Update on ILC Positron source study at ANL

since the Durham/UK Meeting10/2010

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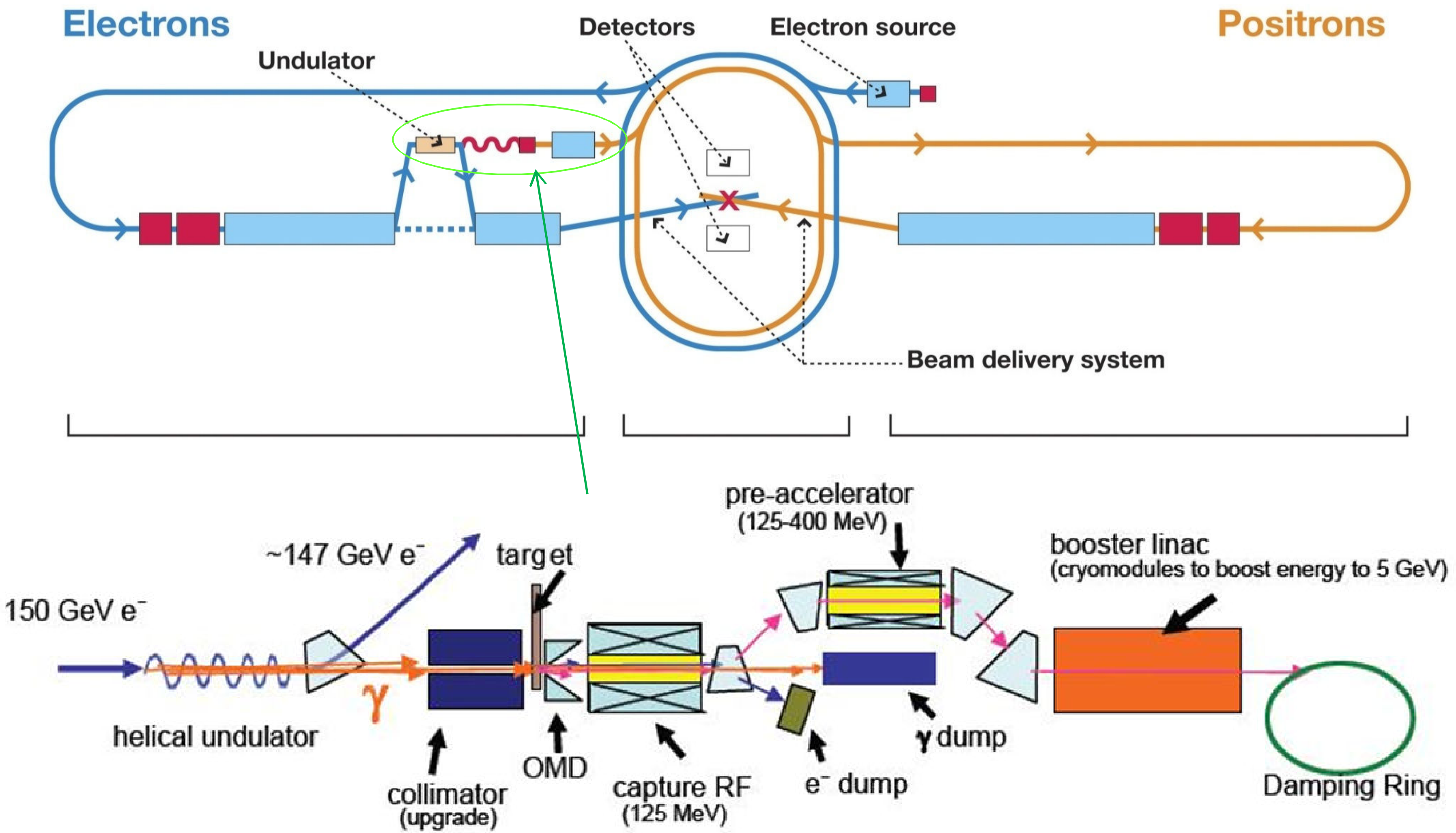
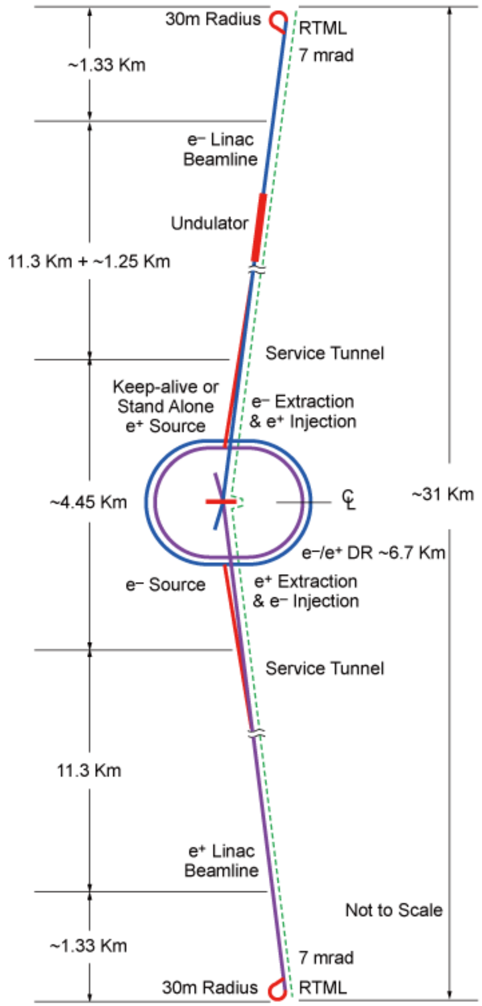
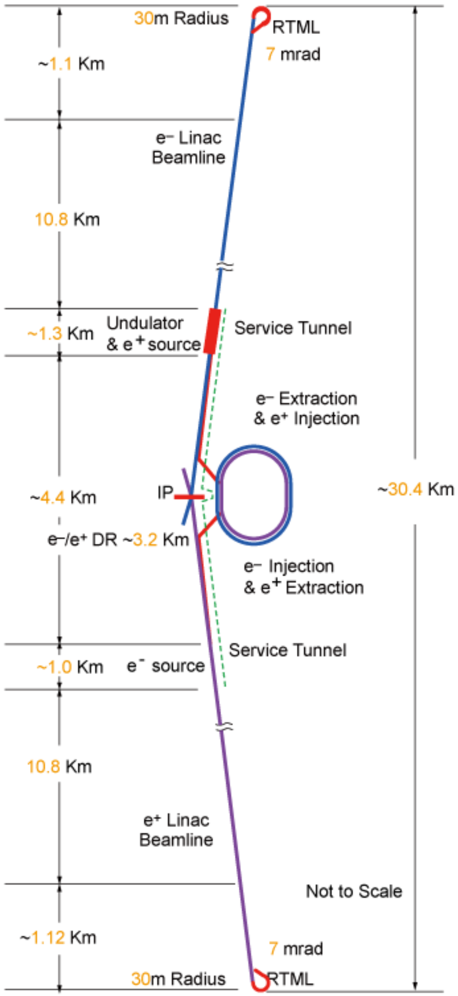
ILC RDR baseline schematic



RDR baseline layout and SB2009 baseline layout





Our contributions

- Numerical model of helical undulator photon radiation
- Start-to-end simulation of ILC positron source
- Undulator parameter comparison
- Initial keepalive source numerical studies
- OMD comparison
- Equivalent circuit model of Flux concentrator
- Eddy current study of spinning target in magnetic field
- comparison between Ti and W target
- Emittance evolution of drive electron beam passing through undulator
- Evaluation of end of linac operation
- Drive beam energy comparison
- Liquid target yield evaluation and heat transfer simulation
- Conventional positron source simulation: yield evaluation, heat deposition and transfer simulation
- RDR undulator length requirements for different scenario
- Accumulated energy deposition in target of bunch train
- Minimum machine simulation: undulator based and conventional scheme
- Post IP scheme

Our efforts/contributions in 2009

- Evaluation of end of linac operation
- Minimum machine simulation: undulator based
- Drive beam energy comparison
- Liquid target yield evaluation and heat transfer simulation (Conventional, different timing structure)
- Liquid target yield evaluation and heat transfer simulation (Undulator based scheme)
- RDR undulator length requirements for different scenario
- Accumulated energy deposition in target of bunch train
- Post IP scheme

Short term tasks from Durham collaboration meeting

1). Impact of undulator angular errors on yield and polarizations:

Suggested approach, generate random kicks along the beam trajectory in the undulator line. Determine the maximum kicks the ILC could accept, this will impose tolerance on the undulator.

2). Study the yield and polarization dependents on K for 250 GeV drive beam.

Suggested approach: Sweep through the K factor from 0.3 – 0.9. Study the yield for 237 meter long undulator. Have a detailed photon distribution and correlate them with the e+ production.

3). Study the energy deposition for Ti and W, a detailed comparison is needed.

4). To simulate a radiation damage experiment, we propose to use FLASH beam for a test that to determine the radiation damage threshold for Ti target or Tungsten.

Approach, use Flash beam parameters, calculates the energy deposition in the target by varying the beam spot size. The goal is to have a set of parameters for 50J/g, 100 J/g, 200 J/g and 300 J/g. This will provide a basis for a possible experiment at DESY.

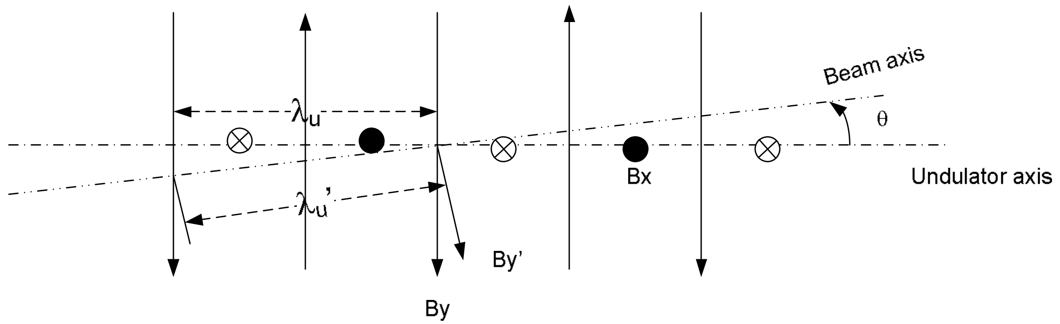
5). Calculate energy deposition for the auxiliary source. 500 MeV drive beam, using the undulator target, try to get 1 or few percent of intensity.

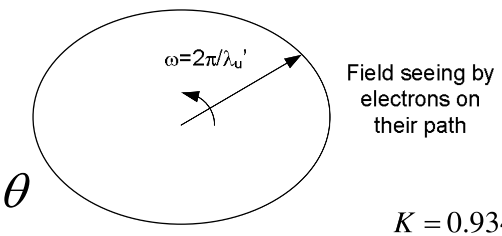
OMD comparison

- Same target
- Beam and accelerator phase optimized for each OMD
- OMD compared:
  - AMD
  - Flux concentrator
  - ¼ wave transformer
  - Lithium lens

OMD	Capture efficiency
Immersed target, AMD (6T-0.5T in 20 cm)	~30%
Non-immersed target, flux concentrator (0-6T in 2cm, 6T-0.5T 20cm)	~21%
1/4 wave transformer (1T, 2cm)	~15%
0.5T Back ground solenoid only	~10%
Lithium lens	~29%

1. Impact of undulator angular errors on the yield and polarization





$$\lambda_u' = \lambda_u / \cos\theta$$

$$By' = By \cdot \cos\theta$$

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

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

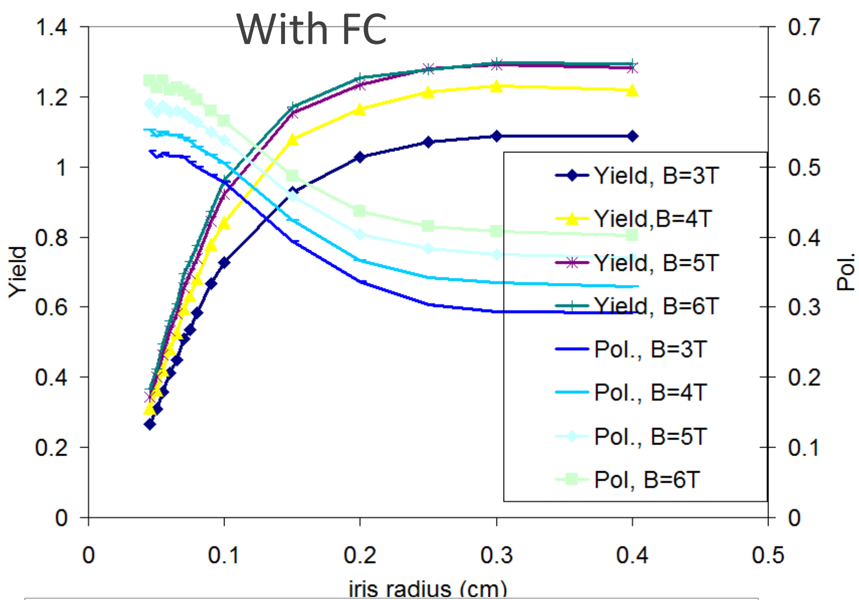
As a result of angular error of undulator, the drive beam will see an increased undulator period and an "elliptically polarized" field. But since the length of undulator module is 4m and the aperture is about 6mm, the maximum value of θ without scrapping the electron beam is less than 0.0015 and thus the impact on both period and B field is only on the 6th digit after floating point.

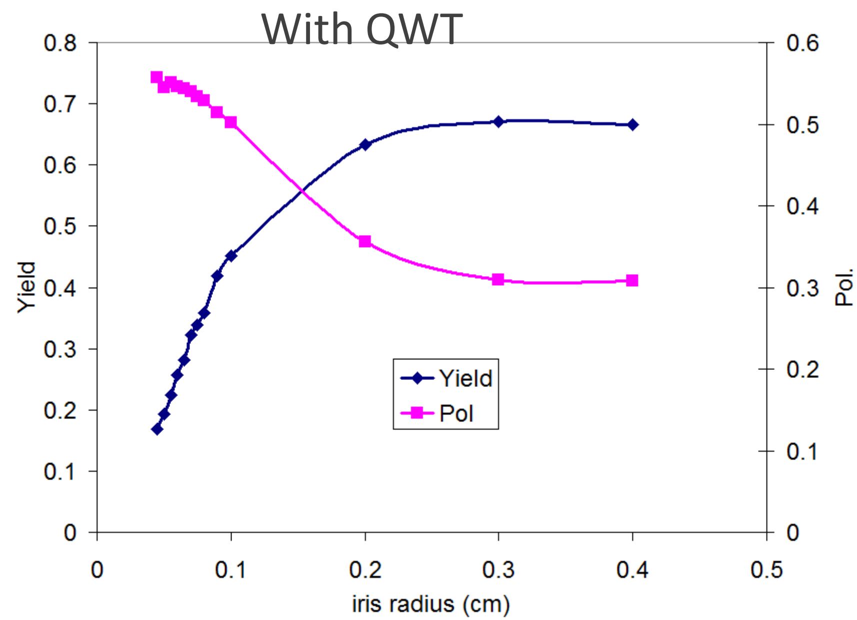
The angular errors of undulator on the yield and polarization should be negligible. But will do some simulation to confirm it in the future.

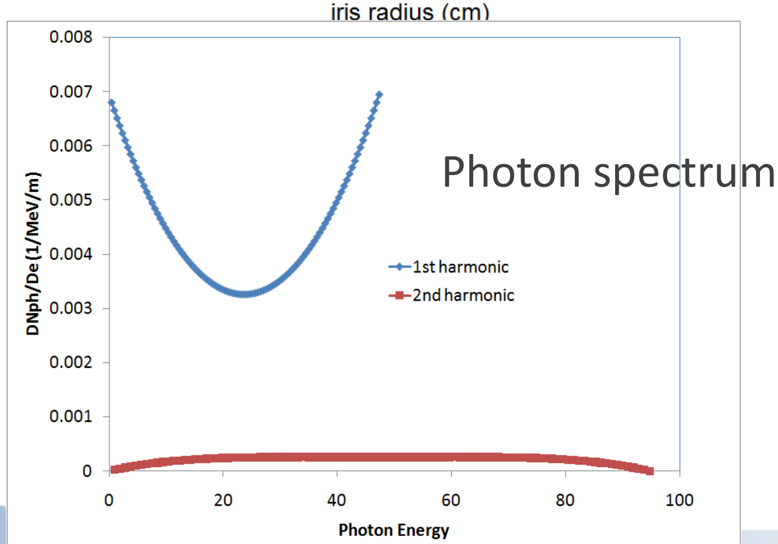
2. Varying K for RDR undulator at the end of linac.

- 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.
  - QWT, ¼ wave transformer with conventional solenoid. 1T max
- Length of undulator 237m
- Target: 0.4X0 Ti target
- Drift from Undulator end to target: 400m
- No photon collimation

K=0.3, Drive beam energy 250GeV

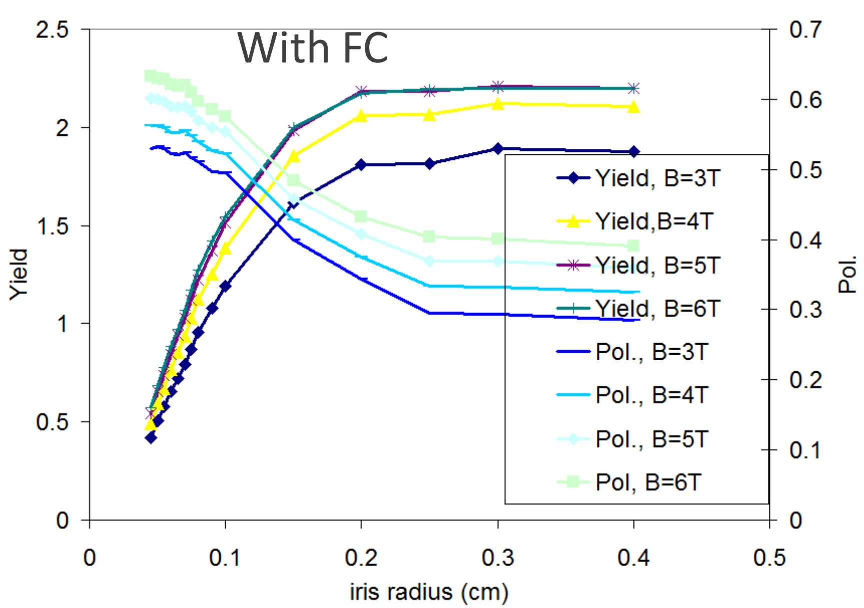


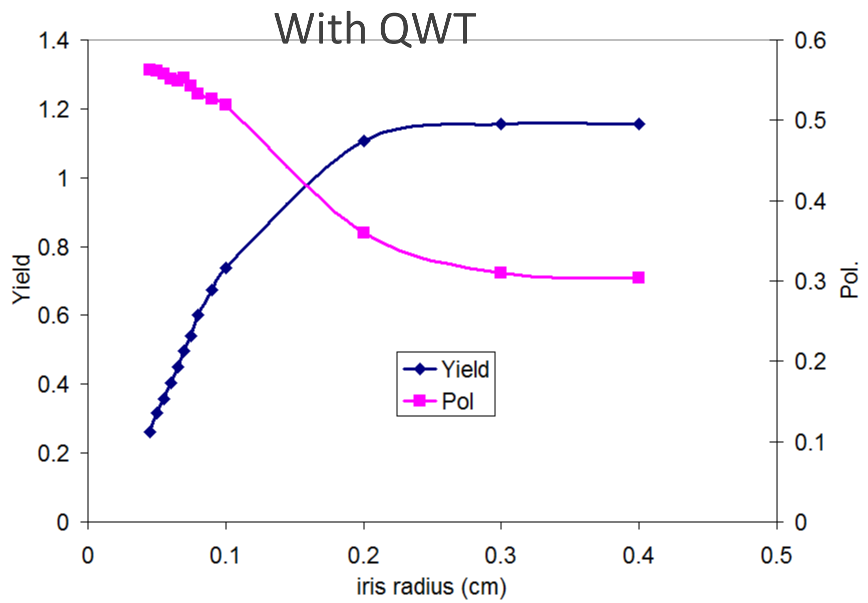


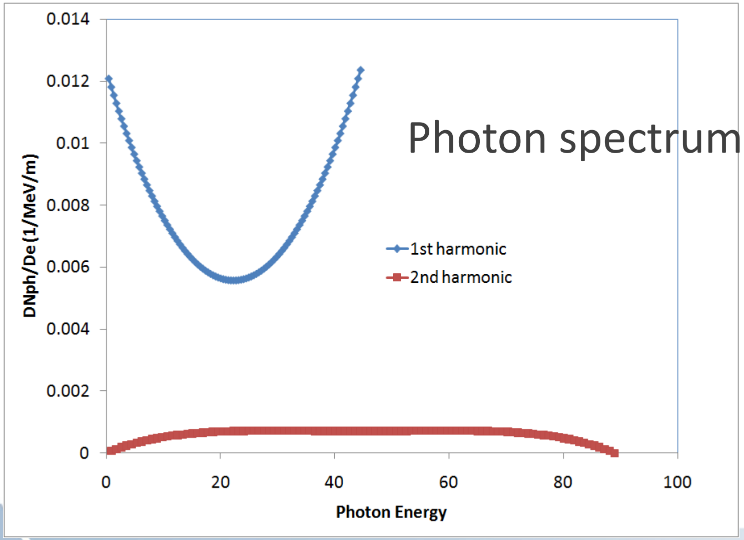


When K is 0.3, the total number of photon is small and also the photon from 2nd harmonic is very small comparing with 1st harmonic radiation.

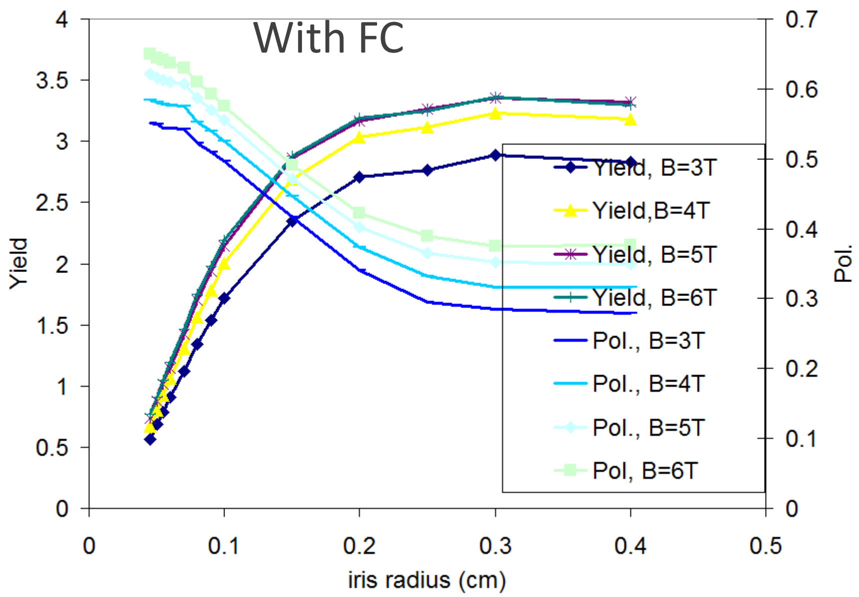
K=0.4, Drive beam energy 250GeV

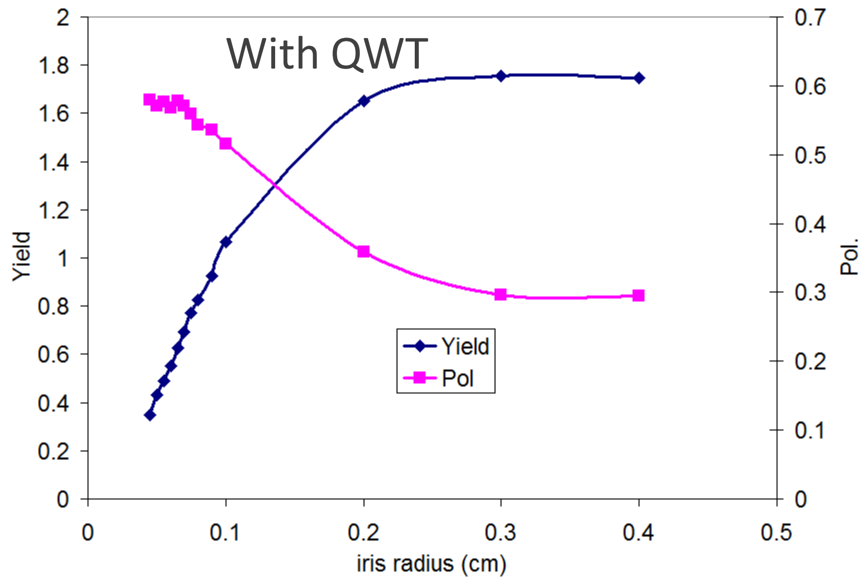


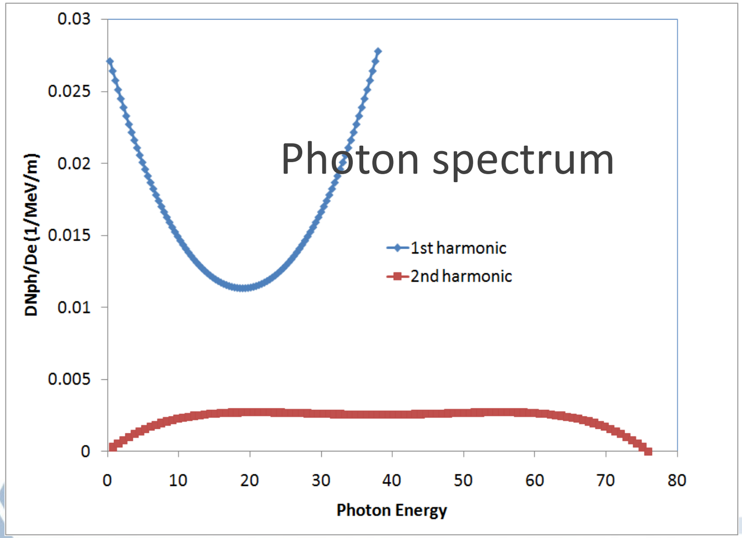




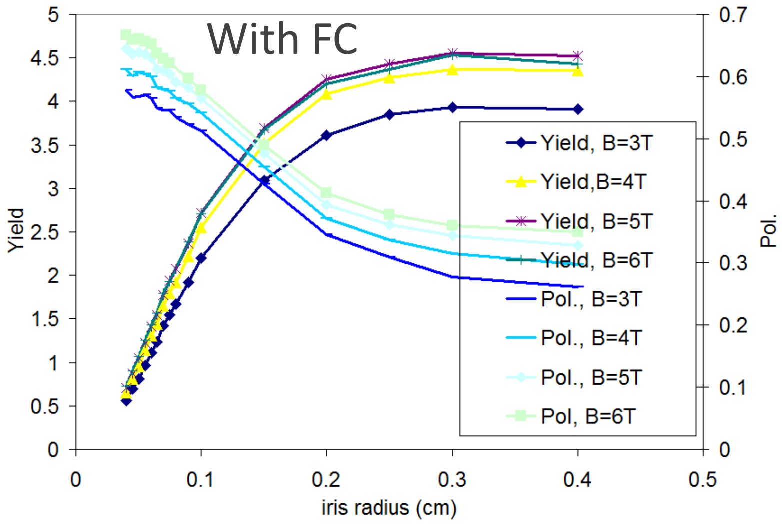
K=0.5, Drive beam energy 250GeV

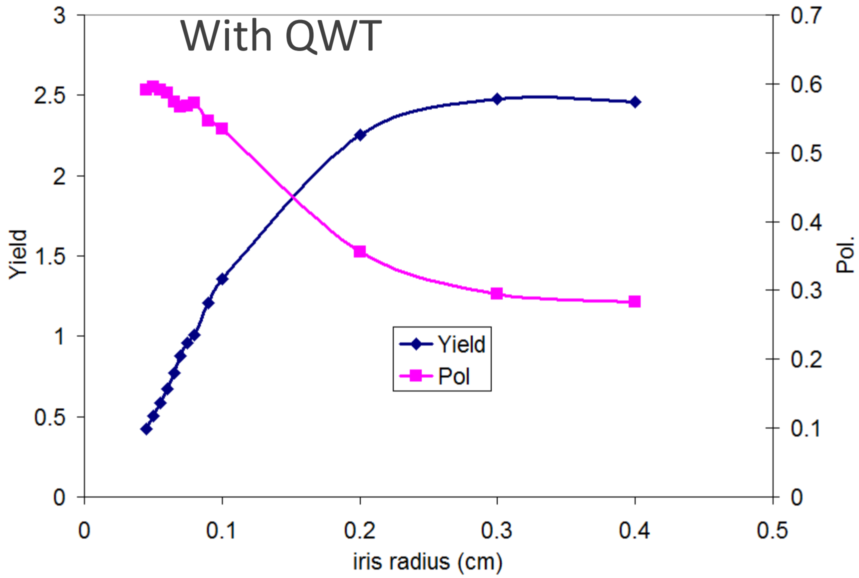


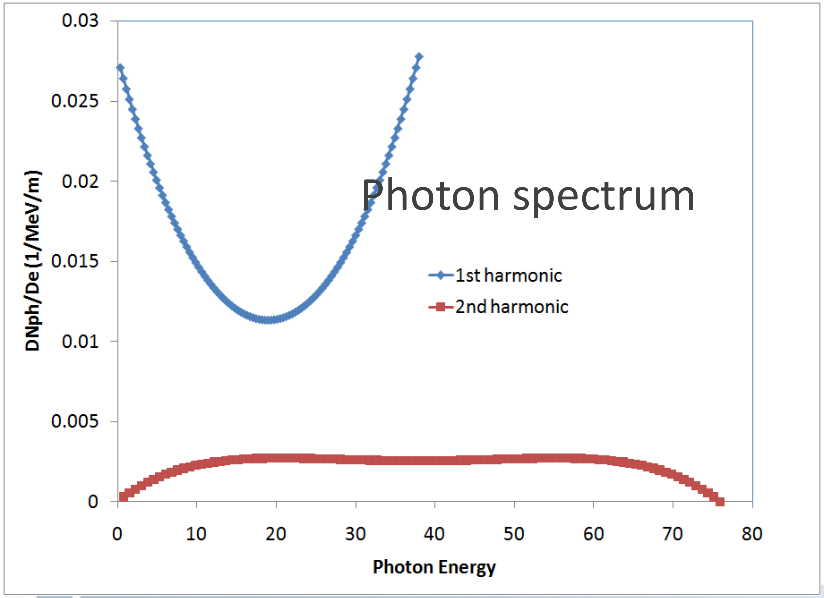




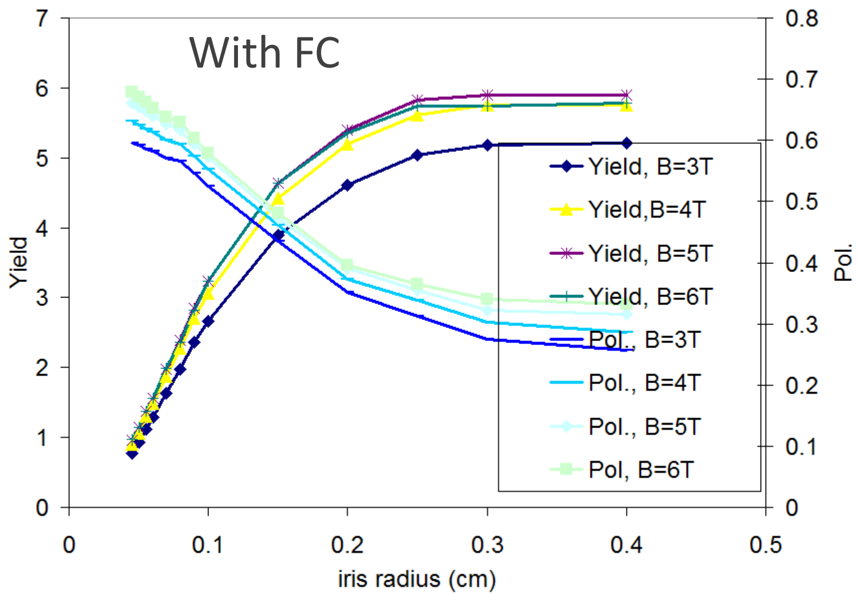
K=0.6, Drive beam energy 250GeV

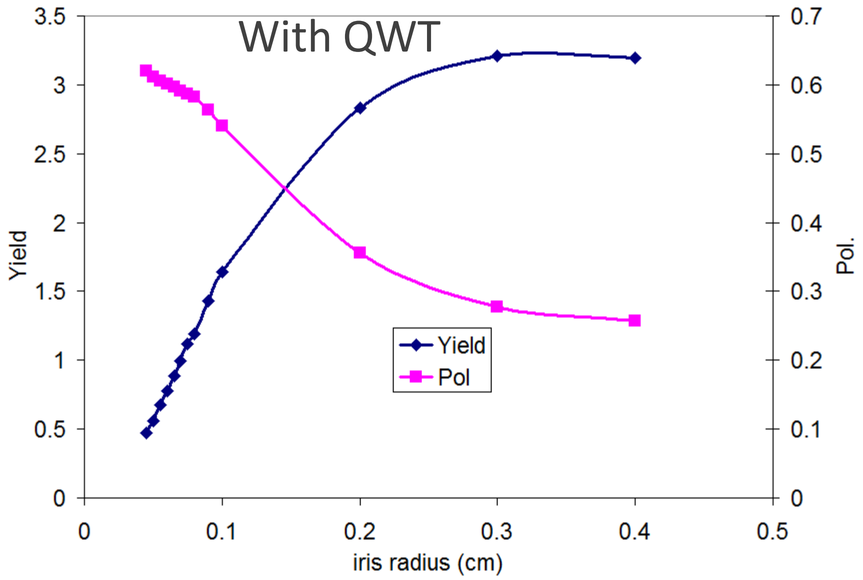


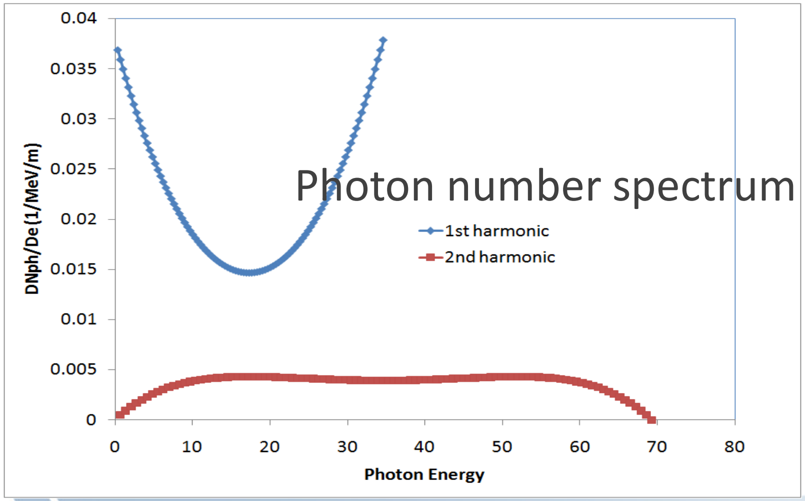




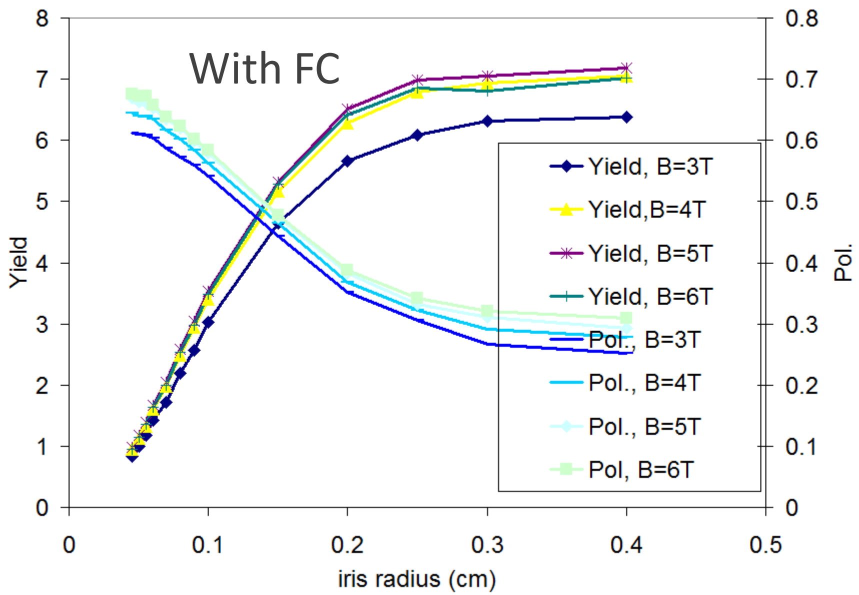
K=0.7, Drive beam energy 250GeV

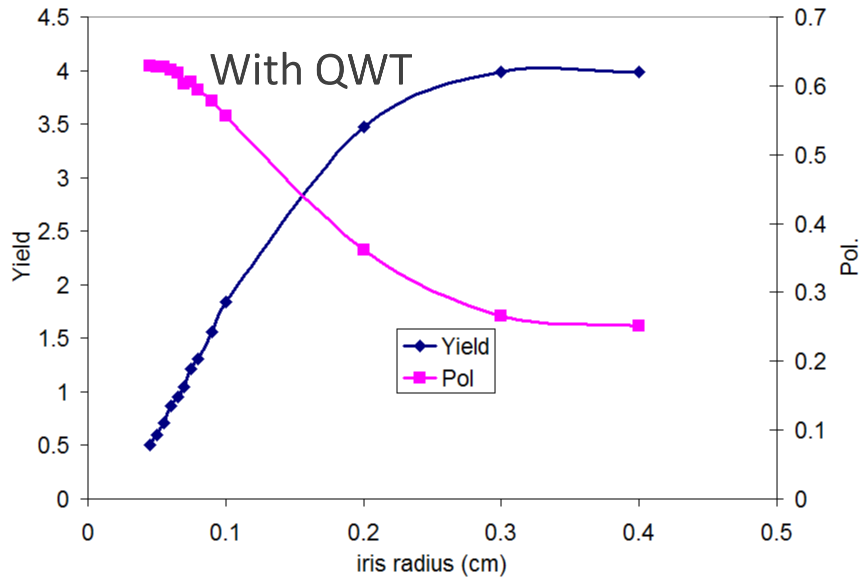


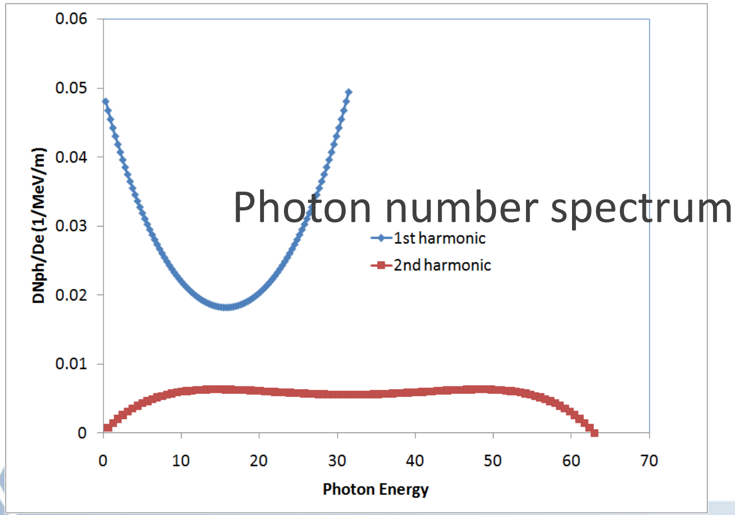




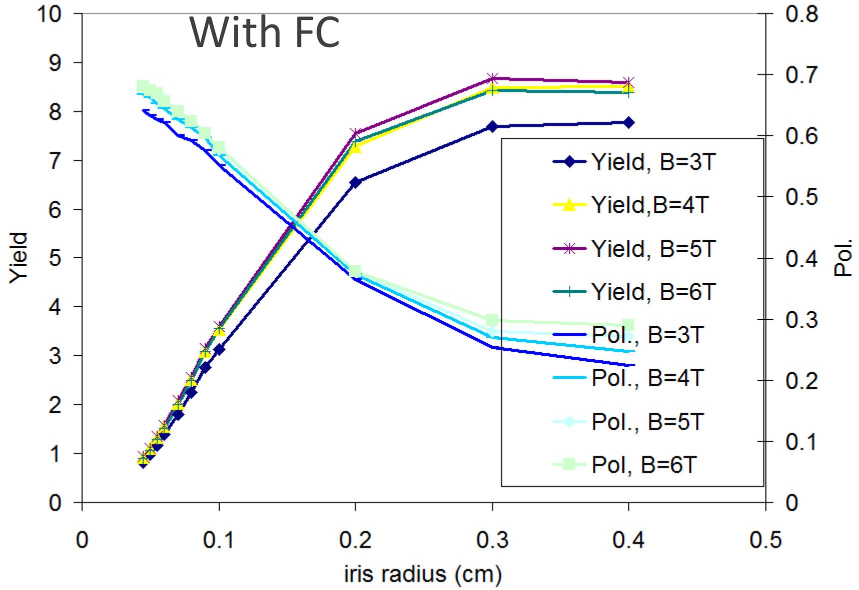
K=0.8, Drive beam energy 250GeV

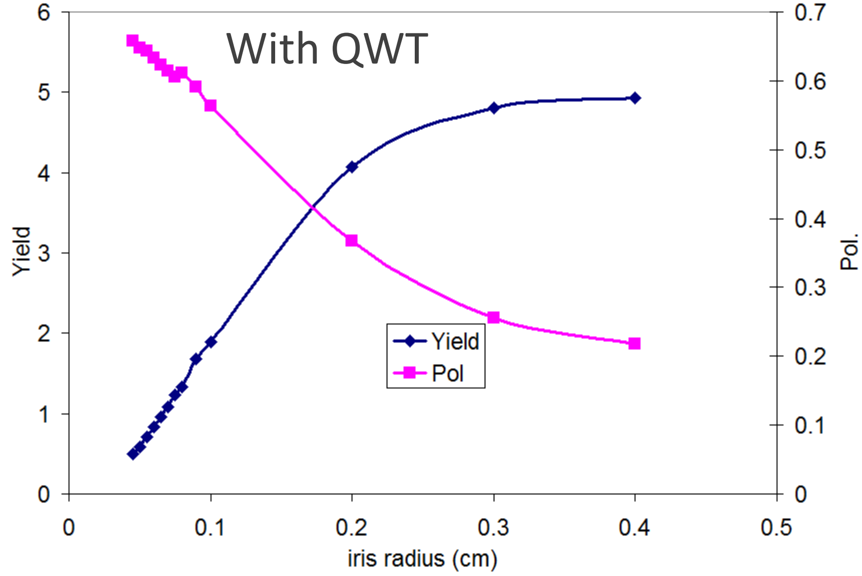


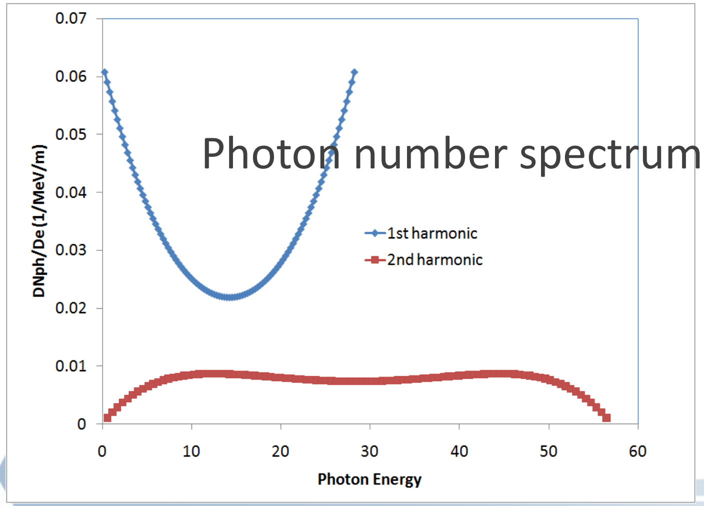




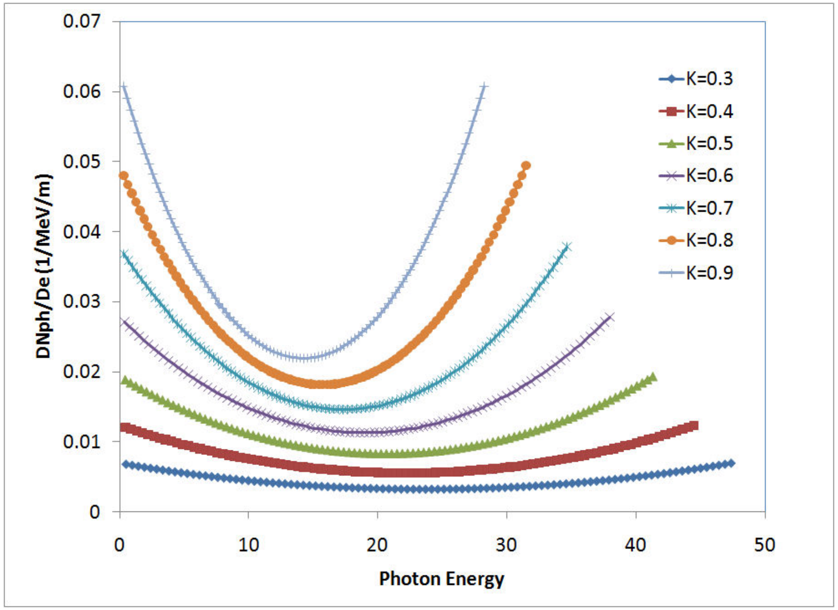
K=0.9, Drive beam energy 250GeV







Summary on varying K

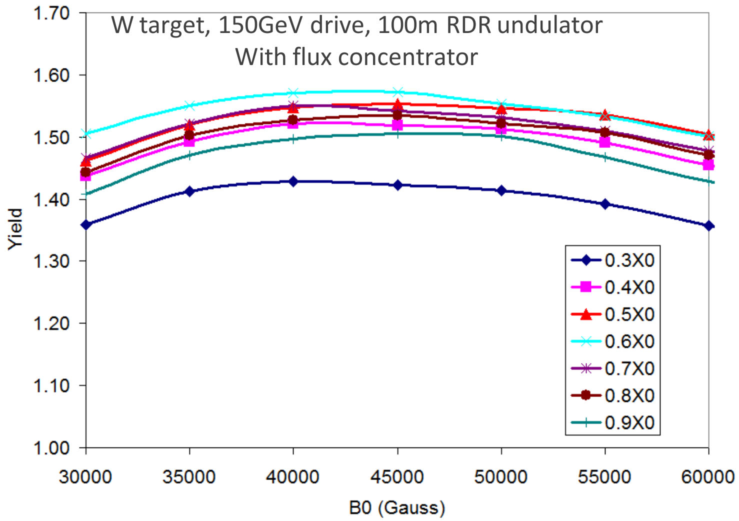


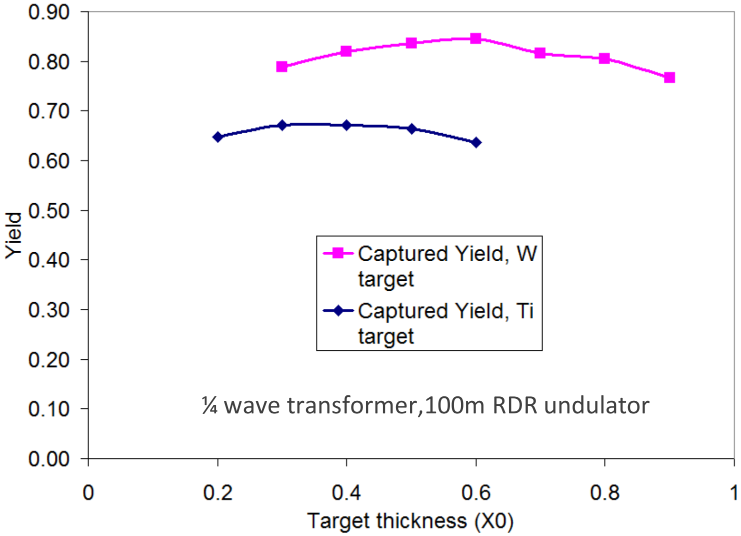
- Disadvantage of Low K: increase the critical energy of photon of helical undlator radiations and lower the number of photon produced for a given length of undulator.
- Advantage of low K: lower high order harmonic radiation

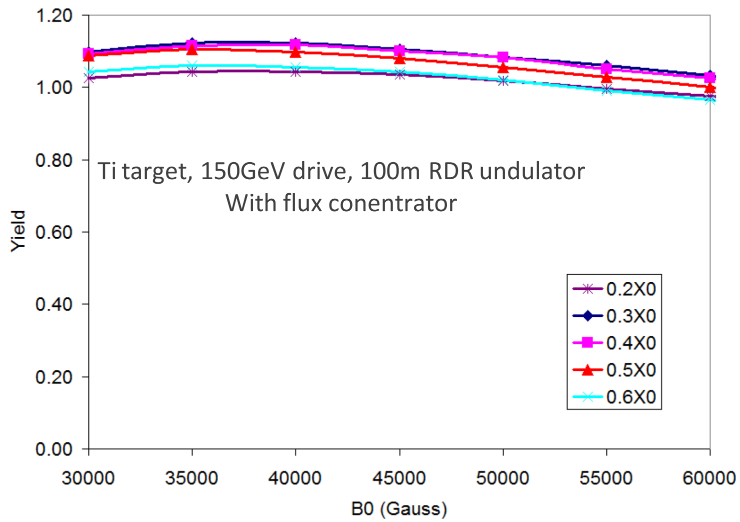
3. W target and Ti target comparison

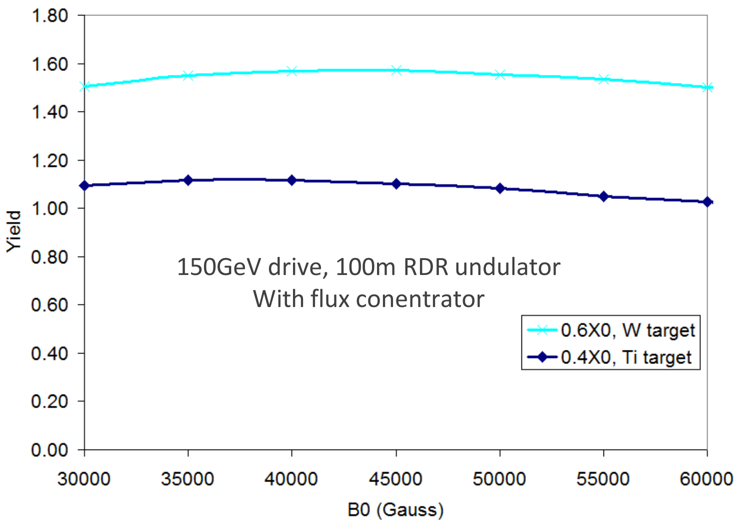
- RDR undulator,
- OMD: Flux concentrator, ¼ wave tansformer
- Drive beam energy: 150GeV, 250GeV
- Drift from end of undulator to target: 400m

150GeV drive





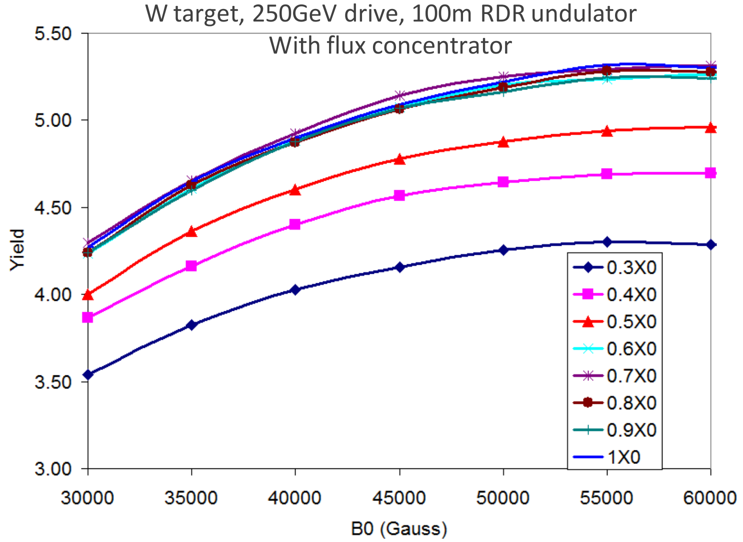


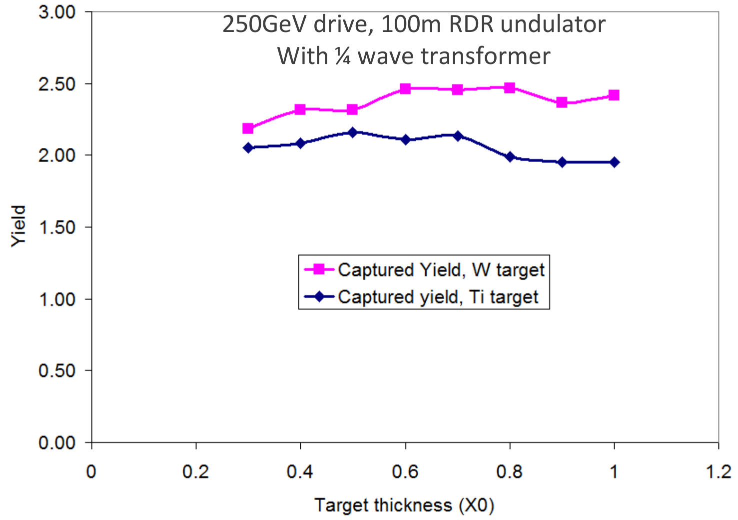


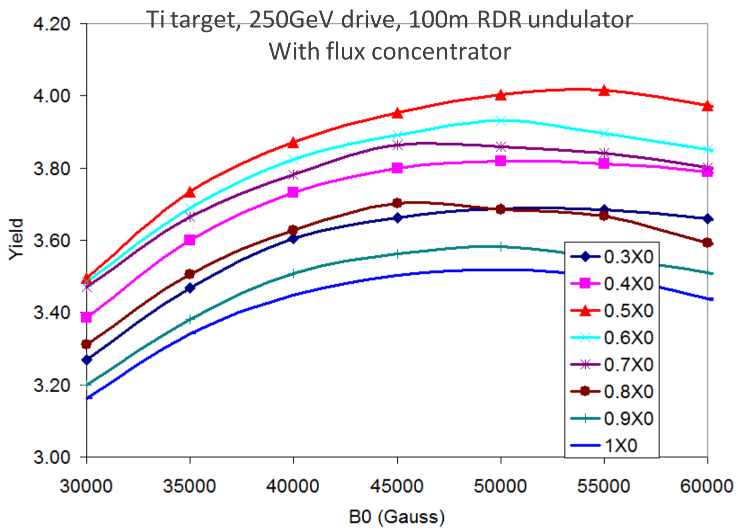
For 100m long RDR undulator, 150GeV drive beam, using FC, W target gives the highest yield of ~1.57 when the thickness is 0.6X0. While Ti target gives its highest yield of ~1.12 when the thickness is 0.4X0 or 0.3X0

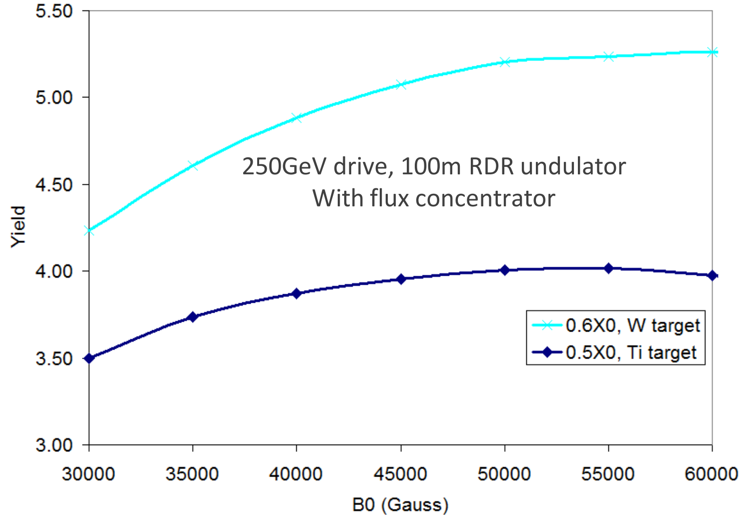
If ¼ wave transformer is used, the highest yield is 0.84 for W target and 0.67 for Ti target.

250GeV drive









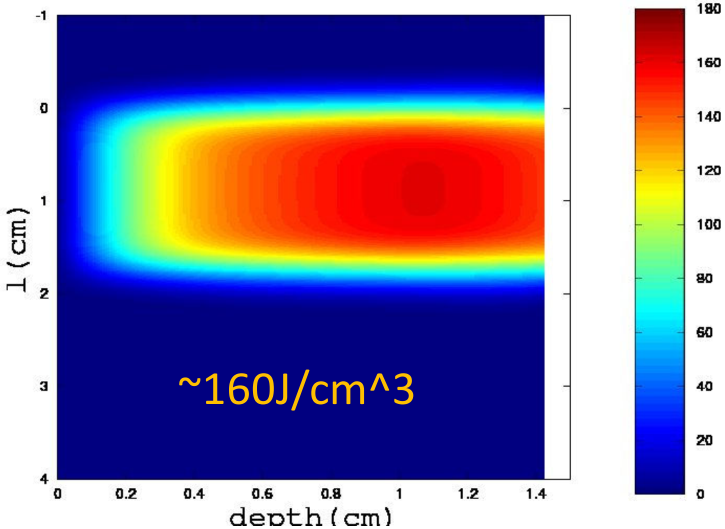
For 100m long RDR undulator, 250GeV drive beam, using FC, W target gives the highest yield of ~5.3 when the thickness is 1X0. But it only dropped to ~5.2 when the thickness is 0.6X0, thus 0.6X0 is chosen for W target. For Ti target, highest yield is ~4.0 when the thickness is 0.5X0. If ¼ wave transformer is used, the highest yield is ~2.46 for W target and 2.16 for Ti target.

Energy deposition

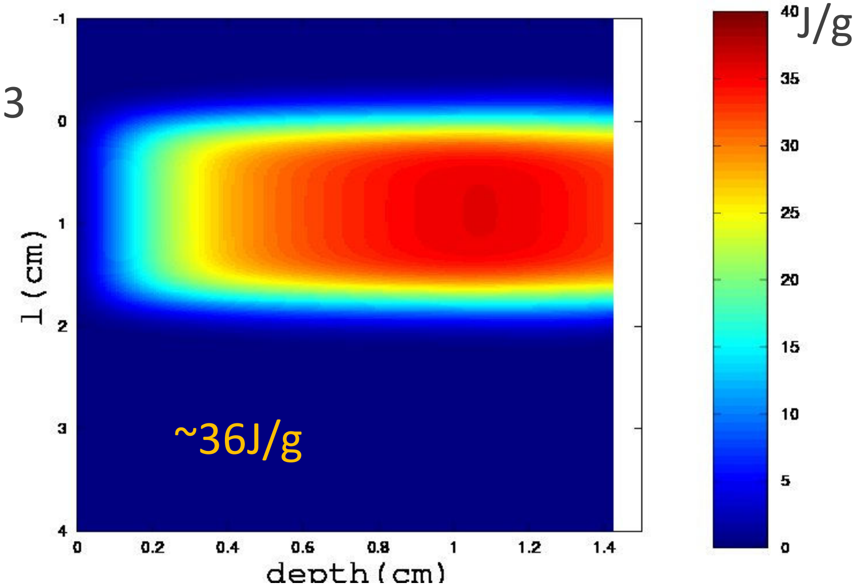
100m long RDR undulator	Ti target			W target		
	Thickness for highest yield (X0)	Energy deposition per bunch (J.)	Average power (KW)	Thickness for highest yield (X0)	Energy deposition per bunch (J.)	Average power (KW)
150GeV drive	0.3	0.3371	4.42	0.6	0.4457	5.85
250GeV drive	0.5	1.2483	16.38	0.6	0.721	9.46

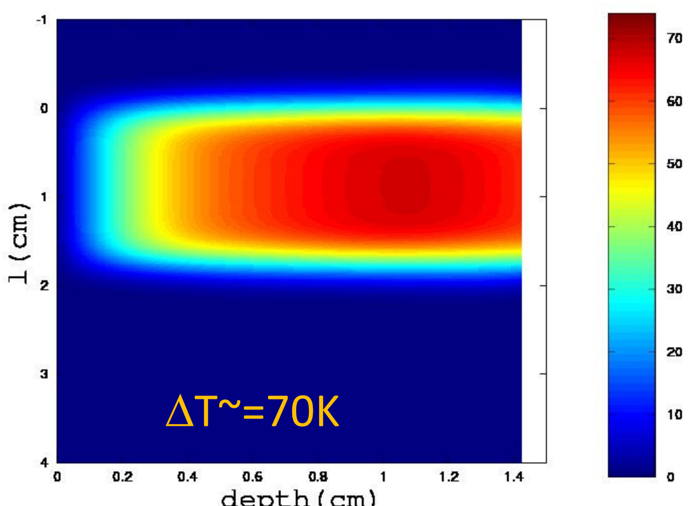
1.5 Yield, (3e10 e+ captured), RDR undulator	Ti target			W target		
	Thickness for highest yield (X0)	Energy deposition per bunch (J.)	Average power (KW)	Thickness for highest yield (X0)	Energy deposition per bunch (J.)	Average power (KW)
150GeV drive, FC	0.3	0.4535	5.95	0.6	0.4260	5.59
250GeV drive, FC	0.5	0.4697	6.16	0.6	0.2087	2.74
150GeV drive, QWT	0.3	0.7493	9.83	0.6	0.8051	10.57
250GeV drive, QWT	0.5	0.8693	11.41	0.6	0.4468	5.86

Energy density and estimated temperature change after 500 bunchs. RDR undulator, 150GeV drive , AMD Immersed 0.4X0 Ti target. 2e10 e+ assume captured



J/cm^3

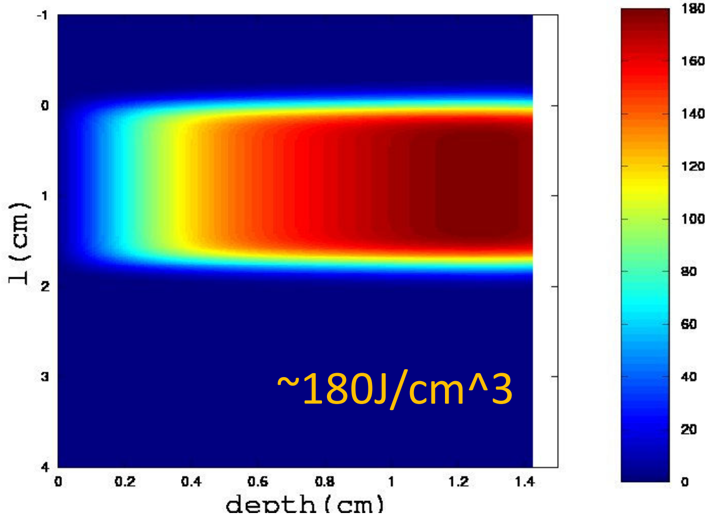


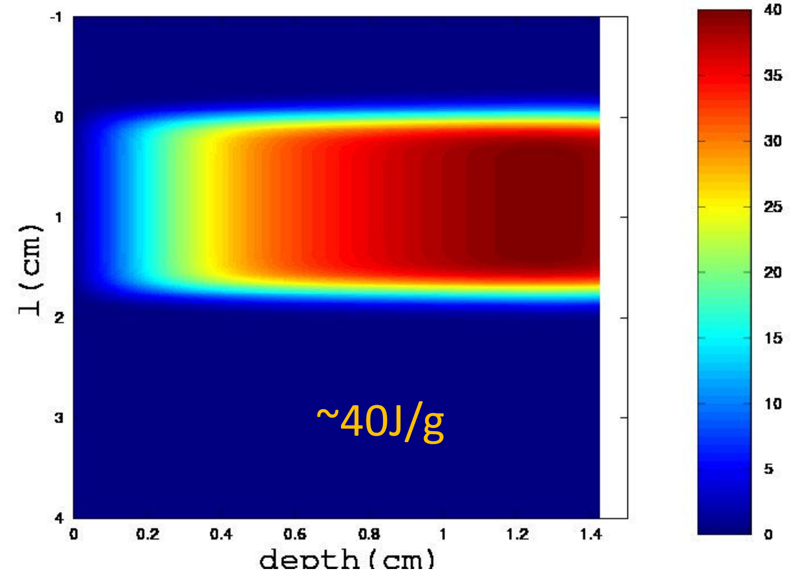


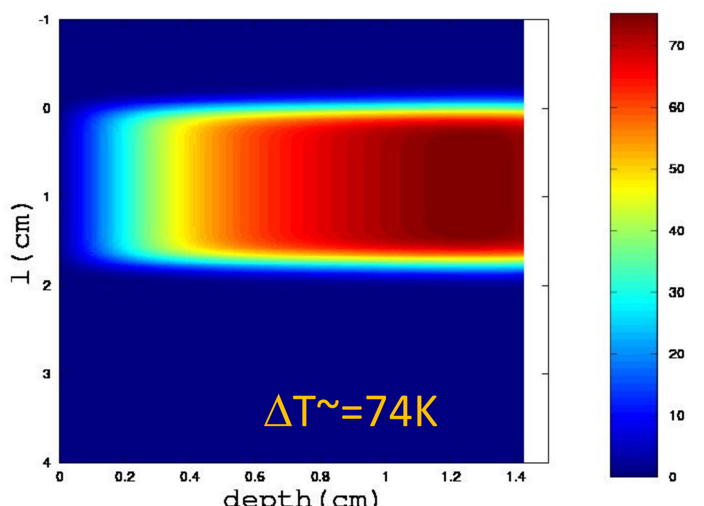
K

The 2m diameter target wheel is rotating at 900RPM.

Energy density and estimated temperature change after 500 bunchs. RDR undulator, 250GeV drive , AMD Immersed 0.4X0 Ti target. 2e10 e+ assume captured



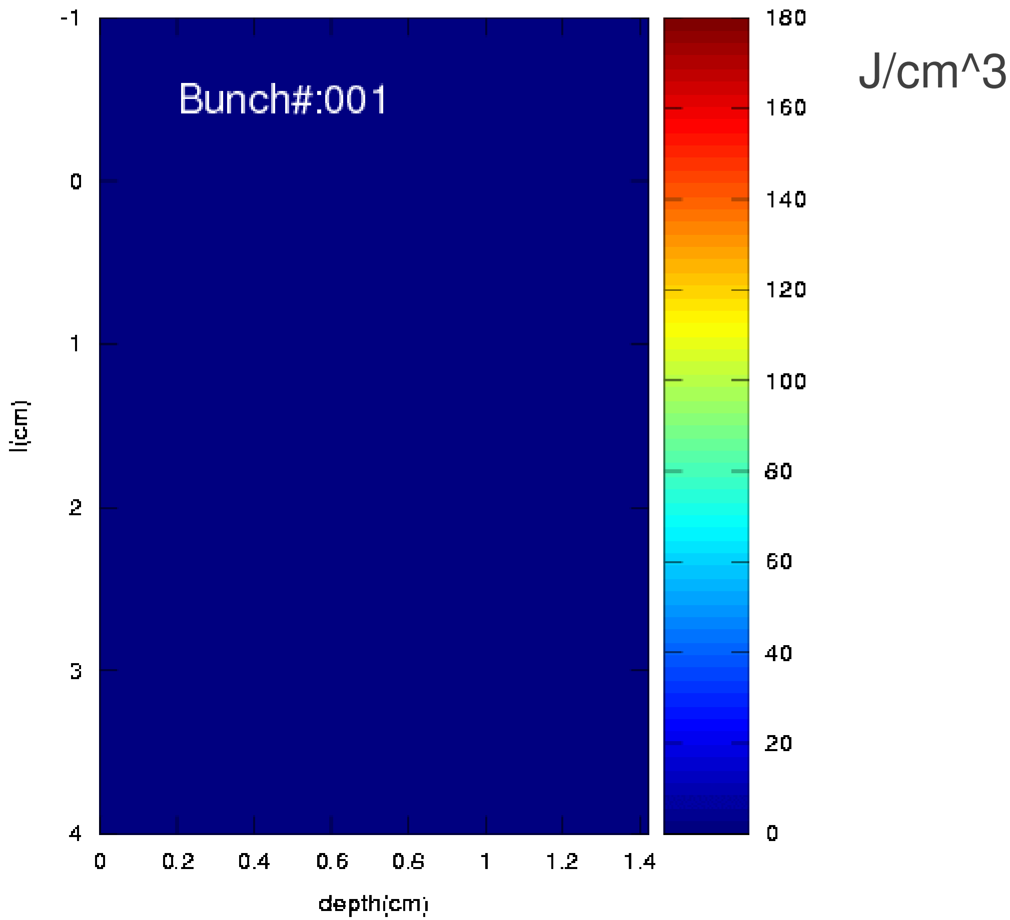




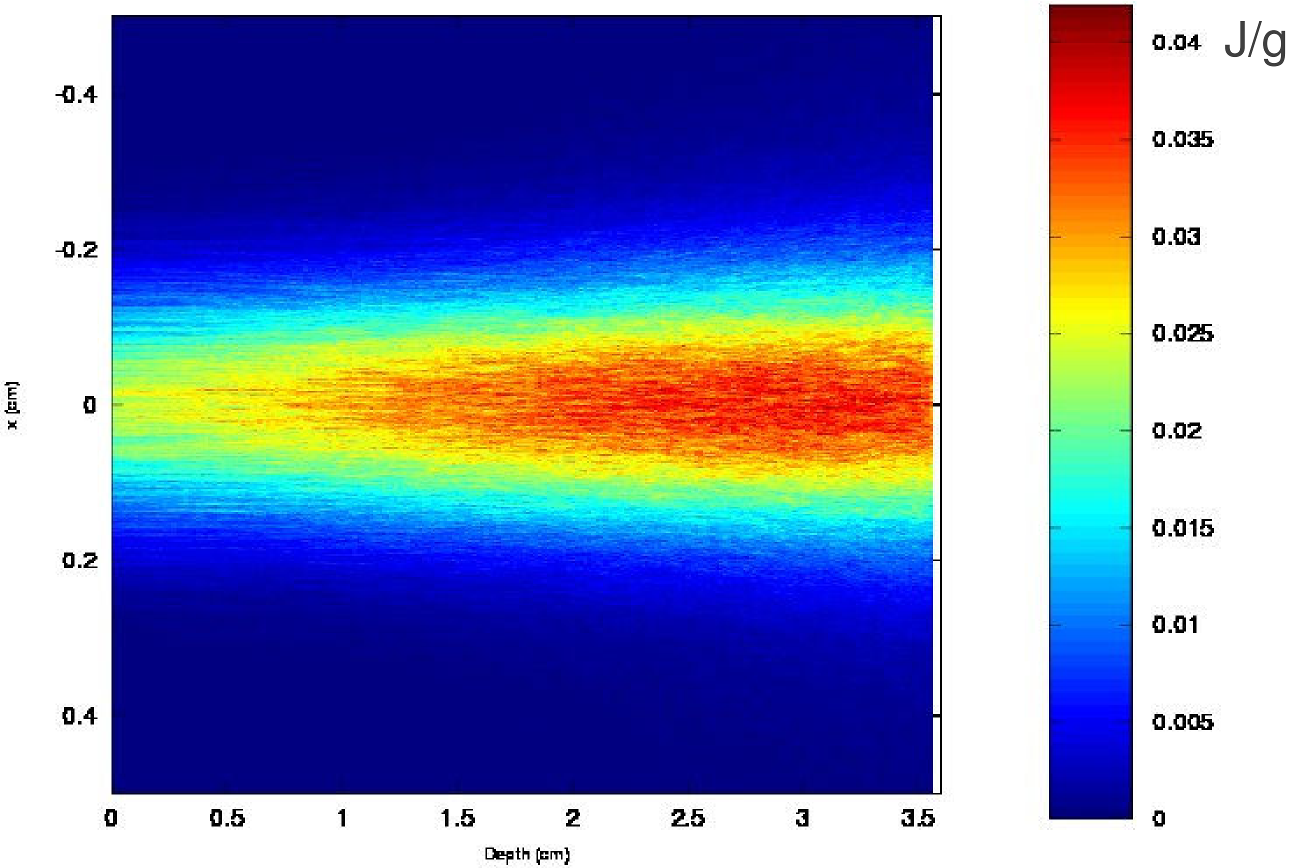
The 2m diameter target wheel is rotating at 900RPM.

Even though the energy density per bunch is ~60% higher for 250GeV drive beam when comparing with 150GeV drive beam, the accumulated effect is not significant due to the smaller spot size from 250GeV drive beam.

Accumulated Energy Deposition, drive beam energy 250GeV, RDR undulator, 2e10 e+ assume captured.

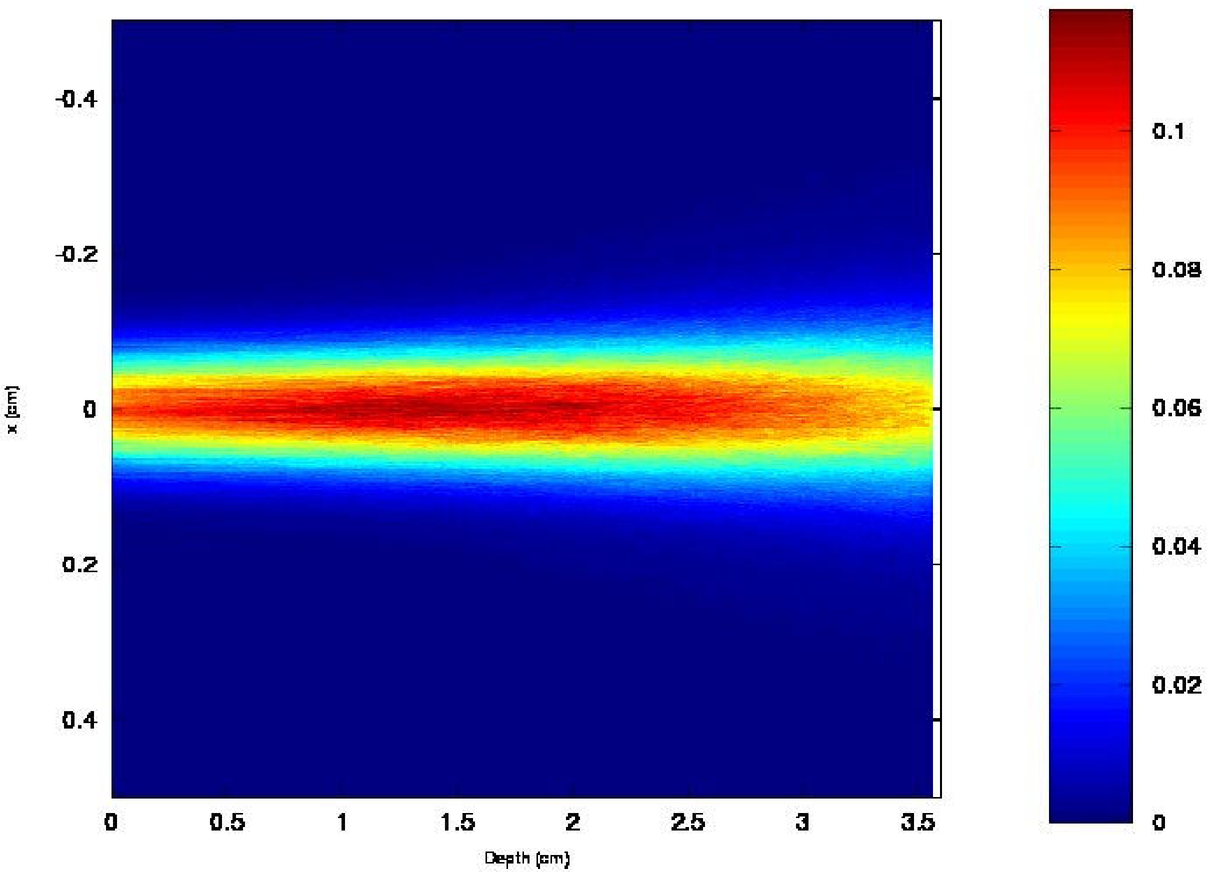


Energy deposition of FLASH beam, 1mm rms spot size



For 1nc, 700MeV electron beam with 1mm spot size, the peak density of deposition is 0.04J/g. For a train of 2625 bunches of such beam, the density reaches 105J/g

Energy deposition of FLASH beam, 0.5mm rms spot size



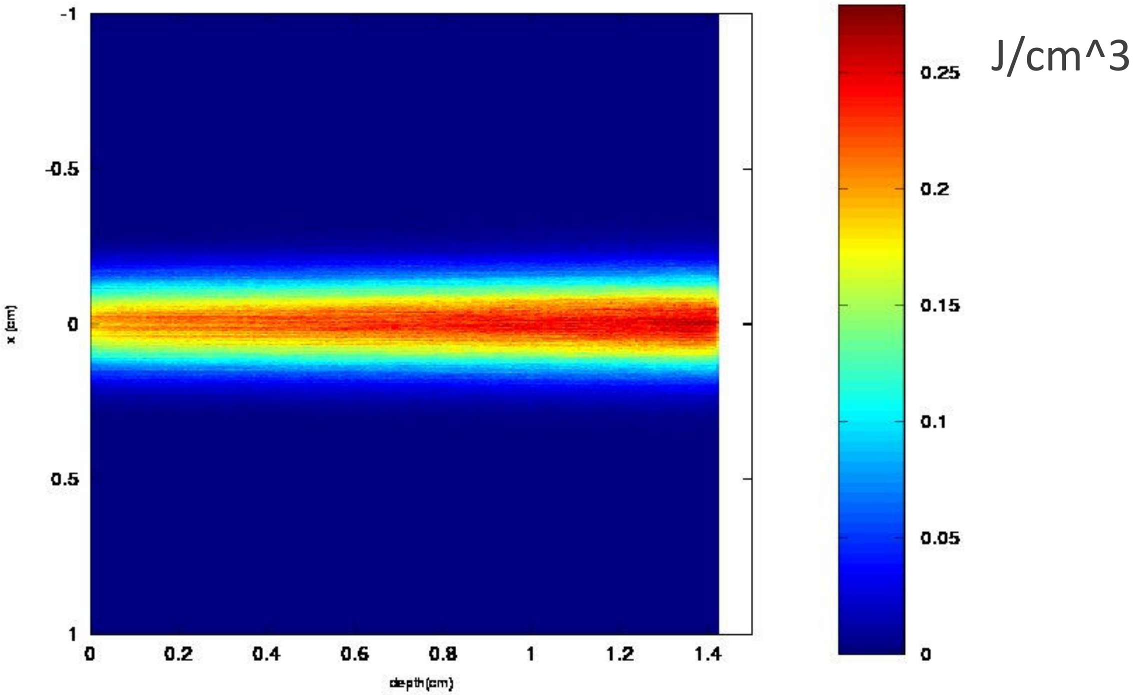
For 1nc, 700MeV electron beam with 0.5mm spot size, the peak density of deposition is 0.12J/g. For a train of 2625 bunches of such beam, the density reaches 315J/g

Density of accumulated deposit energy (for rdr rotating target)

1.5 Yield, (3e10 e+ captured), RDR undulator	Ti target (density=4.5 g/cm^3)				W target (density=19g/cm^3)			
	Thickness for highest yield (X0)	Energy deposition per bunch (J.)	Average power (KW)	Peak energy density (J/cm^3)	Thickness for highest yield (X0)	Energy deposition per bunch (J.)	Average power (KW)	Peak energy density (J/cm^3)
150GeV drive, FC	0.3	0.4535	5.95	380	0.6	0.4260	5.59	2400
250GeV drive, FC	0.5	0.4697	6.16	360	0.6	0.2087	2.74	2100
150GeV drive, QWT	0.3	0.7493	9.83	610	0.6	0.8051	10.57	4550
250GeV drive, QWT	0.5	0.8693	11.41	660	0.6	0.4468	5.86	4400

Auxiliary source, 500MeV, 0.4X0 Ti target

- When using ¼ wave transformer as OMD, the yield is about 0.017. 3nC 500MeV drive electron beam hitting on the target can give us the required e+ beam (1%) intensity for keep alive purpose.
- The energy deposition will ~0.02 J per bunch if 1 percent e+ intensity is required.
- The peak deposit energy density is 0.28J/cm^3

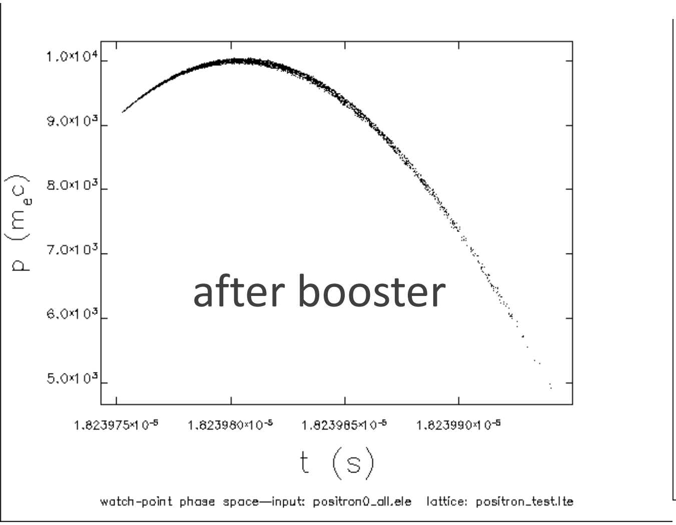


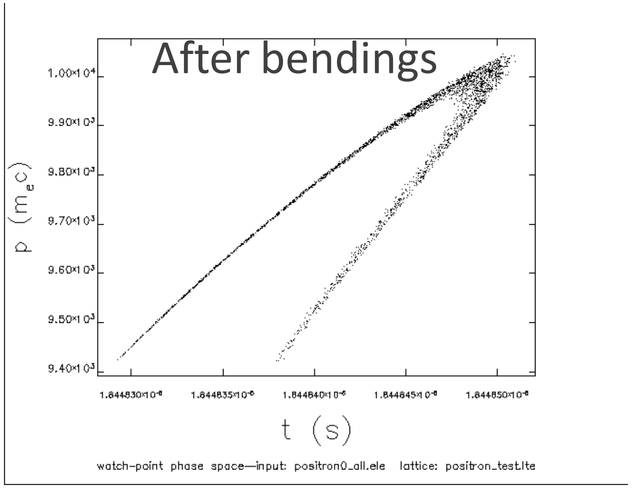
Summary

- We have completed the works assigned to us at last ILC e+ collaboration meeting.
- Looked several major issues:
  - Straightness of the undulator should not be an issue, but we will do a detailed study to verify.
  - Tungsten and Titanium comparison were made,
  - Energy depositions for Ti and W were calculated : May need to do experiment at FLASH for target survivability studies.

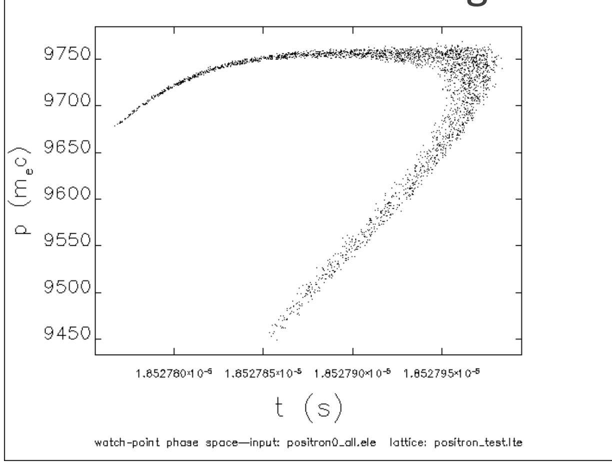
Energy Compression before damping ring

- Spin rotation:
  - Longitudinal to 90^0 in horizontal plane, 7 bending of 7.929^0
  - Horizontal to vertical, 8.3m long superconducting solenoid with Bz=3.16T
- Energy compressing: 6m long superconducting linac with 30MV/m gradient and proper phase.





After the comressing linac

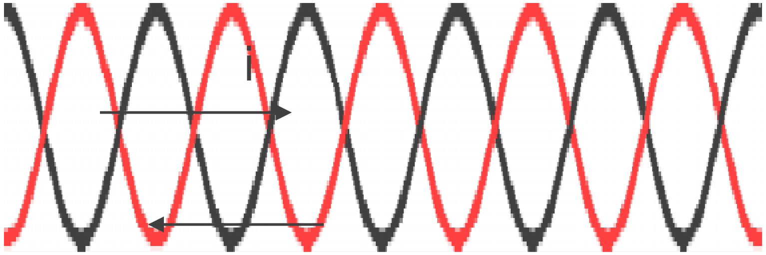


Ref: F Zhou, slac-pub-12239

Major critical issues

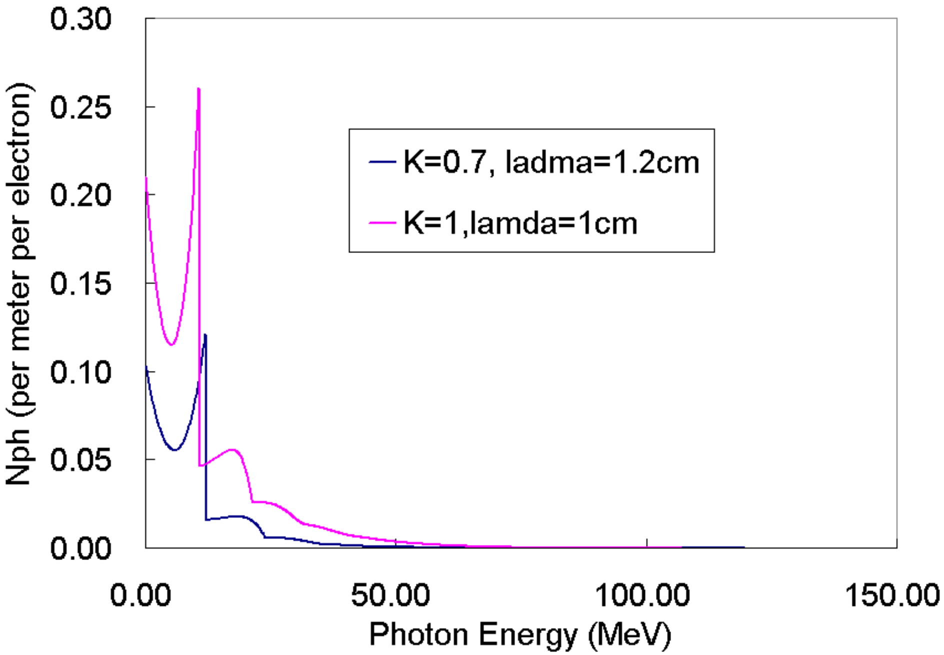
- Target
  - Survivability
  - Rotating under strong magnetic field
  - Mechanical design
  - Radiation damage
- OMD
  - Engineering design of flux concentrator
  - R&D of lithium lens

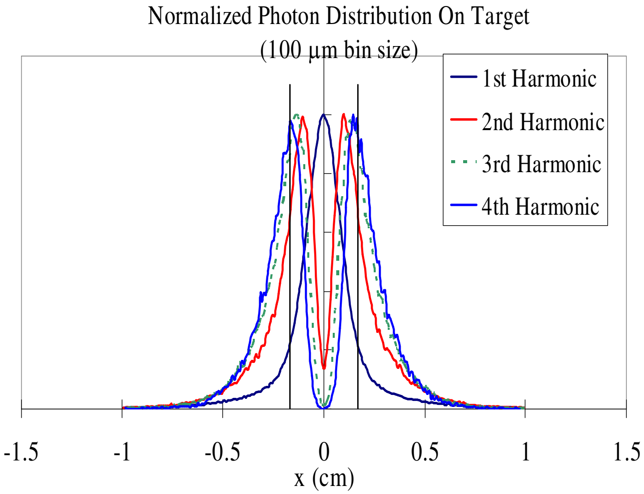
Helical undulator:



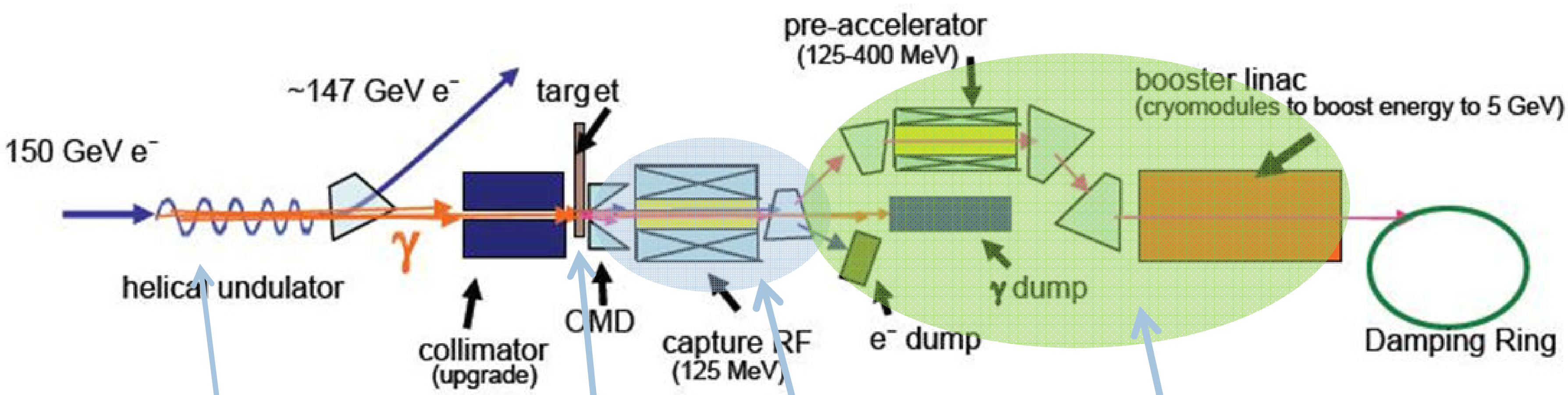
Supper conducting helix

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





Positron source start to end simulation



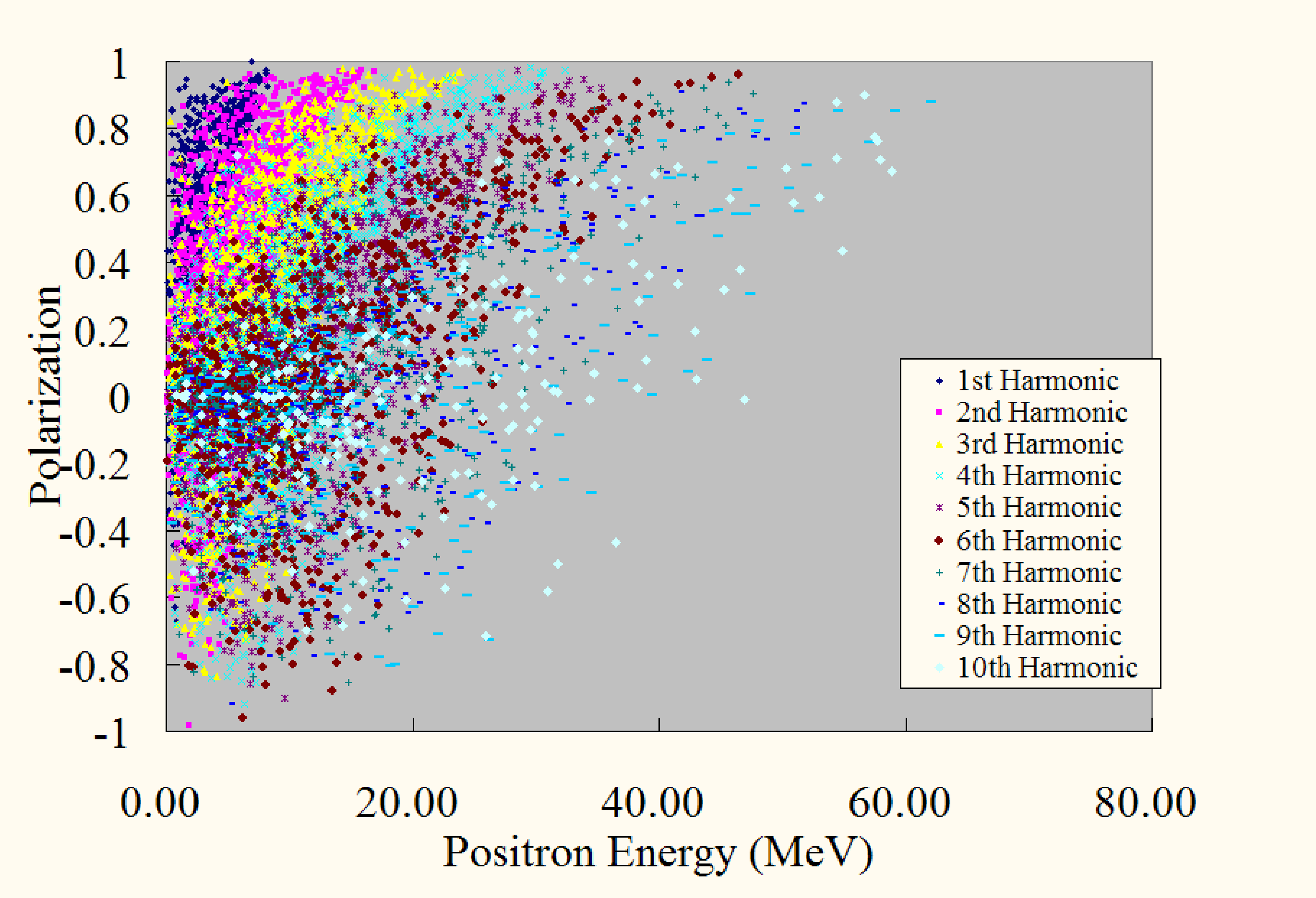
Undulator radiation:
Monte Carlo model

Positron production:
EGSnrc

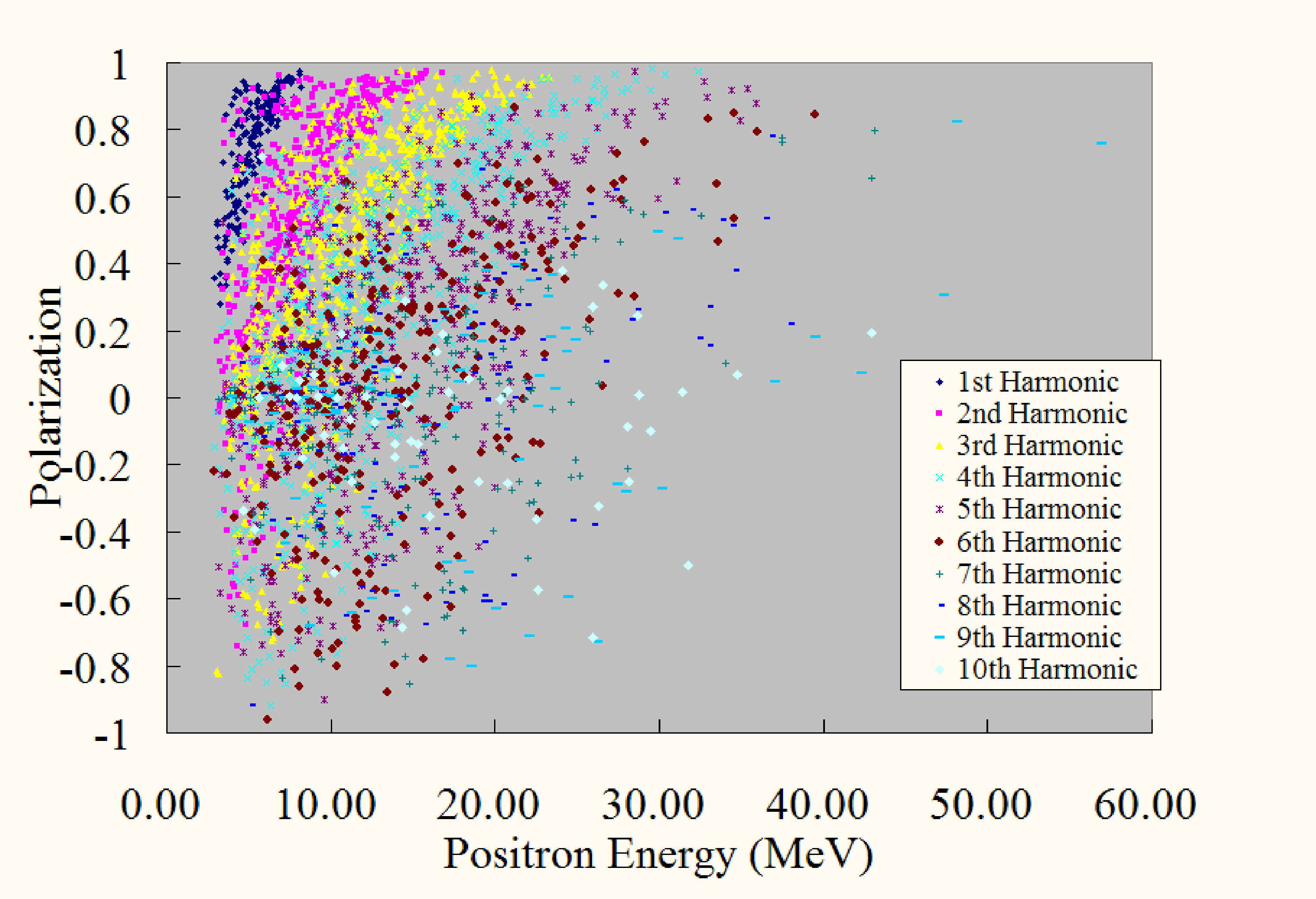
Positron pre-accelerating
and booster: elegant

Positron capture: PARMELA

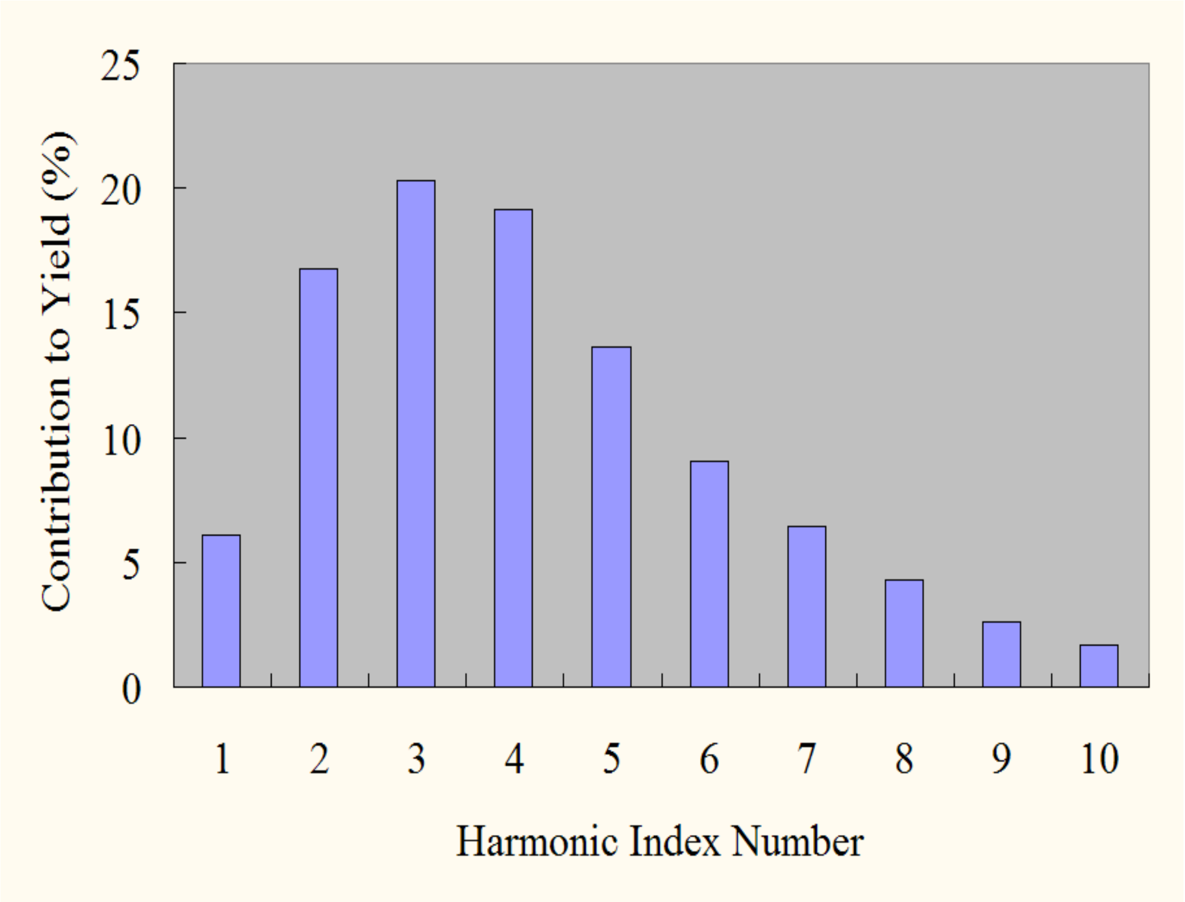
Initial Polarization of Positron beam at Target exit(K=0.92 λu=1.15)



Initial Pol. Vs Energy of Captured Positron Beam



Yield contribution from different harmonics



The contribution from harmonics will change with the length of drift between undulator and target. The result showing here is when drift length at ~ 100 m.

For longer drift, the contribution from 1st harmonic will increase and contribution from high order harmonics will decrease.

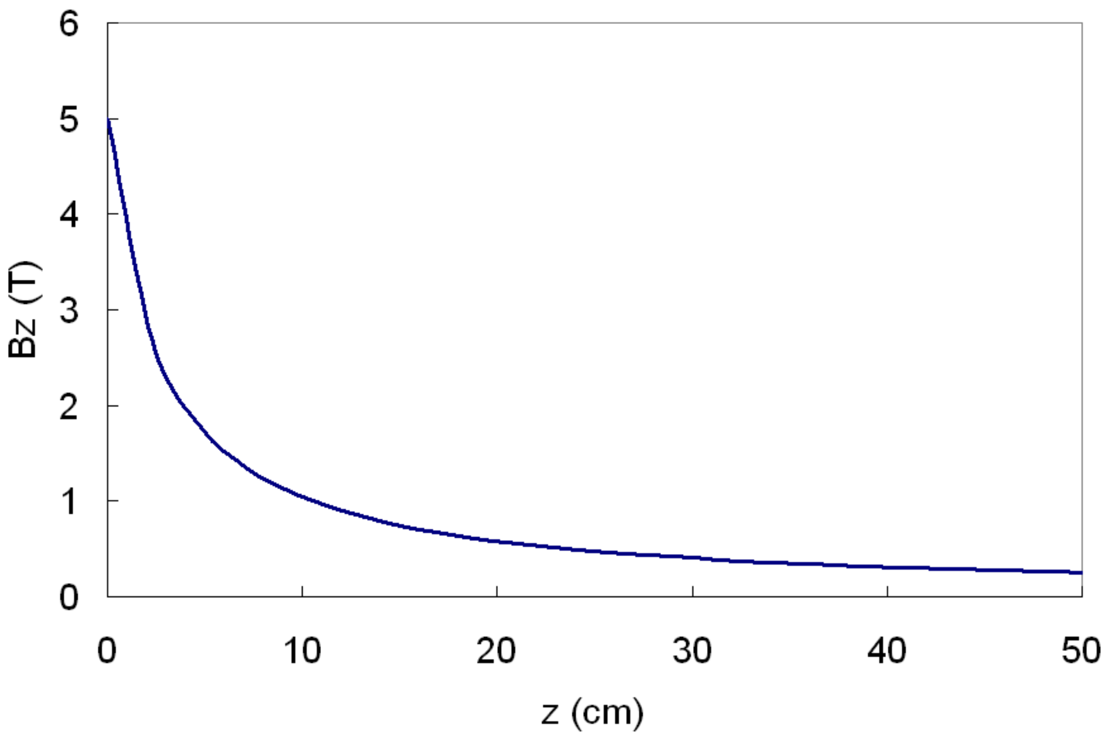
Comparison of positron yield from different undulators

	High K Devices				Low K Devices		
	BCD	**UK I**	**UK II**	**UK III**	**Cornell I**	**Cornell II**	**Cornell III**
Period (mm)	10.0	11.5	11.0	10.5	10.0	12.0	7
K	1.00	0.92	0.79	0.64	0.42	0.72	0.3
Field on Axis (T)	1.07	0.86	0.77	0.65	0.45	0.64	0.46
Beam aperture (mm)	Not Defined	5.85	5.85	5.85	8.00	8.00	
First Harmonic Energy (MeV)	10.7	10.1	12.0	14.4	18.2	11.7	28
Yield(Low Pol, 10m drift)	~2.4	~1.37	~1.12	~0.86	~0.39	~0.75	~0.54
Yield(Low Pol, 500m drift, 25%)	~2.13	~1.28	~1.08	~0.83	~0.39	~0.7	~0.54
Yield (Pol. 60%)	~1.1	~0.7	~0.66	~0.53	~0.32	~0.49	~0.44

Target: 1.42cm thick Titanium

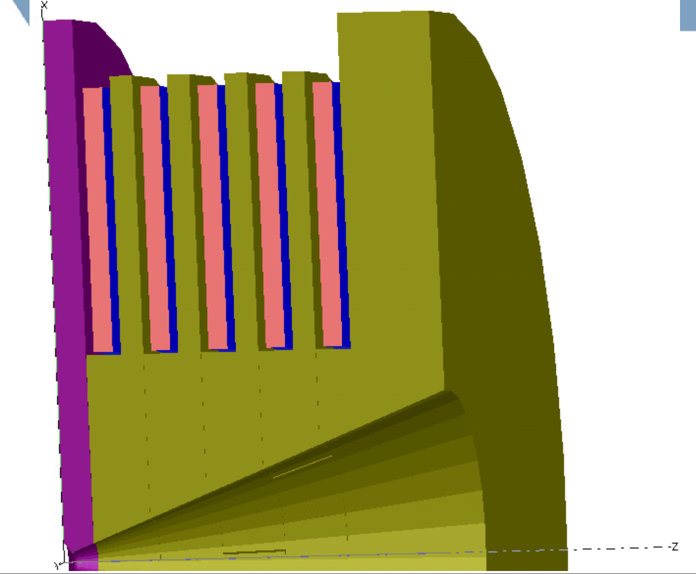
OMD Comparison:
AMD, Target rotating in 5T B field

AMD field:5T-0.25T in 50cm

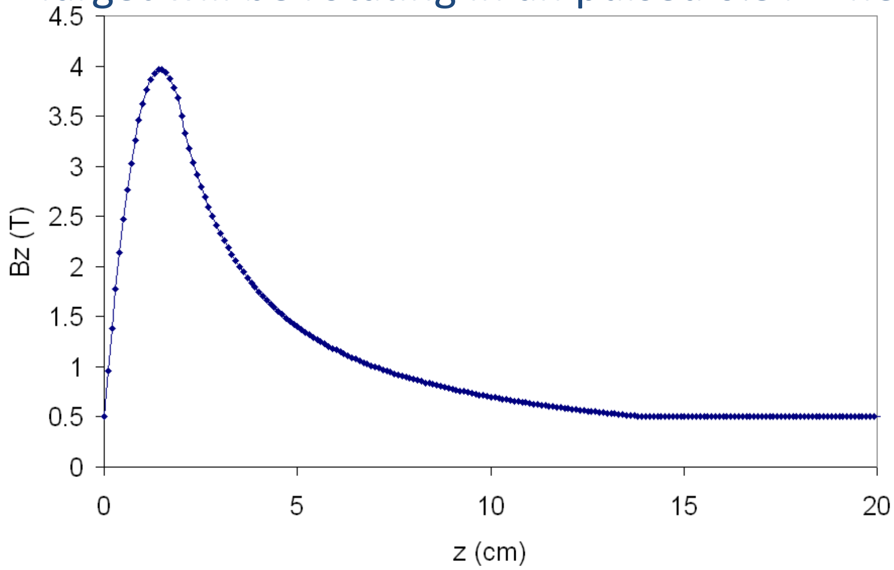


Another proposed solution:
A pulsed flux concentrator

- Pulsing the exterior coil enhances the magnetic field in the center.
  - Needs ~ 1ms pulse width flattop
  - Similar device built 40 years ago. Cryogenic nitrogen cooling of the concentrator plates.
  - ANL and LLNL did initial rough electromagnetic simulations. Not impossible but an engineering challenge.
  - No real engineering done so far.



Target will be rotating in an pulsed 0.5T B field



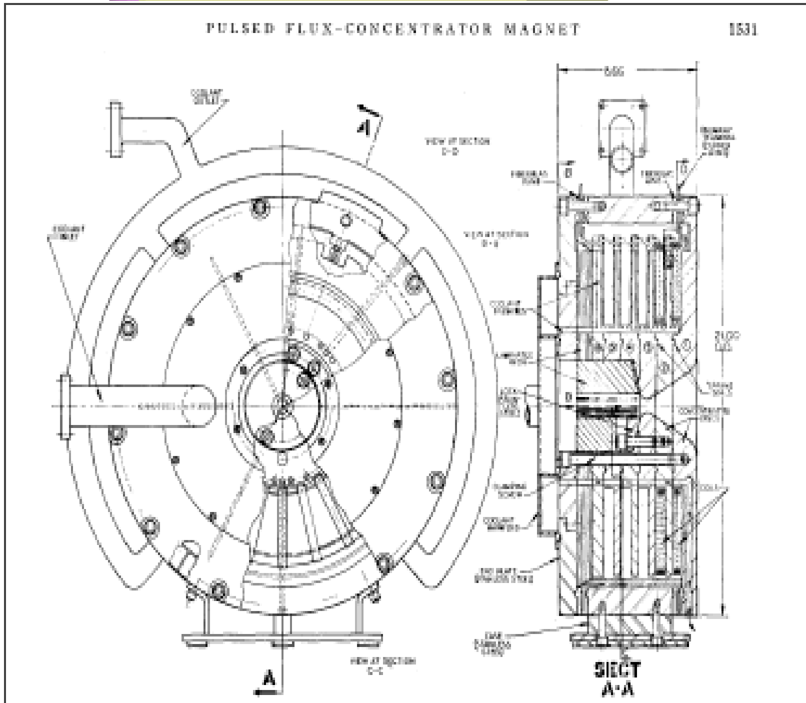
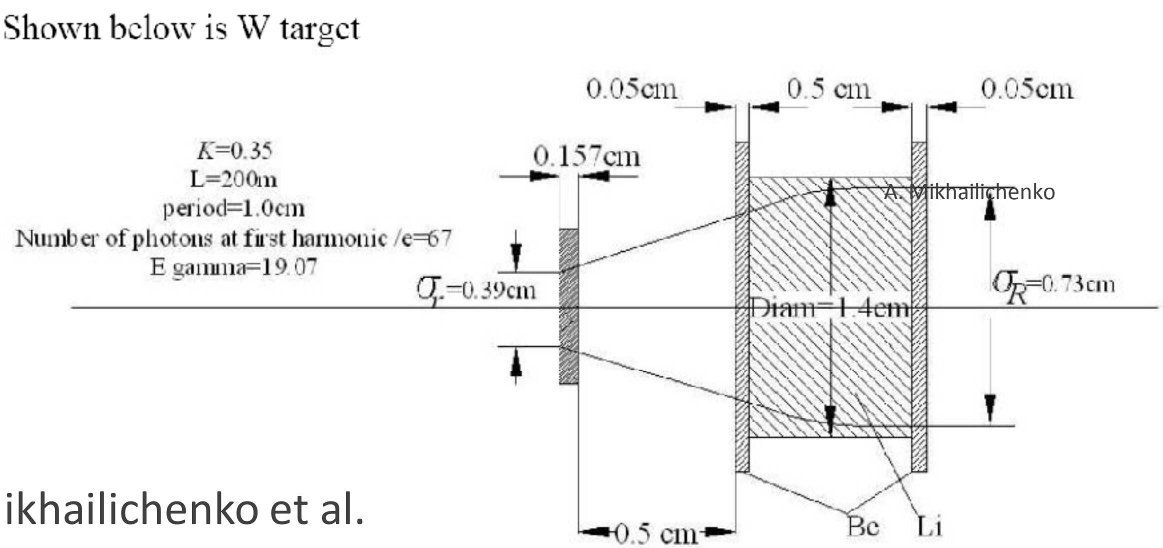


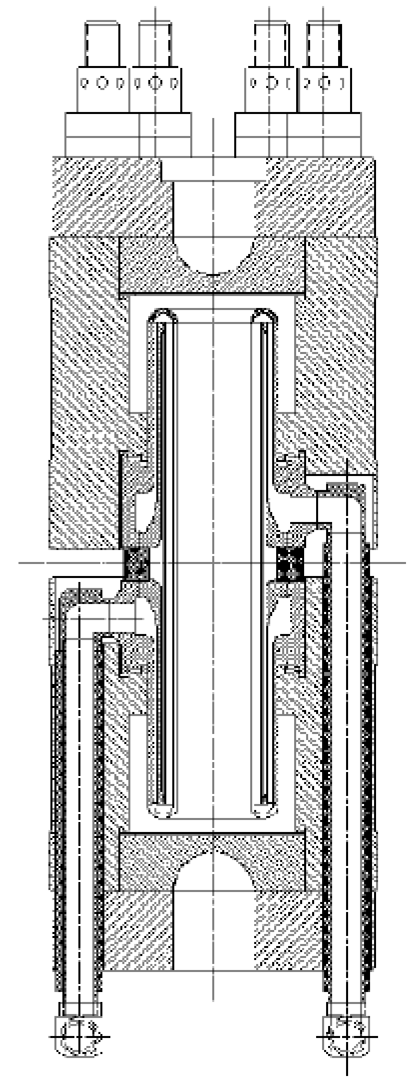
Fig. 4. End view and side section of flux concentrator final design.

Advanced Solution: Lithium lens

- Lithium Lens
  - Will lithium cavitate under pulsed heating?
    - window erosion
  - Will lithium flow adequately cool the windows?
  - Increased heating and radiation load in the capture section
  - Needs R&D to demonstrate the technology.



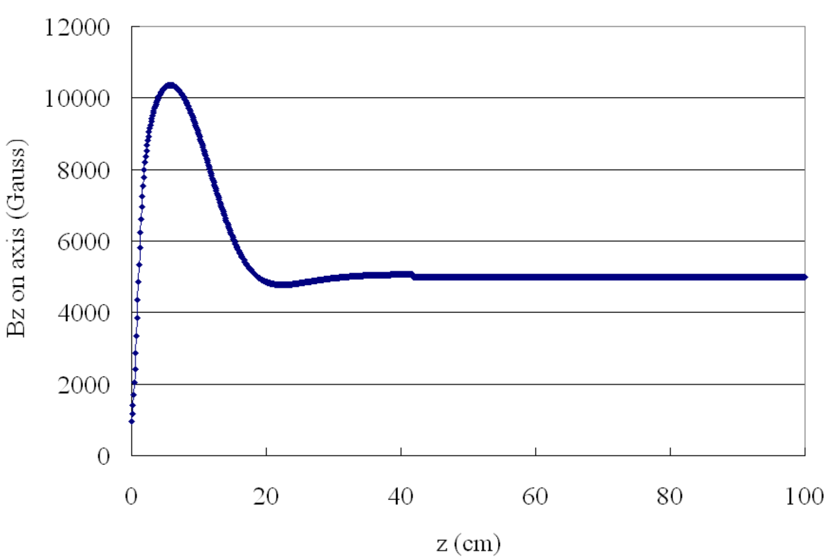
A. Mikhailichenko et al.



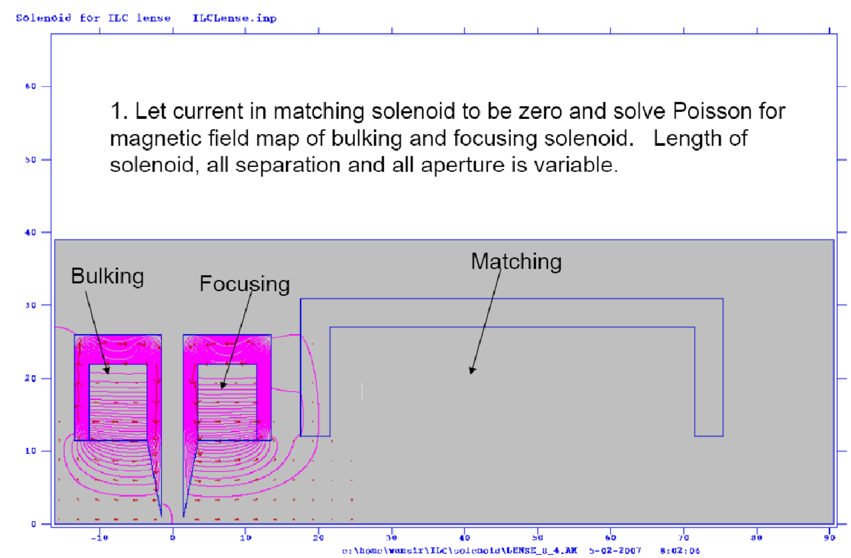
P.G. Hurh & Z. Tang

What if every capturing magnet technology fails, a safe solution: ¼ wave solenoid

- Low field, 1 Tesla on axis, tapers down to ¼ T.
- Capture efficiency is only 25% less than flux concentrator
- Low field at the target reduces eddy currents
- This is probably easier to engineer than flux concentrator
- SC, NC or pulsed NC?



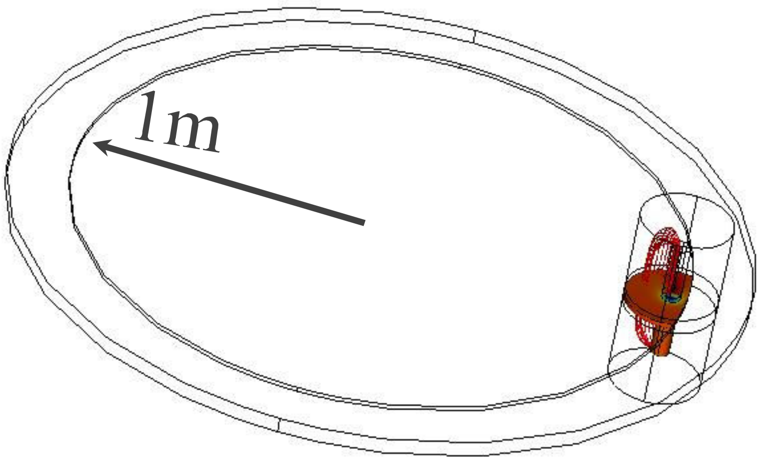
ANL ¼ wave solenoid simulations

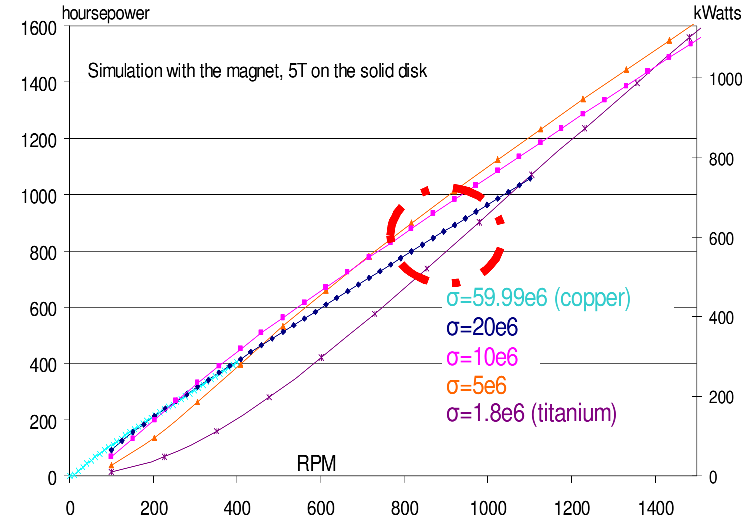


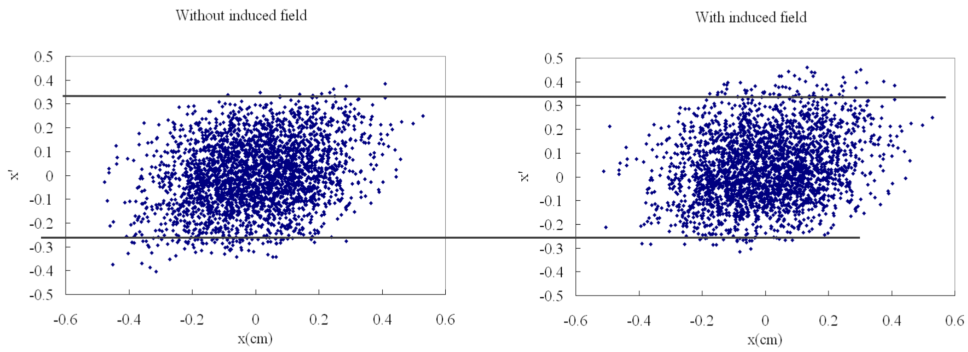
W. Liu

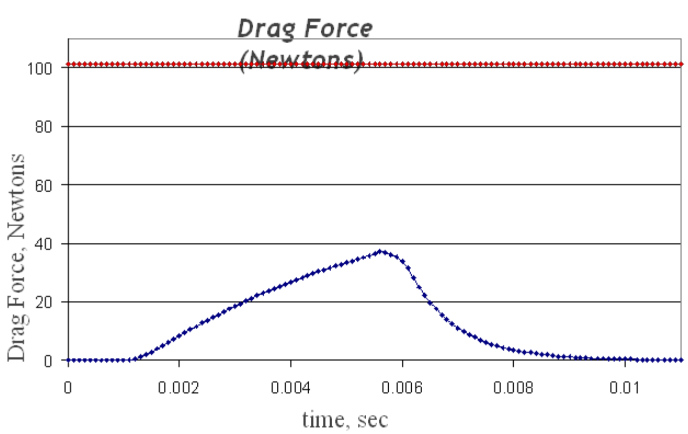
The target will be rotating in a B field of about 0.2T

Proposed ILC target geometry and simulation of the target rotating in magnetic fields.









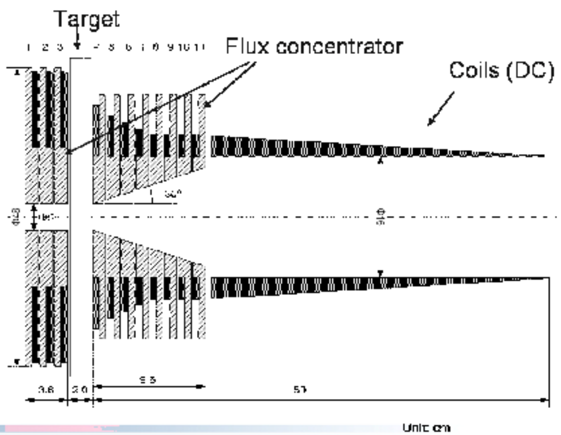
- Induced field kicked some positrons out but also kicked some in. The lost of yield is only ~5%(from ~1.27 down to ~1.20) for σ=3e6.
- For σ=1.5e6, since the eddy current induced field is small compared with the OMD field, and also due to the broad band matching provided from OMD field, the distortion of field does not cause any noticeable change to the e+ yield.

Equivalent circuit model of Flux concentrator and our OMD design using this model

Schematic of Our AMD Design

Design requirements:

- Peak on-axis magnetic field at target exit > 5 Tesla,
- Pulse width = 5ms,
- Pulse repetition rate = 5 Hz.



Parameters of the Designed OMD

Parameters of flux concentrator

Work mode	pulse
Operation Temperature	78ºK
Pulse width	5 ms
Repetition rate	5 Hz
Number of turns of primary coil	105
Peak power input to magnet	5.1 MW
Average power input	113 KW
Peak current	7000 A
Magnetic field at target exit	5 Tesla
Time constant of current in primary coil	3 ms
Wire size of primary coil	0.475 × 0.381 cm²

Parameters of DC coil

Work mode	DC
Operation Temperature	293ºK
Power input	81 KW
Current	926 A
Total Number of turns	135
Wire size of coil	0.475 × 0.381 cm²

Emittance evolution through undulators

- Tool used: Elegant (a well known beam dynamics code includes synchrotron radiation effects);
- Performed systematic studies using the six undulator parameters;
- Bench marked the energy loss results in undulator against the well known analytical formula.

•Beam Parameters: Using the beam parameters at IP, with assumed β function= 40 meters, the beam parameters at undulator can be obtained as:

σx=37 microns

σy=2.4 microns

$\sigma x'$=0.9 micron-radians

$\sigma y'$= 0.06 micro_radians

Result with energy spread at different undulator length

- Undulator investigated: UK1, 25MeV sigma of energy spread,
- *Surprise: Vertical damping does not scale vs undulator length.*

configuration	Δεnx/εnx (%)	Δεny/εny (%)
~100m	-1.36	-1.18
~200m	-2.69	-1.27
~300m	-3.93	0.84

These results can be explained by an analytical approach with some approximations (from Kwang-Je Kim):

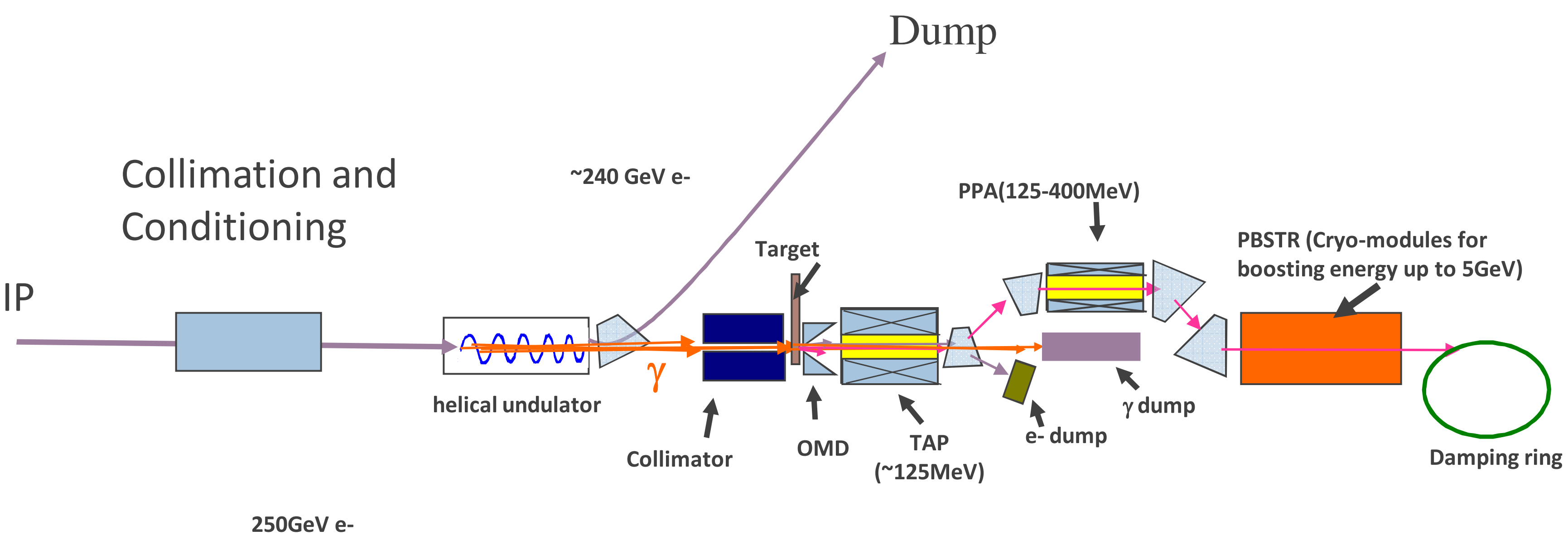
$$\Delta\varepsilon_n = -\varepsilon_n \frac{|\Delta E|}{E} + (\beta_0 + \frac{L^2}{3\beta_0}) \frac{K}{\gamma} \frac{1}{E^2} \frac{\hbar\omega_{max}}{2} |\Delta E| \qquad (1)$$

where the first term on the right is the damping effect and the 2nd term is the excitation. For 100m RDR baseline undulator (UK1), the damping/excitation ratio can be obtained using equation (1) as 3 in vertical and 600 in horizontal.

Revisiting Scheme with Undulator after IP

- Current IP configuration:
  - 14 mr extraction (1.4 m offset for 100 m drift).
  - Beam energy and angle perturbed, but only slightly. (most beam < 1% energy spread and < 10 μrad?).
- Reasons to revisit this scheme
  - No-need to make up the energy loss for the drive beam.
  - Need beam collimation and dump anyway.
  - Undulator aperture ~ cm. Allow most of beam pass through.
  - Perturbed beam will have little effects on the positron production.

Schematic of the After IP Layout



Injection and extraction

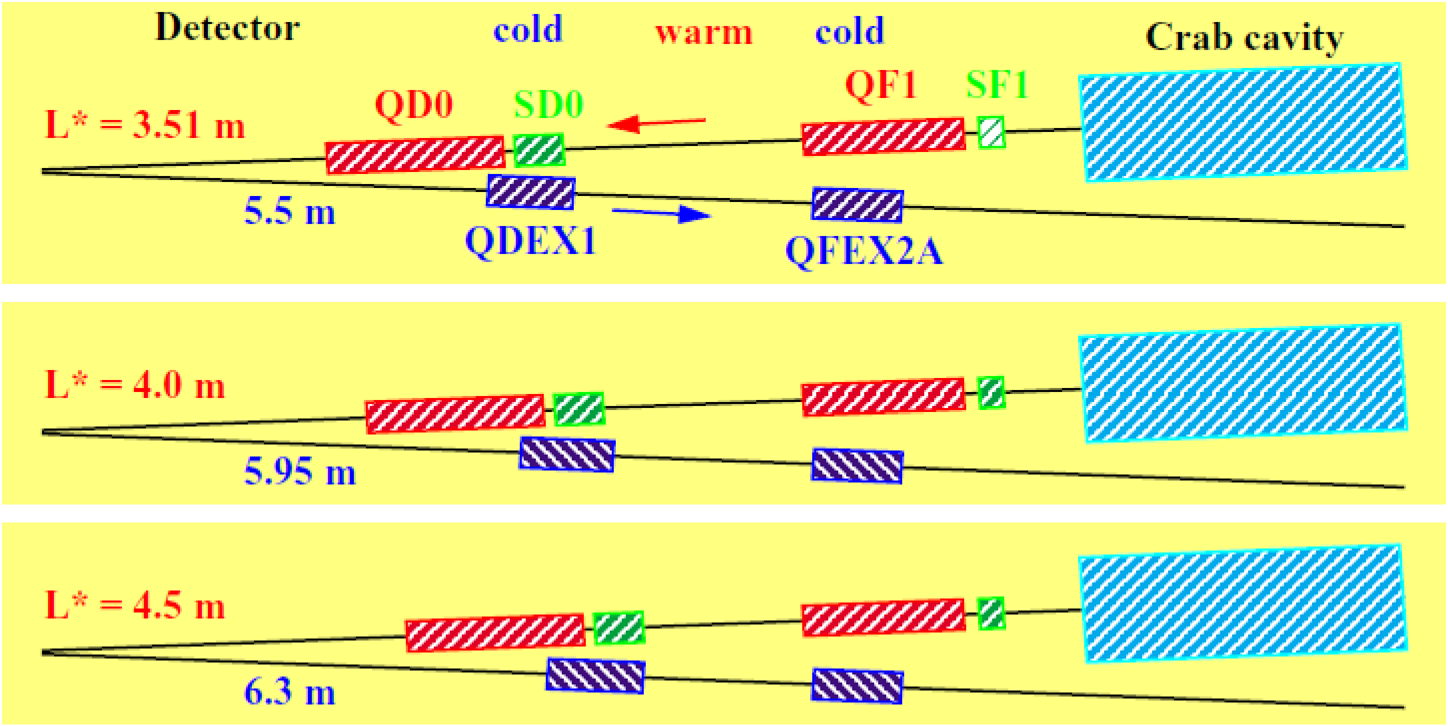


Figure 1: Magnets near IP for $L^* = 3.51, 4.0, 4.5$ m.

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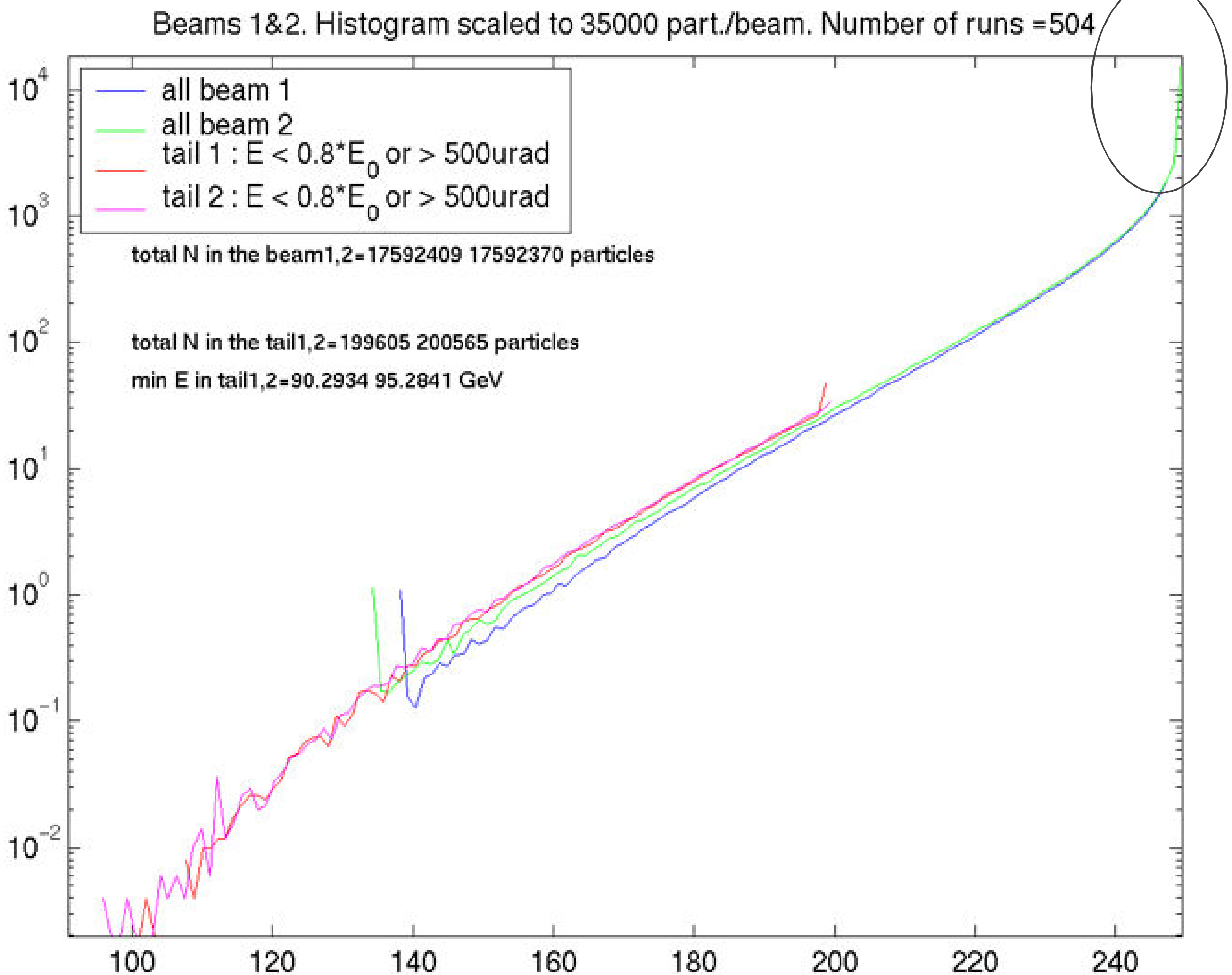
Example Particle distribution after the collision IP



Most particles unperturbed.

From Andrei Seryi

Thanks for your time

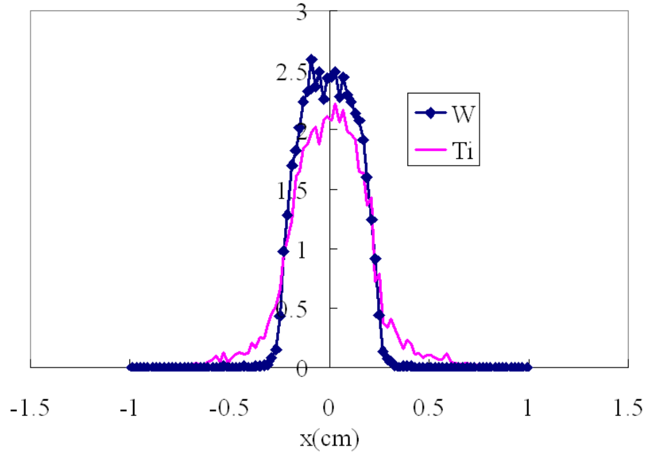
Comparing Tungsten target and Titanium target (Skip next 10 slides)

- Same undulator
- Same target length (measured in radiation length)
- Same beam line
- Same collimator settings

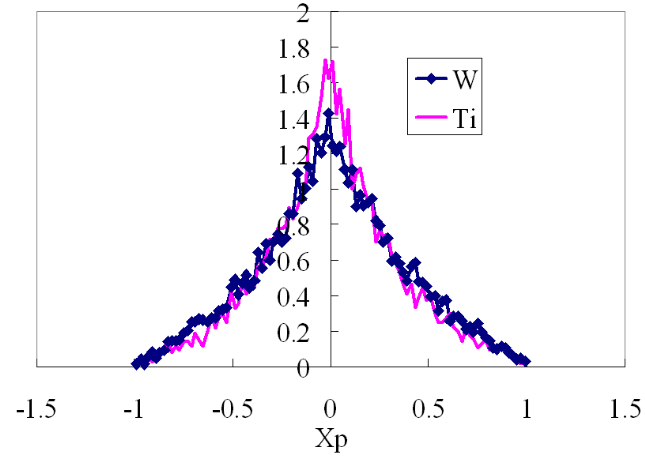
Tungsten target gives about 50% higher raw yield in positron production but the captured yield only enhanced by ~10% due to broader divergence distribution of e+ produced in tungsten target.

The density of deposited energy in tungsten target is about 10 times higher than titanium target.

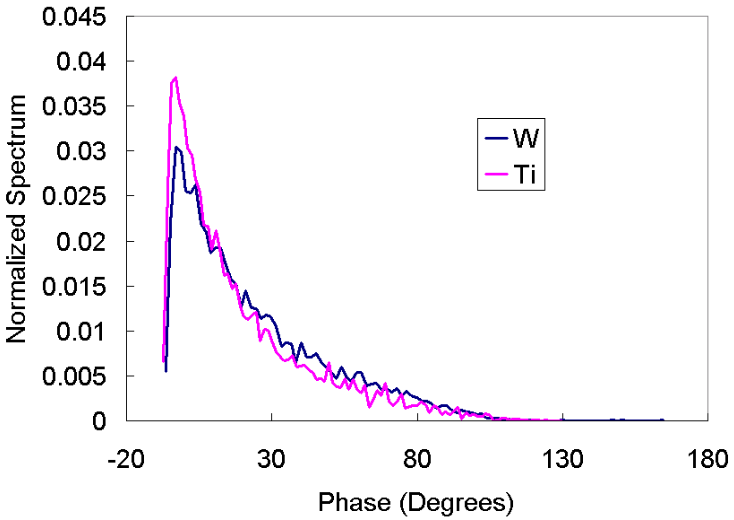
Normalized transverse distribution of e+ when exiting from target



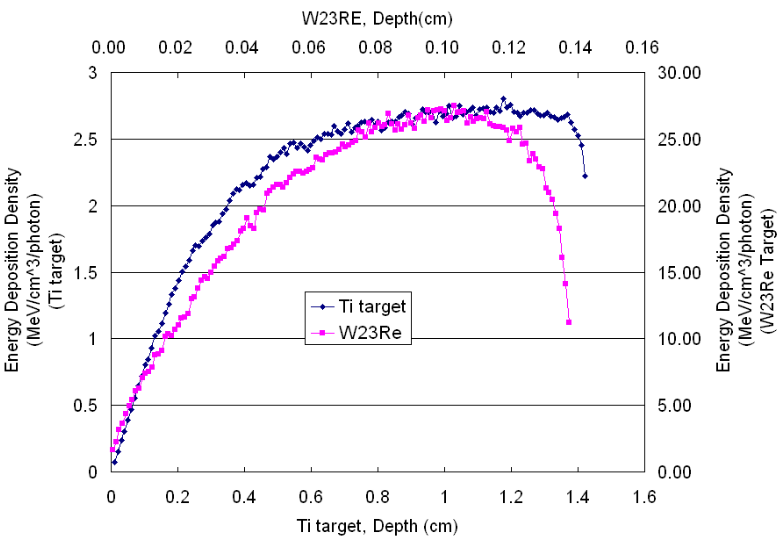
Normalized divergence distribution of e+ when exiting from target



Normalized longitudinal distribution of e+ at end of tracking

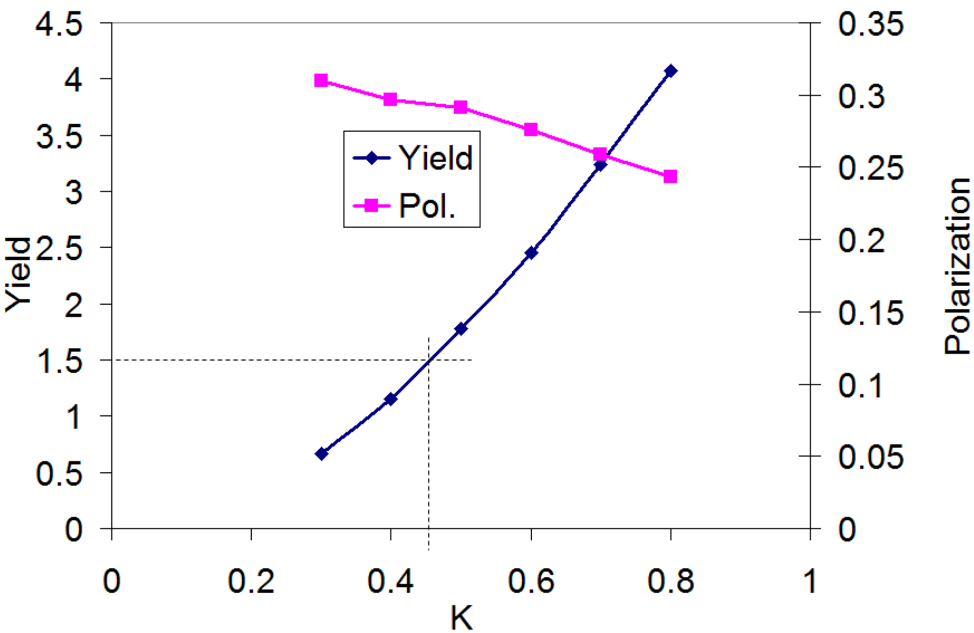


On beam axis profile of deposit energy density



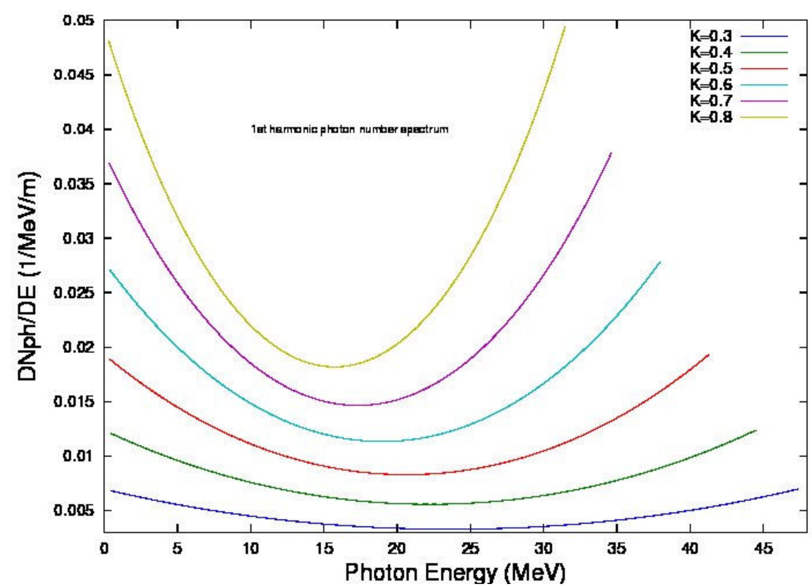
End of linac operation

Yield and Polarization for 231 meters long undulator with 250GeV and different K

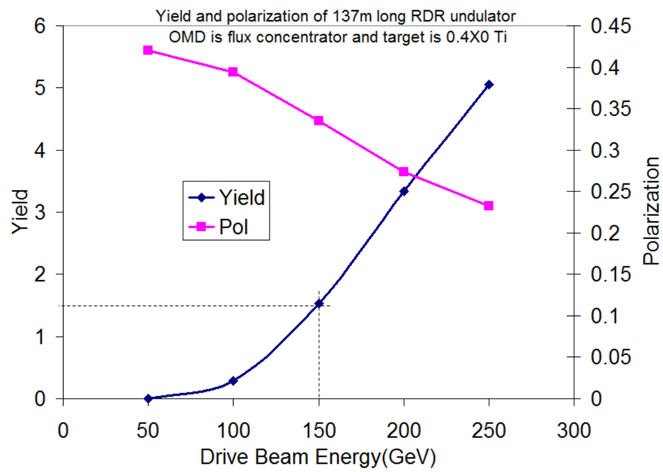


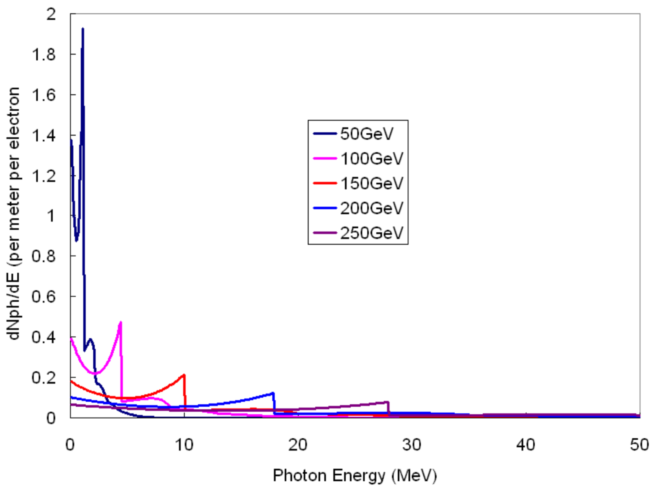
231m long undulator is required in order to reach a yield of 1.5 with 150GeV drive beam and ¼ wave transformer.

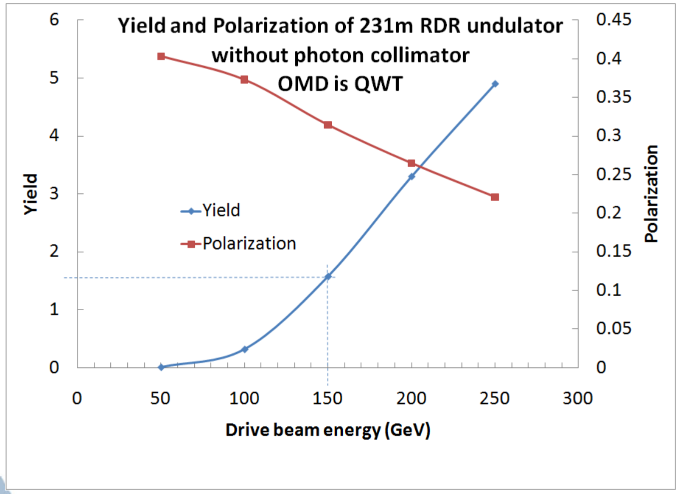
When such 231m long undulator is installed at the end of linac, we have the option to change the K instead of turning off sections of the undulator to keep the yield to 1.5



Drive beam energy comparison
RDR undulator, Flux concentrator, ¼ wave transformer





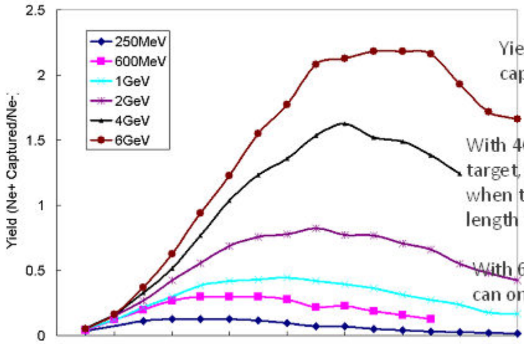


- We compared the yield and polarization of RDR undulator driven with beam energy from 50GeV up to 250GeV
- We also compared the energy lost of drive beam per 100m undulator and per 1.5 yield for each case
- Both ¼ wave transformer and Flux concentrator were considered

Conventional source simulation

Simulation with AMD, immersed liquid lead target,

For conventional scheme minimum machine

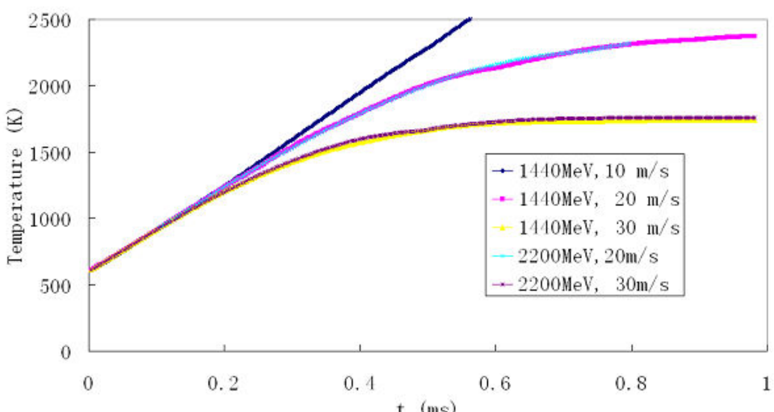


Yield is evaluated as Ne+ captured over Ne- in drive beam

With 4GeV drive beam and immersed target, yield of > 1.5 can be reached when target is about 5 radiation length thick.

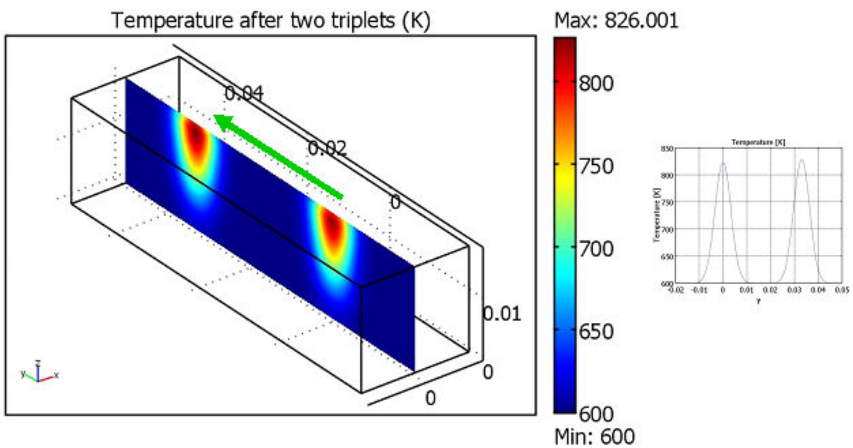
With 600MeV drive beam, the yield can only reach 0.3.

Evolution of Temperature

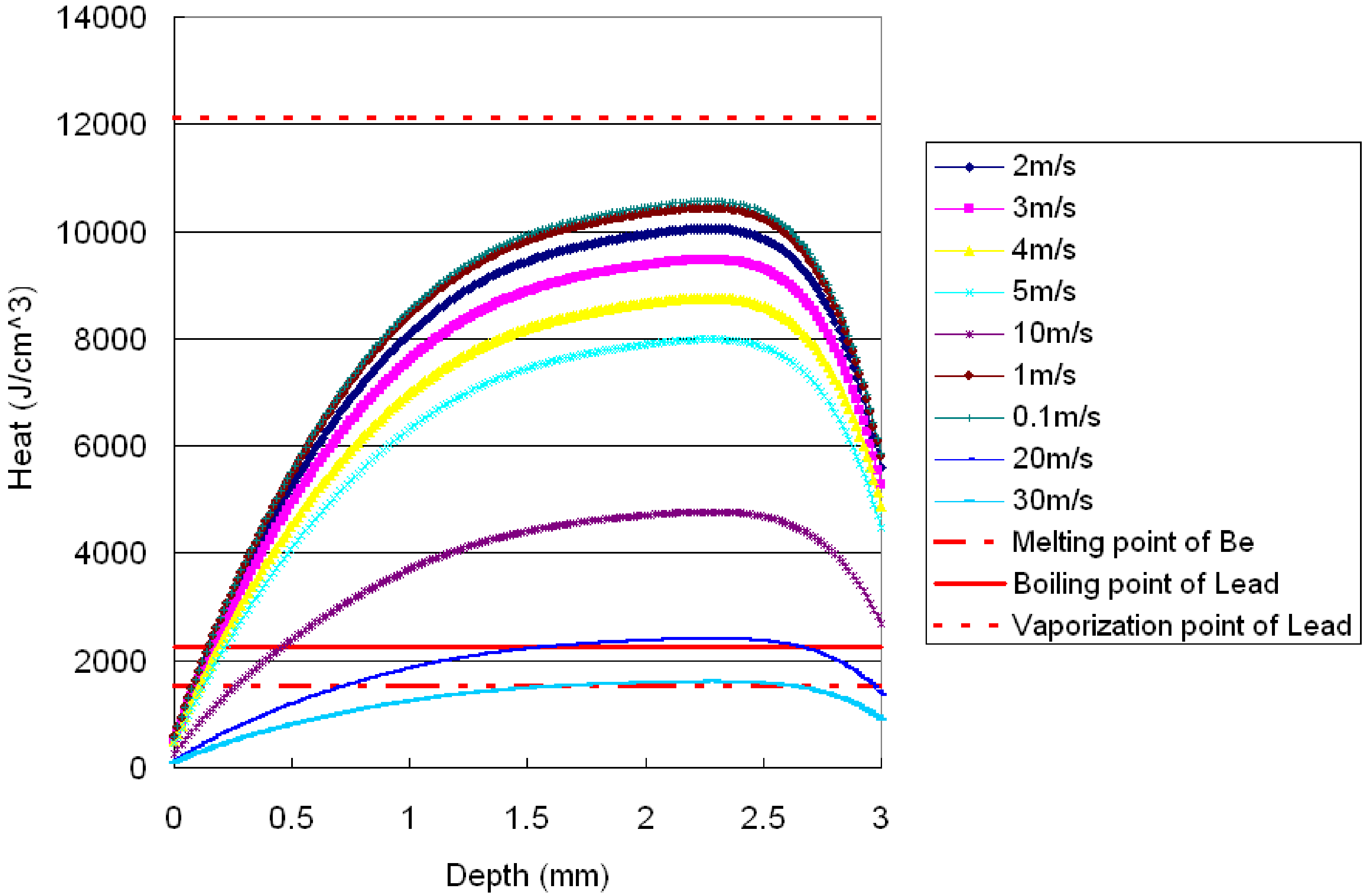


Drive beam spot size: rms 3mm for both 1440MeV and 2200MeV.
Target thickness: 3X0 for 1440MeV, 3.5X0 for 2200MeV

Temperature in target after 2 triplets
Target is moving at 10m/s



Liquid target, RDR undulator
Heat density at the middle of bunch train for different pumping speeds



Undulator length required under different conditions

- Conditions:
  - RDR undulator
  - 0.4X0 Ti target
  - AMD: 14cm long
  - Flux concentrator: 14cm total length, 2cm ramping
  - Lithium lens: 2cm long, 1.4cm in diameter
  - Yield evaluated at 125MeV with damping ring acceptance parameters
  - Drive beam energy 150GeV and 250GeV
- Results:
  - 150GeV drive, AMD, 100m long RDR undulator will give us a yield of 1.5
  - 150GeV drive, flux concentrator, 137m long RDR undulator is required for a yield of 1.5
  - 150GeV drive, ¼ wave transformer, 231m long RDR undulator is required for a yield of 1.5
  - 150GeV drive, lithium lens, a yield of 1.5 can be reached by using 100m RDR undulator with a lithium lens driving by about 30KA current
  - For 250GeV drive and AMD, in order to have a yield of 2, we need only 50m long undulator with an AMD field of 6T
  - For 250GeV drive and flux concentrator, in order to have a yield of 2, we need about 53m long undulator
  - The yield of 2 can be reached with ¼ wave transformer and 100m long RDR undulator driven by 250GeV beam
  - With lithium lens driving by about 40KA current, a yield of 2 can then be achieved with 40m long undulator.