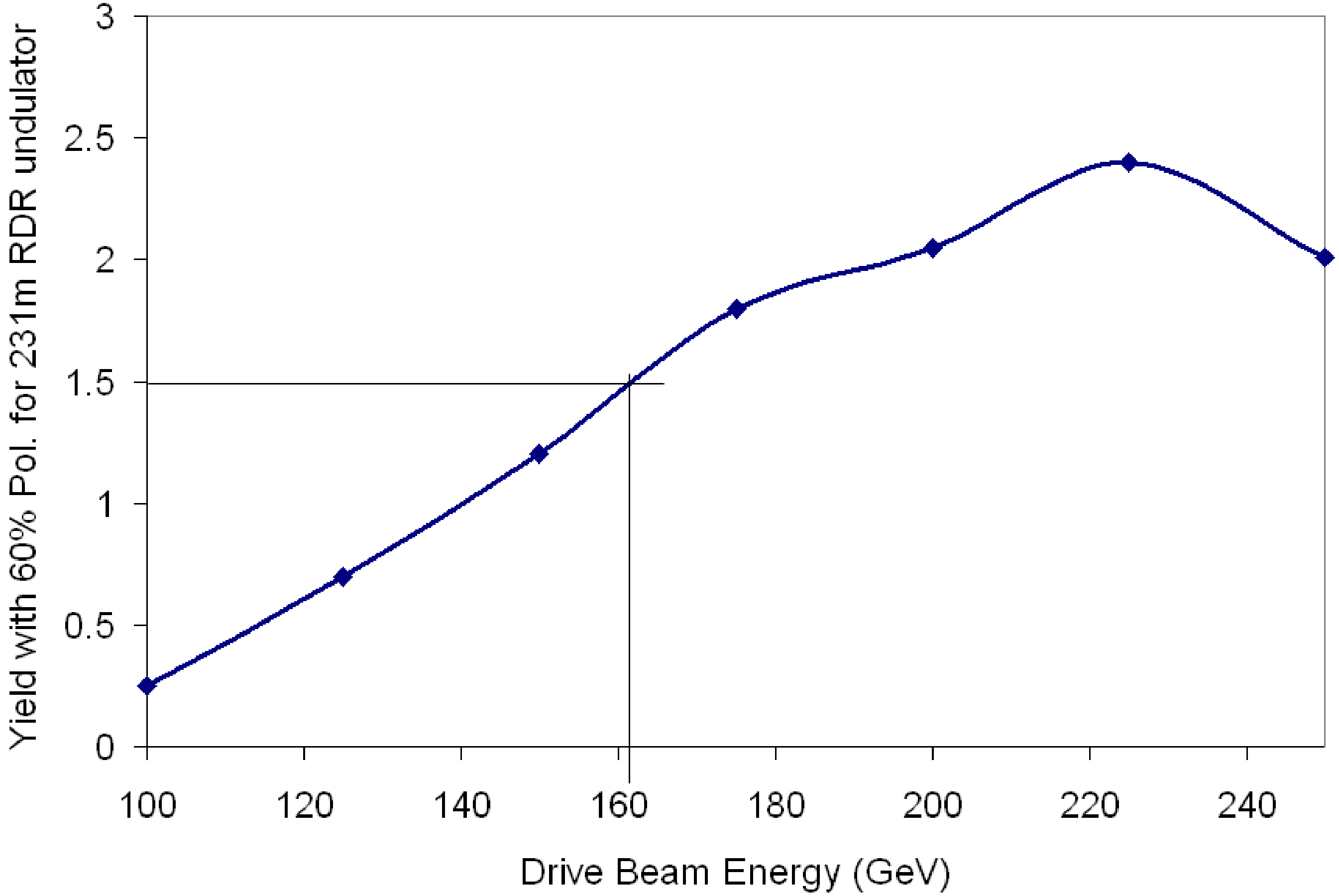
For 225GeV drive beam, 60% polarization required a photon collimator with an iris of ~0.85mm in radius. The corresponding yield is ~2.4 for 231m long RDR undulator

250GeV drive beam, RDR undulator



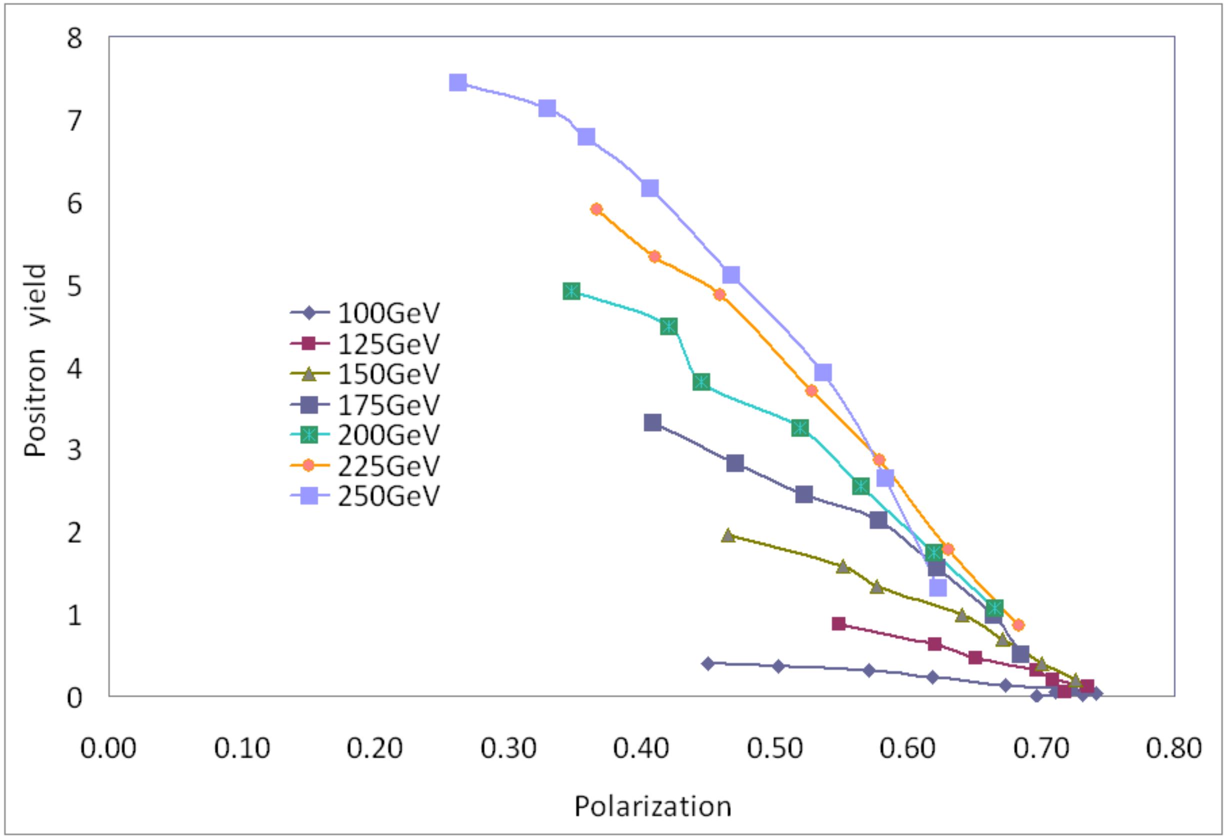
For 250GeV drive beam, 60% polarization required a photon collimator with an iris of ~0.6mm in radius. The corresponding yield is ~2.0 for 231m long RDR undulator

Yield with 60% Pol. As function of drive beam energy. 231m long RDR undulator



- Yield of 1.5 with 60% yield can be reached with drive beam energy of ~162GeV

Yield vs pol for different drive beam energy ILC RDR undulator

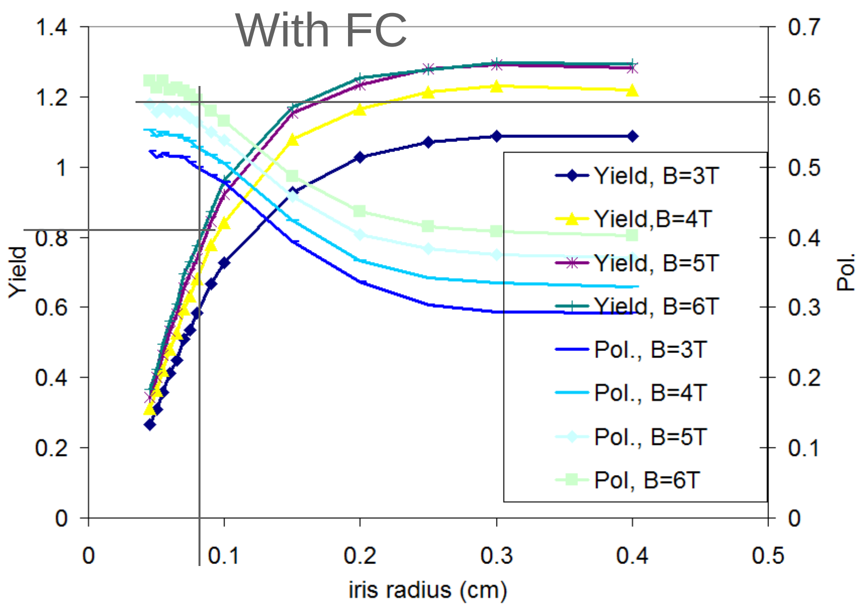


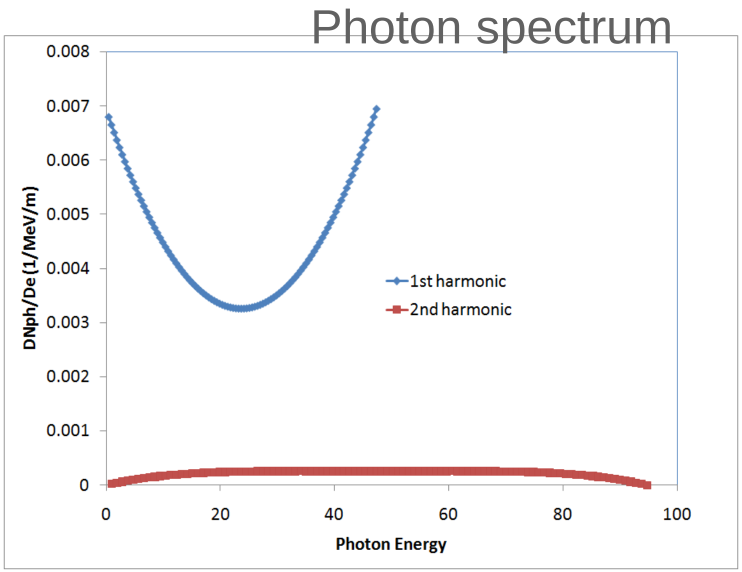
- For a given required polarization, the yield increase with drive beam energy with the penalty of more challenge to design photon collimator
- Higher drive beam energy will have a lower achievable polarization.

Varying K for RDR undulator at the end of linac.

- Undulator: λu=1.15cm, K=0.3 – 0.9
- OMD:
  - FC, 0.5T ramp up to over B in 2cm and then adiabatically fall back to 0.5T at z=14cm, where B varied from 3T to 6T.
- Length of undulator 231m
- Target: 0.4X0 Ti target
- Drift from Undulator end to target: 400m
- Varying photon collimator iris.

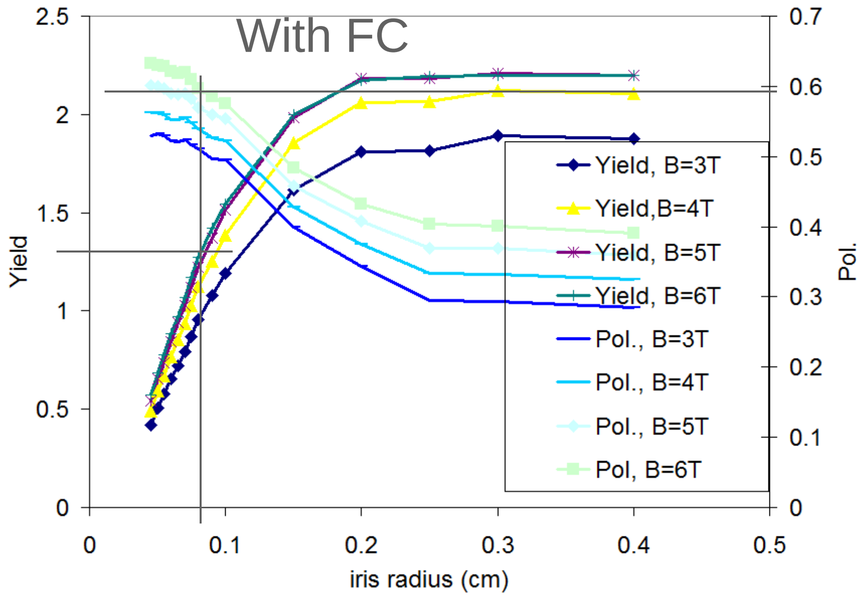
K=0.3, Drive beam energy 250GeV

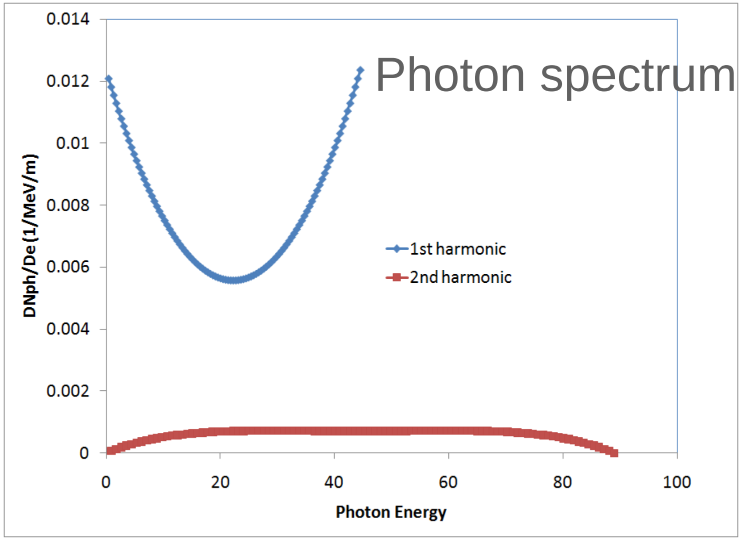




When K is 0.3, the total number of photon is small and also the photon from 2nd harmonic is very small comparing with 1st harmonic radiation. For 60% polarization, the positron yield is about 0.8.

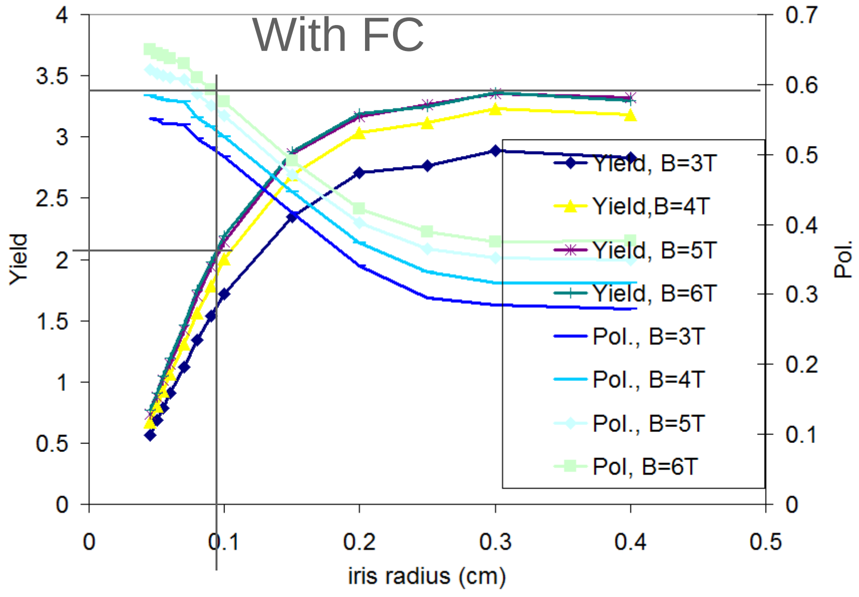
K=0.4, Drive beam energy 250GeV

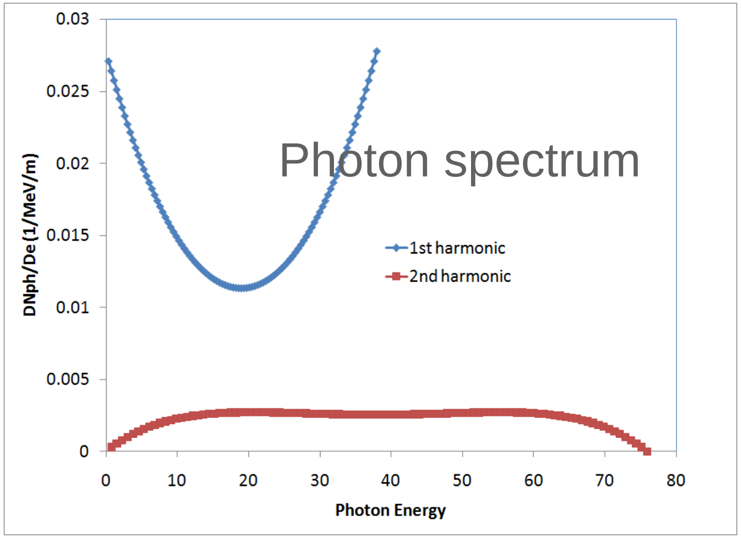




For 60% polarization, the positron yield is about 1.3

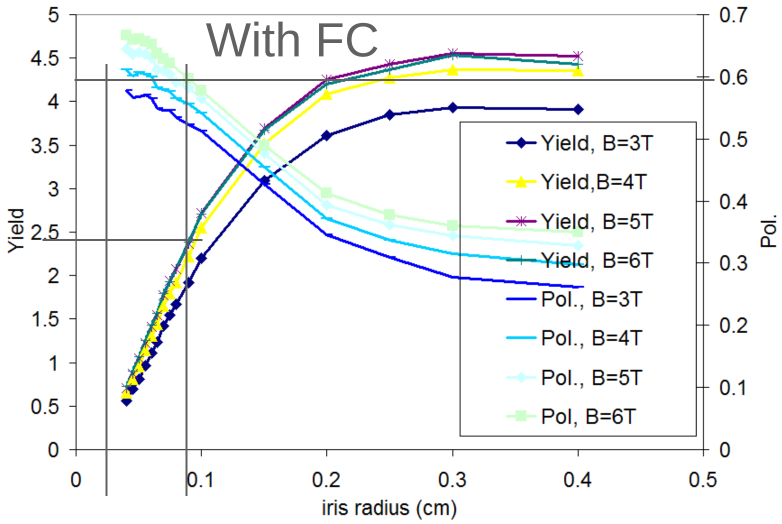
K=0.5, Drive beam energy 250GeV

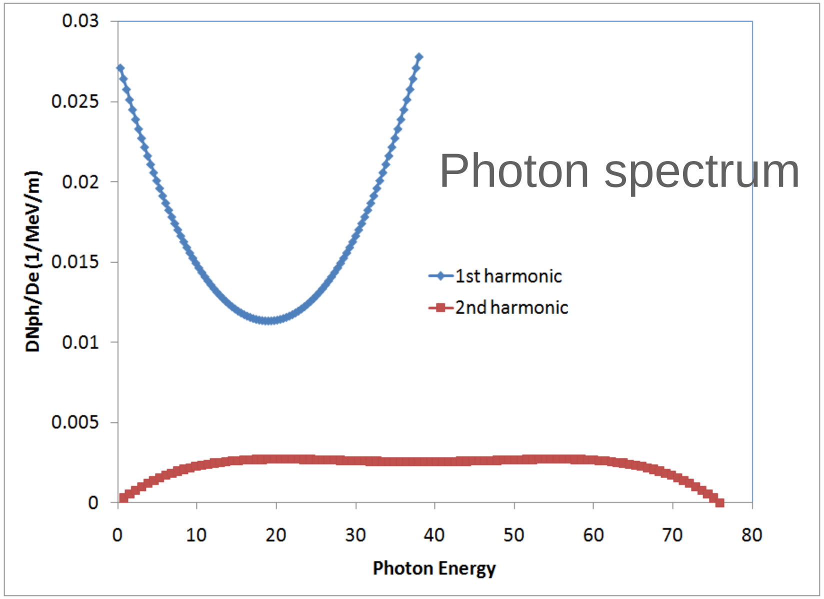




For 60% polarization, the positron yield is about 2.0

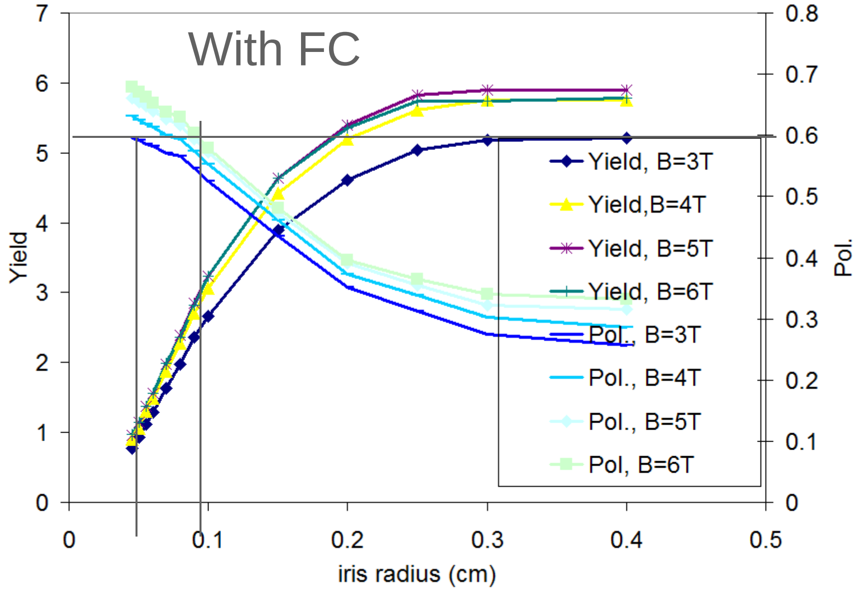
K=0.6, Drive beam energy 250GeV

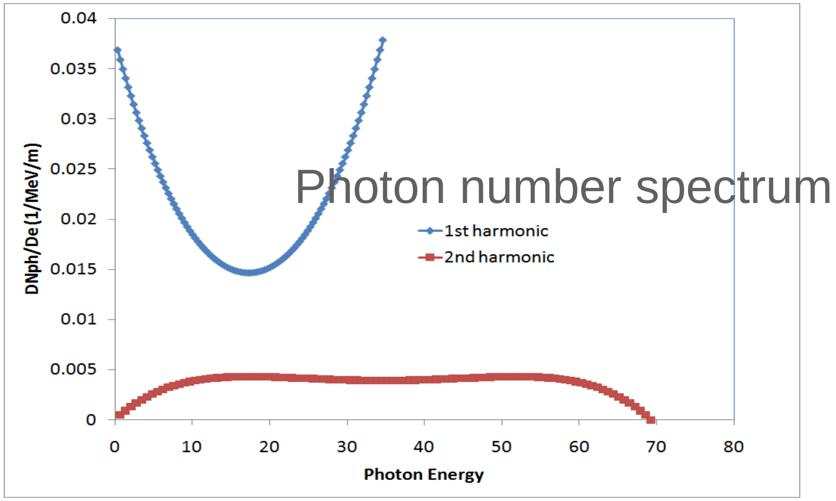




For 60% polarization, the positron yield is about 2.4

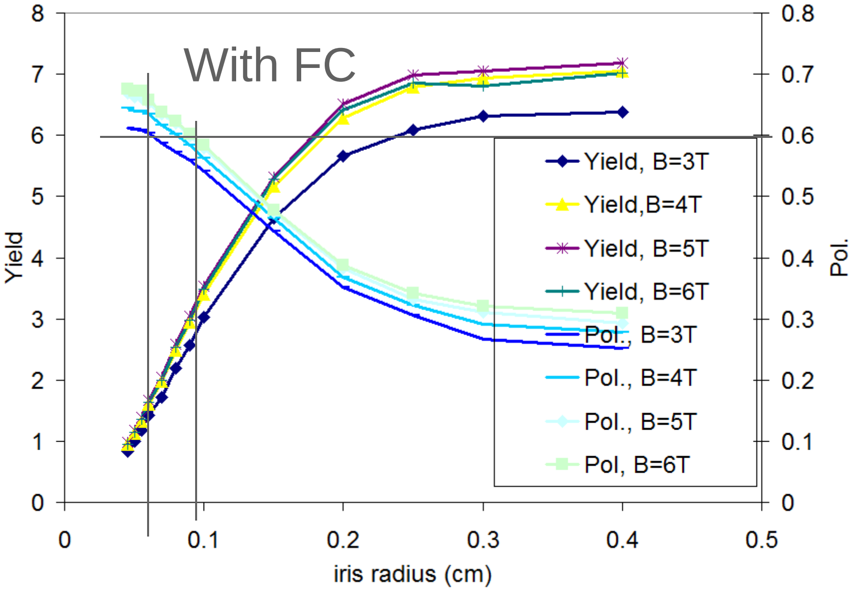
K=0.7, Drive beam energy 250GeV

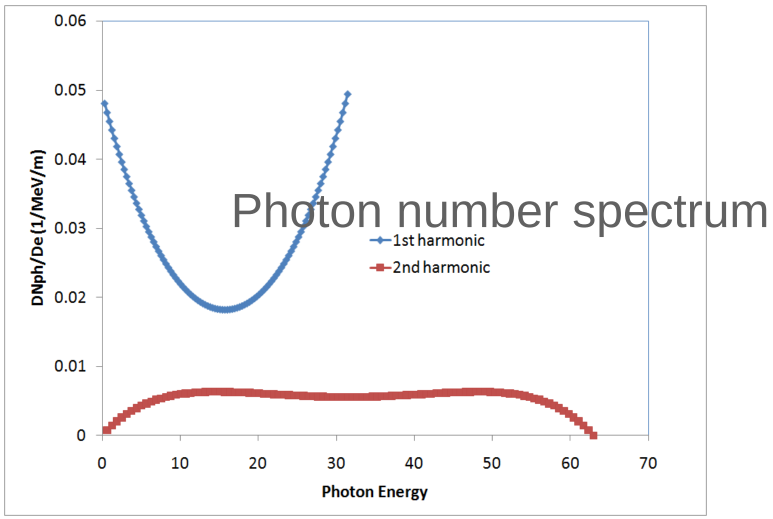




For 60% polarization, the positron yield is about 3.0 when strong FC is applied

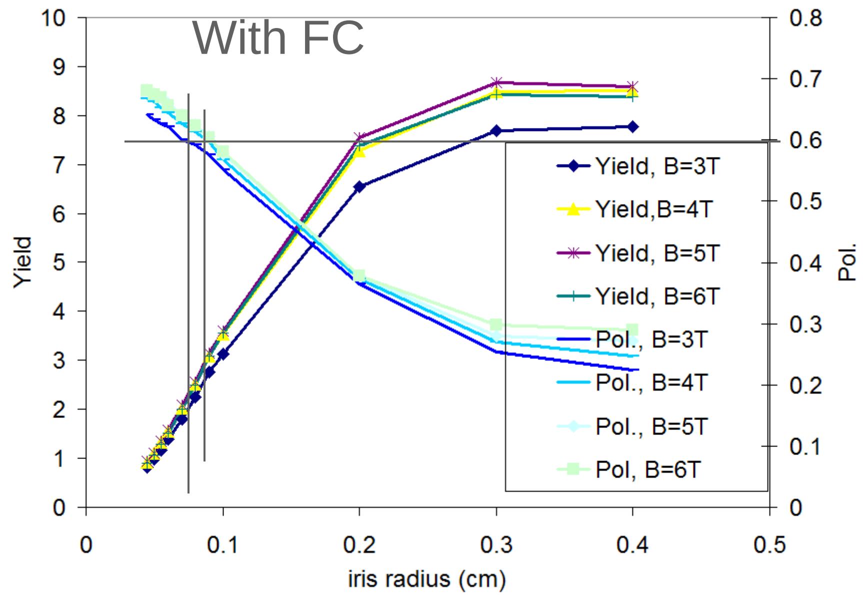
K=0.8, Drive beam energy 250GeV

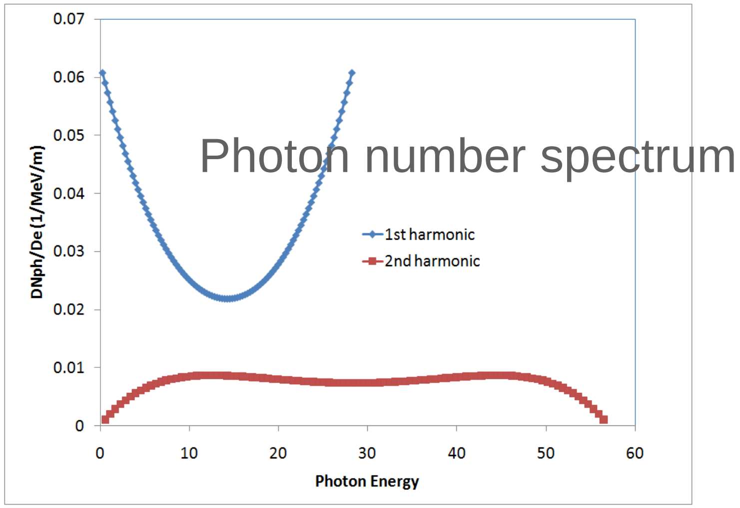




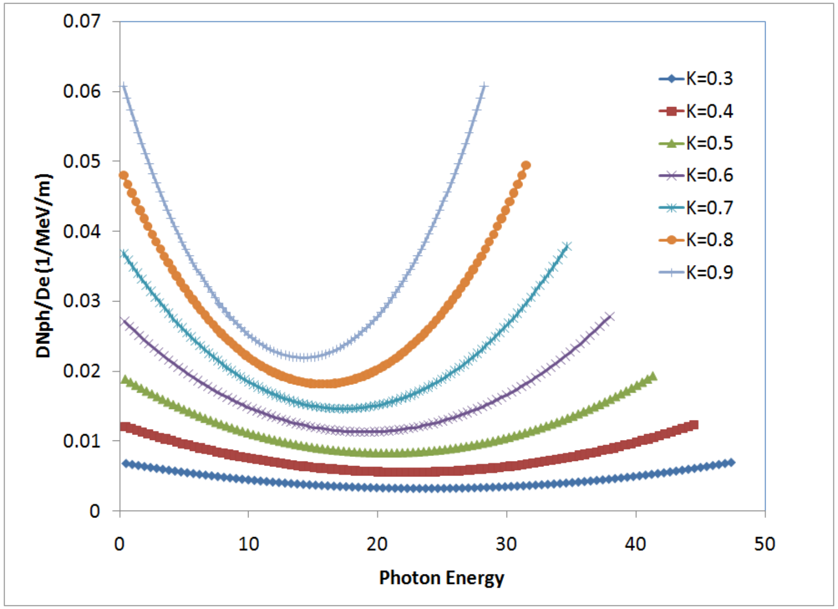
For 60% polarization, the positron yield is about 3.2 when strong FC is applied

K=0.9, Drive beam energy 250GeV

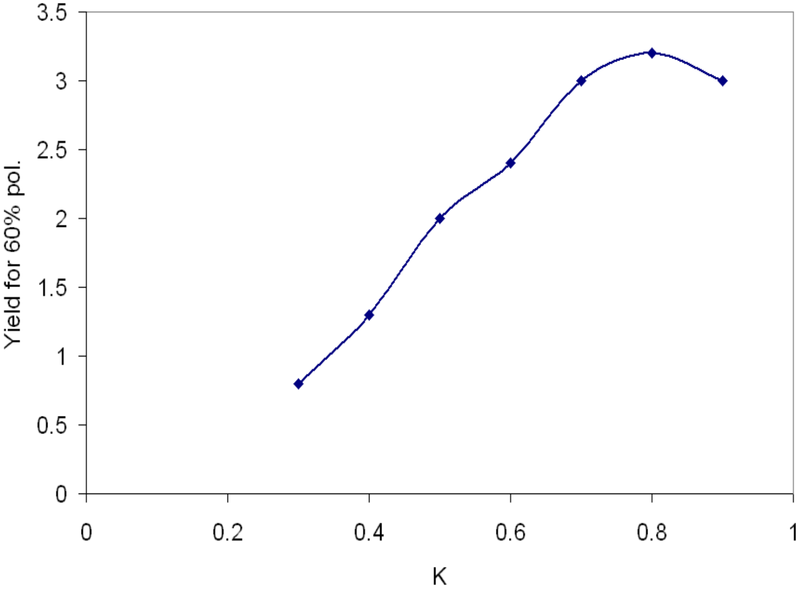




For 60% polarization, the positron yield is about 3 when a strong FC (peak over 6T) is applied. When a softer FC (peak about 3T) is applied, the 60% polarization has corresponding yield of about 2.0

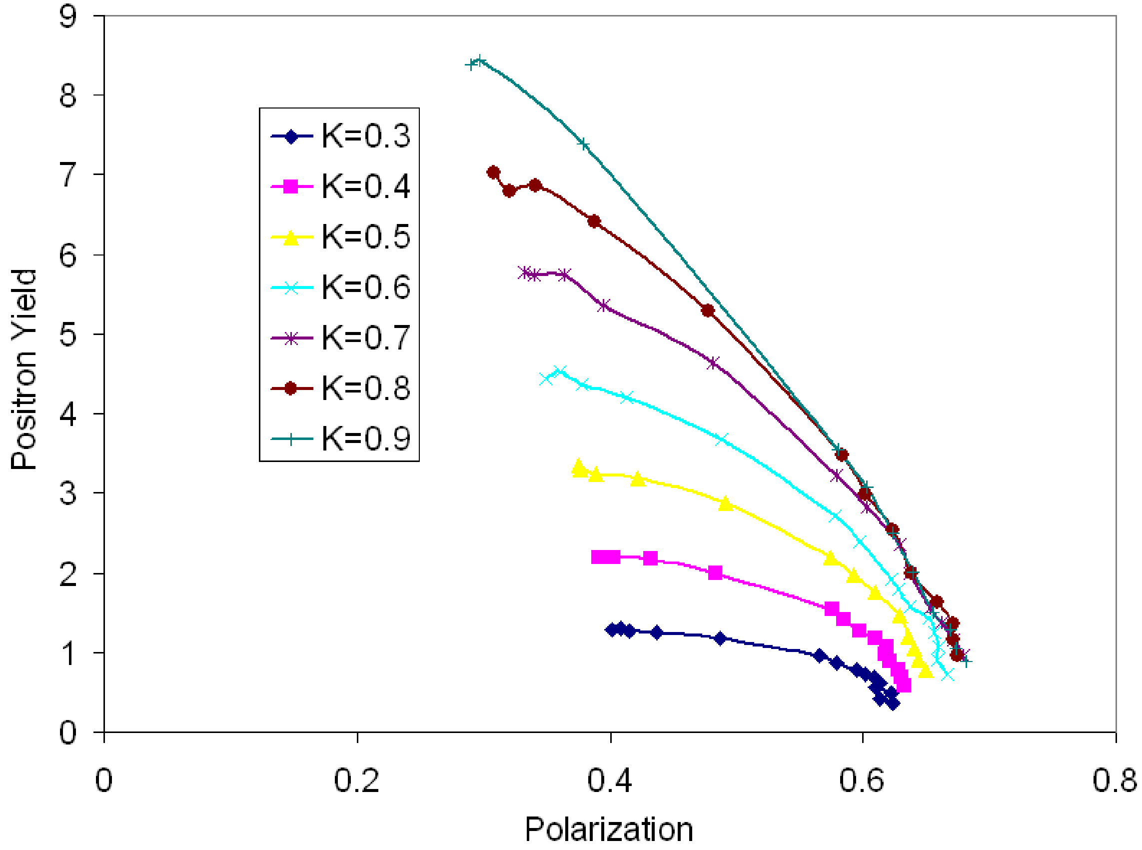


231m undulaotr with λu=1.15cm



- Disadvantage of Low K: increase the critical energy of photon of helical undlator radiations and lower the number of photon produced for a given length of undulator.
- Advantage of low K: lower high order harmonic radiation
- 1.5 yield with 60% polarization can be achieved by lowering K down to ~0.42 with strong FC

Yield vs Pol for fixed 250GeV drive beam K varies, λu=1.15cm

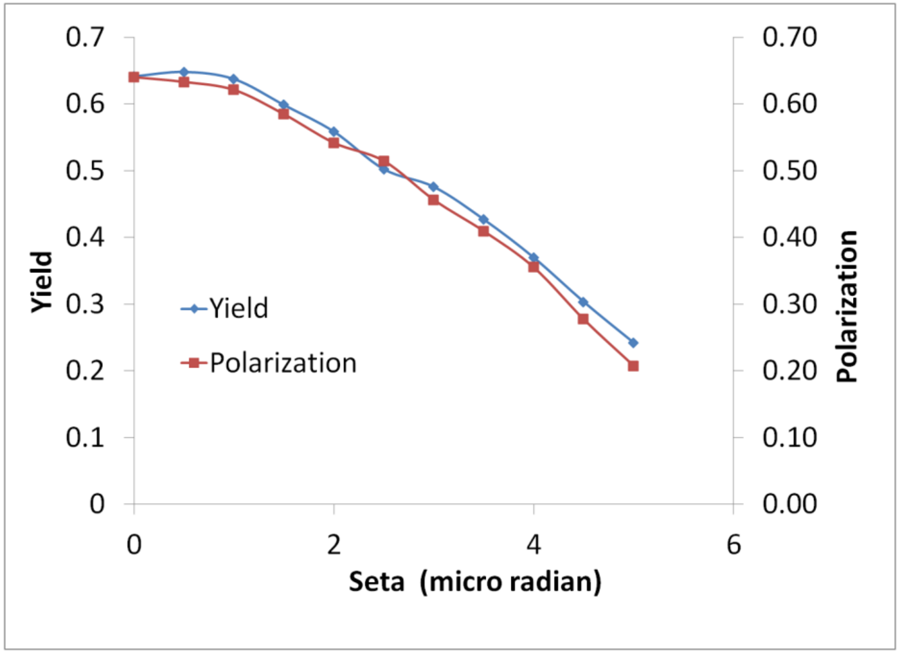


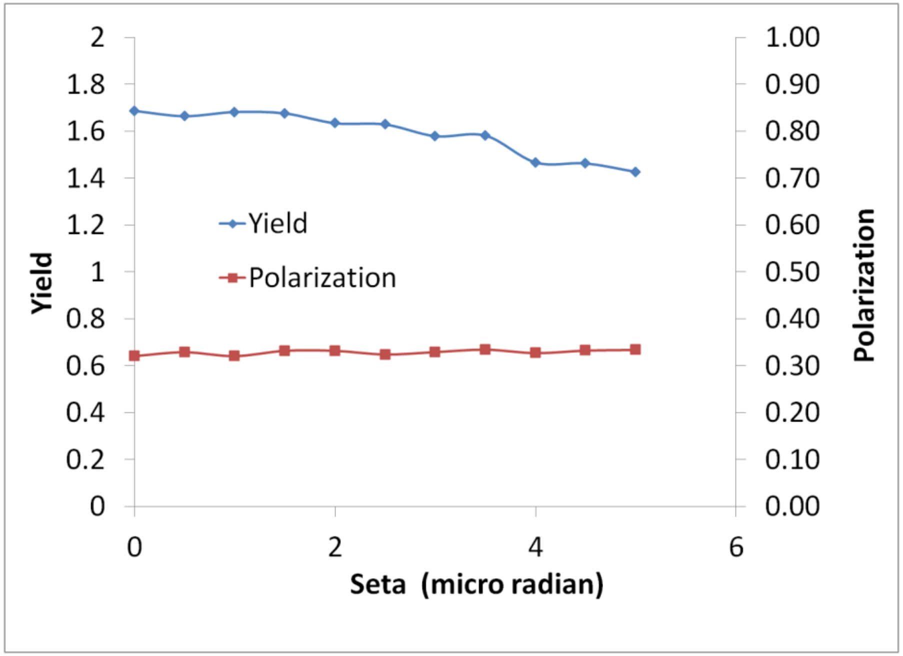
- For a fixed drive beam energy, and given requirement on polarization, higher K gives higher yield. Higher K also gives a higher achievable polarization.

Practical issues

- Alignment
- Drive beam Zigzagging

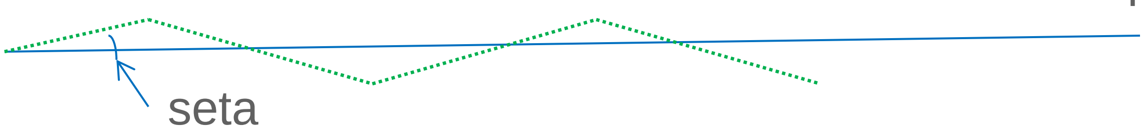
Example of drive beam zigzagging effect





With photon collimator

Without photon collimator



Alignment tolerance as specified in TDR: 0.1mm over 150m =>~0.7 micro radian

Summary

- ILC TDR baseline positron source design is done but upgrade options still need to be studied in detail
- High polarization is desired. It is very challenging but still possible.