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Update on e+ Source Modeling and Simulation

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Outline

- Emittance evolution through undulator
- Start to end tracking
- Positron production and tracking using GEANT4

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.
- The effect Quad-BPM misalignment

Beam Parameters and Undulator parameters

- Using the beam parameters at IP, with assumed β function= 40 meters, the beam parameters at undulator can be obtained as (J. Sheppard):

  Sig_x_und=37 microns
  Sig_y_und=2.4 microns
  Sig_xprime_und=0.9 micron-radians
  Sig_yprime_und=0.06 micro_radians

	K	λu(cm)
UK1	0.92	1.15
UK2	0.79	1.1
UK3	0.64	1.05
Cornell 1	0.42	1.0
Cornell 2	0.72	1.2
Cornell 3	0.3	0.7

Elegant simulation results, beam without energy spread (normalized 100 meter undulator length)

The input e- beam parameters: enx is ~ 7.84e-6 and eny is ~ 4.26e-8

- Using the beam parameters at undulator with 0 energy spread:

	Δεnx/εnx (%)	Δεny/εny (%)	ΔE/E (%)	σ_{x_out}	σ_{xp_out}	σ_{y_out}	σ_{yp_out}
UK 1	-1.37464	-1.06	-1.3756	9.4259e-5	8.8774e-7	6.4835e-6	6.0111e-8
UK 2	-1.10608	-0.912	-1.112	9.4316e-6	8.8907e-7	6.4871e-6	6.0190e-8
UK 3	-0.79802	-0.679	-0.804	9.4381e-6	8.9059e-7	6.4908e-6	6.0274e-8
CO1	-0.38277	-0.395	-0.383	9.4464e-6	8.9258e-7	6.4973e-6	6.0398e-8
CO2	-0.77138	-0.652	-0.789	9.4385e-6	8.9070e-7	6.4928e-6	6.0298e-8
CO3	-0.39768	-0.382	-0.399	9.4462e-6	8.9251e-7	6.4972e-6	6.0394e-8

The normalized emittance of drive electron beam is damped as a result of radiations in undulators. The rate of damping is roughly proportional to the rate of energy lost.

Results with off axis e- beam

- Undulator investigated: UK1, length ~100m. No energy spread

Offset	Δenx (%)	Δeny (%)	$\sigma x_{in}/\sigma x_{out}$	$\sigma y_{in}/\sigma y_{out}$	$\sigma x'_{in}/\sigma x'_{out}$	$\sigma y'_{in}/\sigma x_{out}$
0,10μm,50μm	-1.37	-1.06	2.99e-5 /9.42e-5	2.40e-6 /6.48e-6	9e-7 /8.93e-7	6.05e-8 /6.01e-8
1mm in x	-1.59	-1.13	2.99e-5 /9.40e-5	2.40e-6 /6.48e-6	8.94e-7 /8.83e-7	6.05-8 /6.01e-8
1mm in y	-1.59	-1.14	2.99e-5 /9.42e-5	2.40e-6 /6.46e-6	8.94e-7 /8.88e-7	6.05e-8 /5.98e-8

$$Bx = -|B0|\Sigma_{m,n}Cmn \cosh(k_{xl}x) \cos(k_{ym}y) \cos(k_{zn}z + \theta_{zn}),$$

$$By = -|B0|\Sigma_{m,n}Cmn \cos(k_{xl}x) \cosh(k_{ym}y) \cos(k_{zn}z + \theta_{zn}),$$

Off-axis beam sees stronger fields and thus radiated more photons.

Result with energy spread at different undulator length

- Undulator investigated: UK1, 750MeV sigma of energy spread,
- *Because there is no FODO lattice to maintain the beam spot size in this set of simulation, the spot size is growing and the beam will see a larger spread of undulator field and thus the emittance will start to growing after a certain point.*
- *In real beam line, the FODO lattice will keep the beam spot size down and thus the emittance will be damping down to it's equilibrium which is determined by the balance of the excitation and damping effect of undulator radiation.*

configuration	Δεnx/εnx (%)	Δεny/εny (%)
~100m	-1.36	-1.11
~200m	-2.66	-0.65
~300m	-3.91	1.73

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

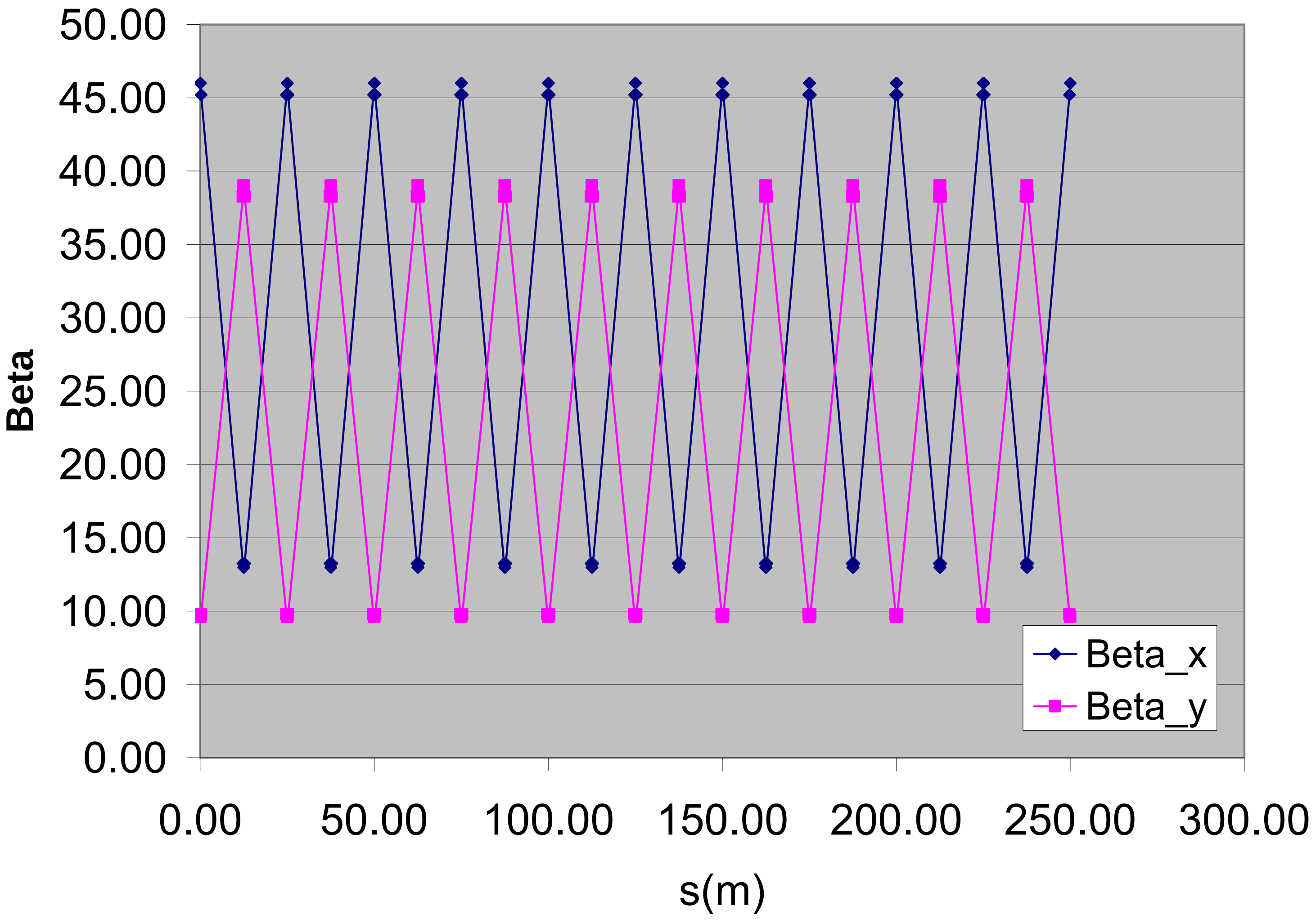
$$\Delta\varepsilon_n = -\varepsilon_n \frac{|\Delta E|}{E} + (\beta_0 + \frac{L^2}{3\beta_0})\frac{K}{\gamma}\frac{1}{E^2}\frac{\hbar\omega_{\max}}{2}|\Delta E| \qquad (1)$$

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.

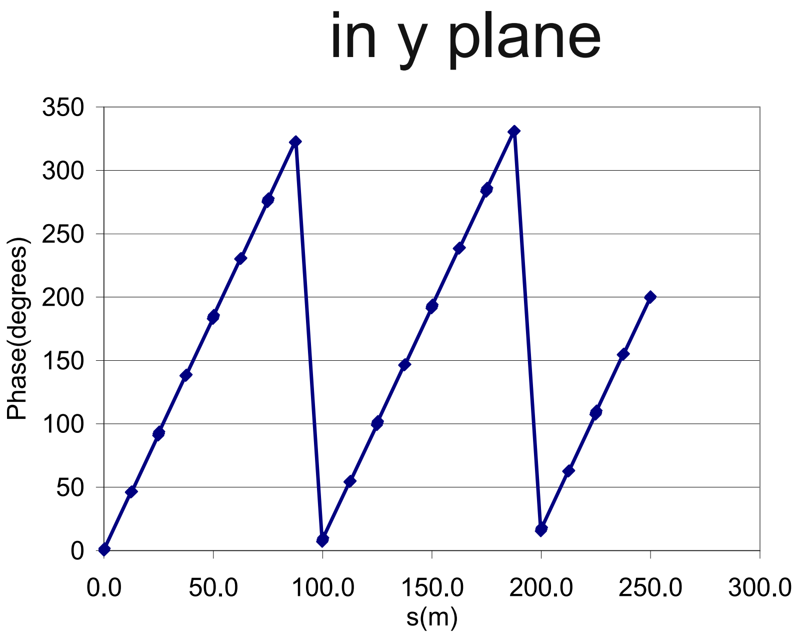
Quads-BPM misalignment

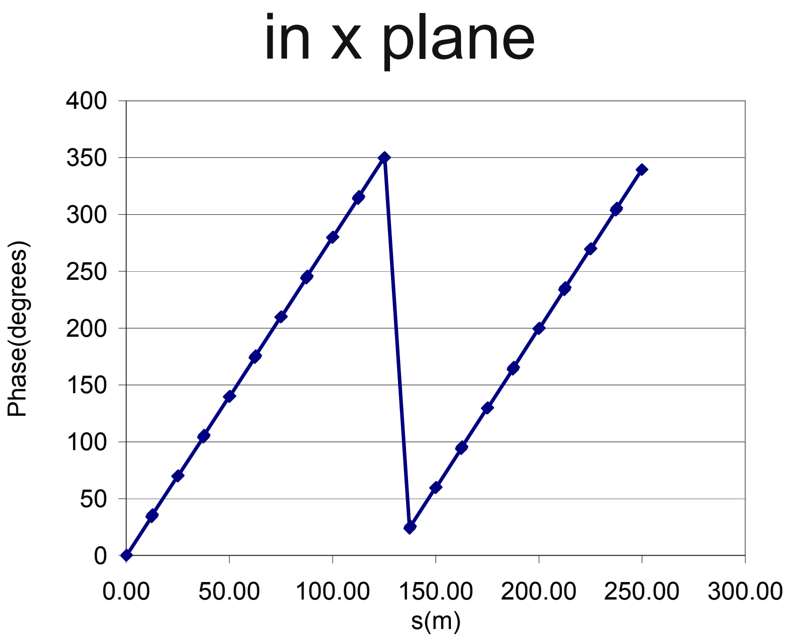
- Beamline:
  - Quad magnet every 12.4 meters, thickness of quad is assumed to be 10cm.
  - 70 degrees phase advance in horizontal plane and 90 degrees of phase advance in vertical plane is assumed.
  - 10 FODO periods, totals at 250 meters of beamline.
- Quad-BPM misalignment dy in vertical plane
  - The σ of dy: 5μm -- 100 μm
  - 50 random seeds used when generating errors.
- Beam in:
  - emittance: 4e-8m.rad in vertical, 10e-6m.rad in horizontal, well matched with the lattice
  - Energy: 150GeV, rms energy spread is 0.5%.

Beta function of beamline



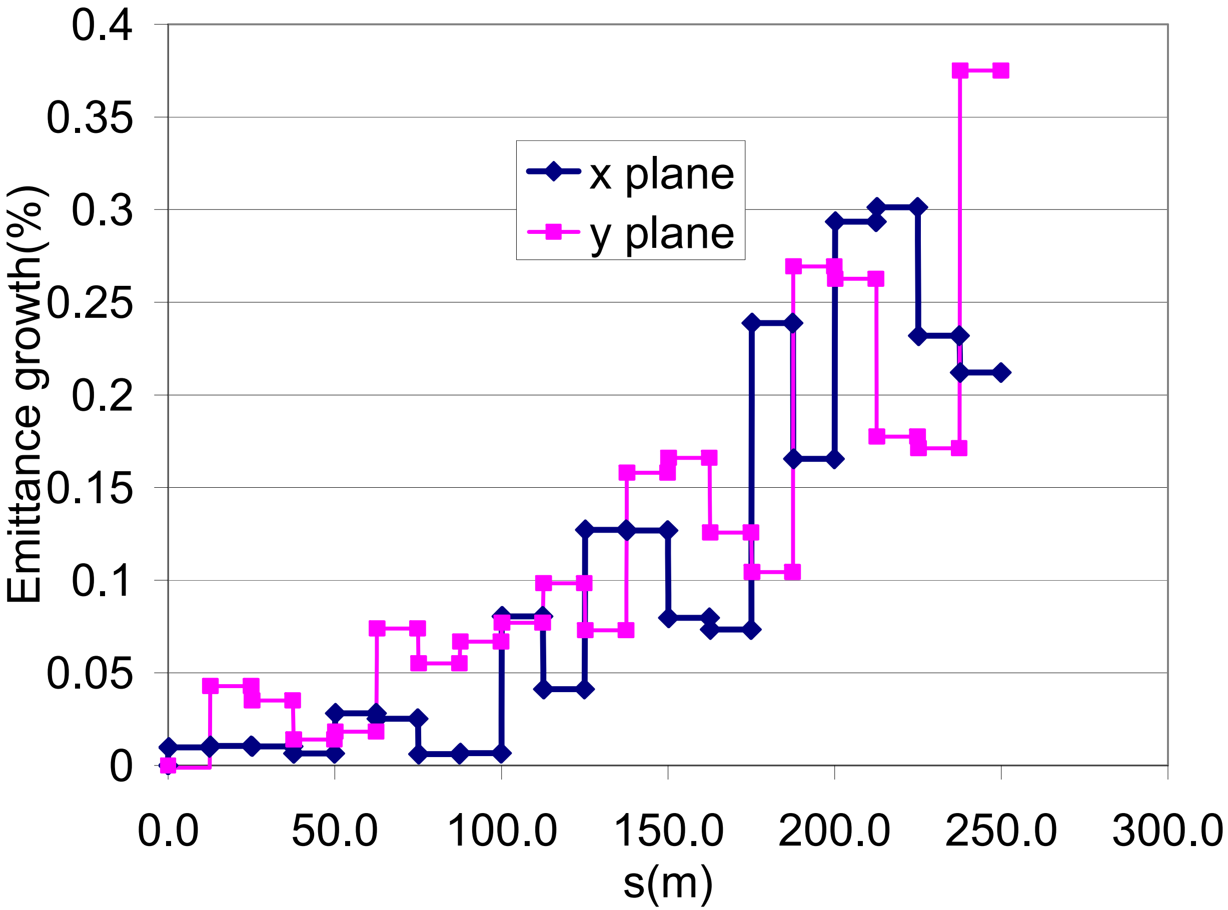
Phase advance in x and y plane





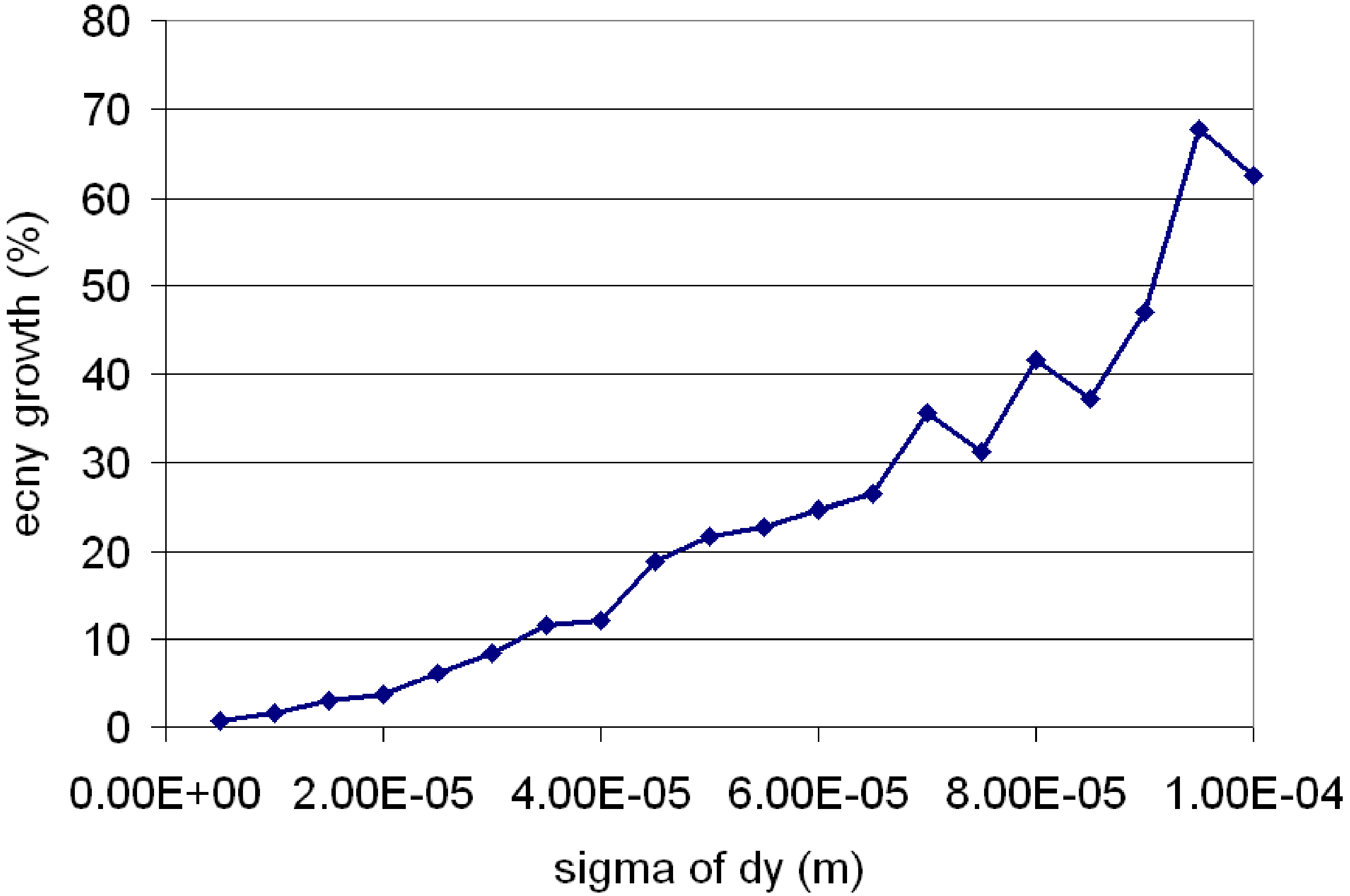
The phase advance per FODO in y plane is ~90 as shown in the figure on the left. The phase advance per FODO is x plane is ~70 degree as shown in the figure on the right.

Emittance growth due to energy spread



Emittance growth due to energy spread is small and can be corrected.

Emittance growth due to Quad BPM error in vertical plane



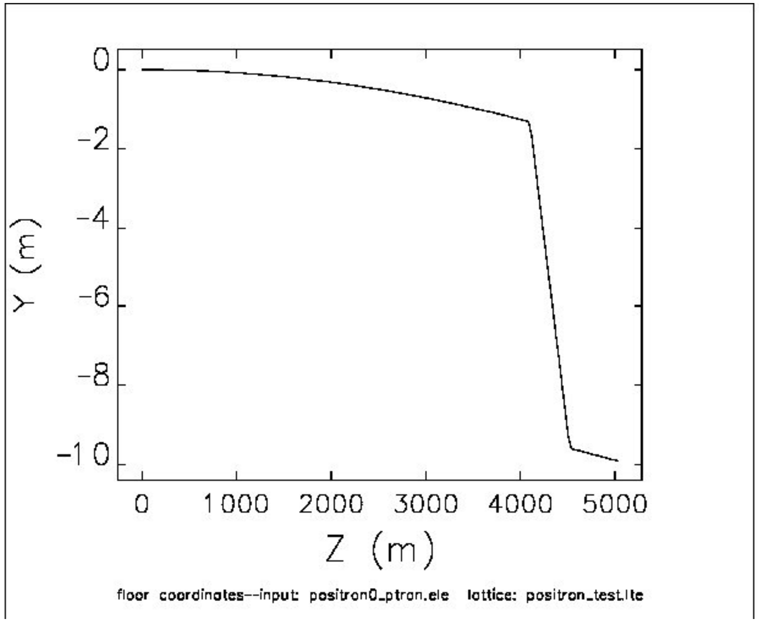
Results obtained with 50 random seeds in simulation.

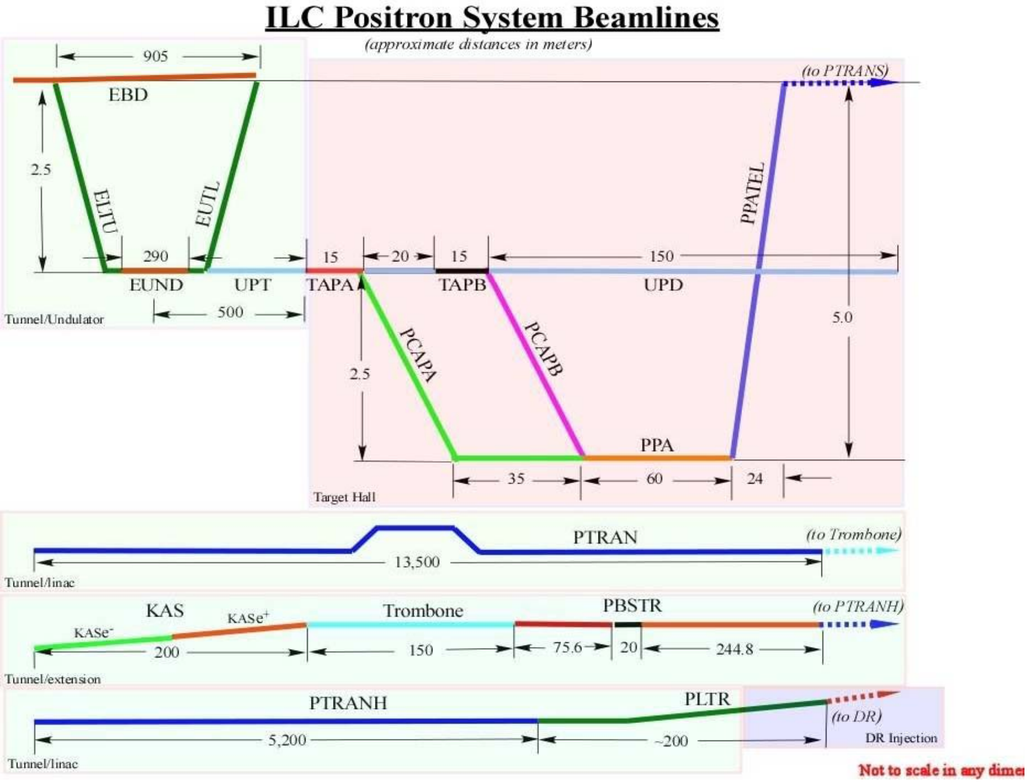
Start to end tracking

- EGS4 for positron production
- PARMELA for tracking e+ from target to 125MeV
- Tracking through the rest of beam line to damping ring using elegant

The first 2 have been presented many times and nothing has changed. The only update is on item 3.
We have gone through the lattice of e+ beamline. We compared the elegant lattice with MAD lattice, and they both agree with each other. We are ready to make further modification / optimization.

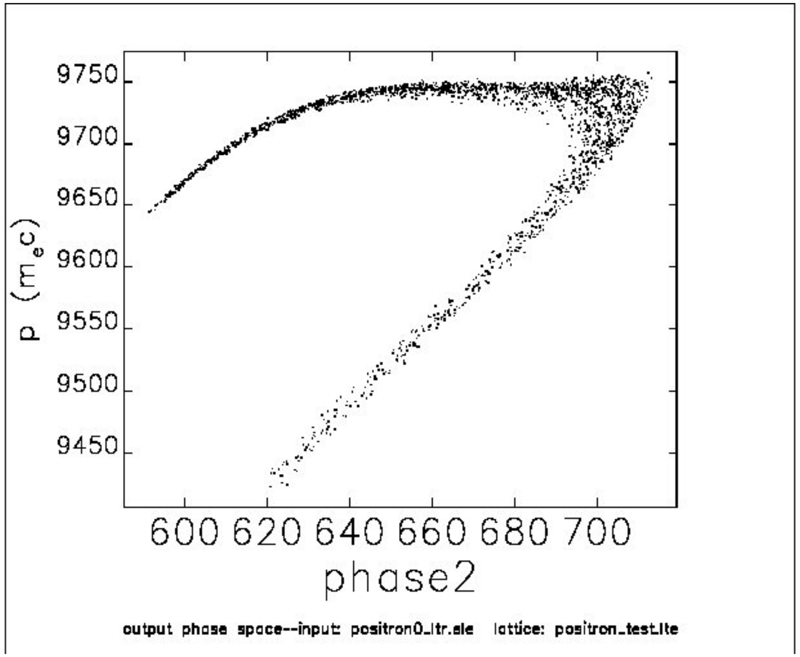
ILC e+ source, PTRAN floor coordinates

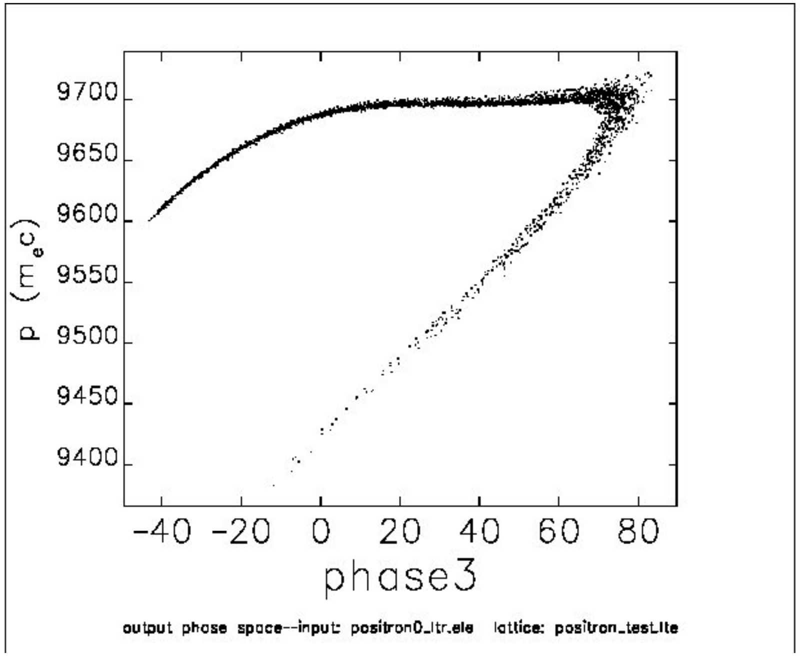




This PTRAN beam line is different from the old layout. Might need some optimizations.

Result with and without PTRAN





With PTRAN

Only 2095 left after LTR
1913 lost in LTR
176 lost in PTRAN
179 lost in PBSTR

Without PTRAN

3023 left after LTR
277 lost in LTR
1065 lost in PBSTR

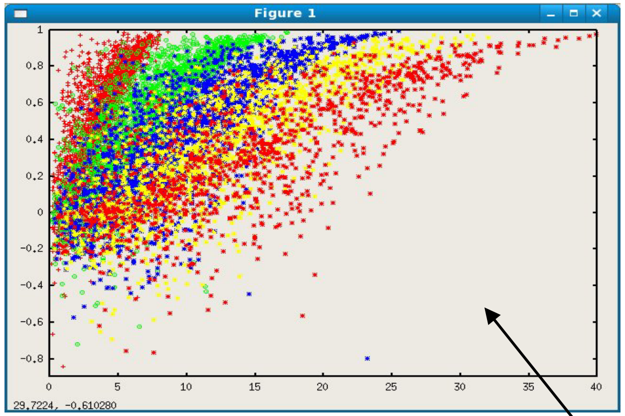
No positron collimation is used in these simulation.

Comparing these two results, PTRAN might need further optimization.

Geant4 e+ production and tracking simulation

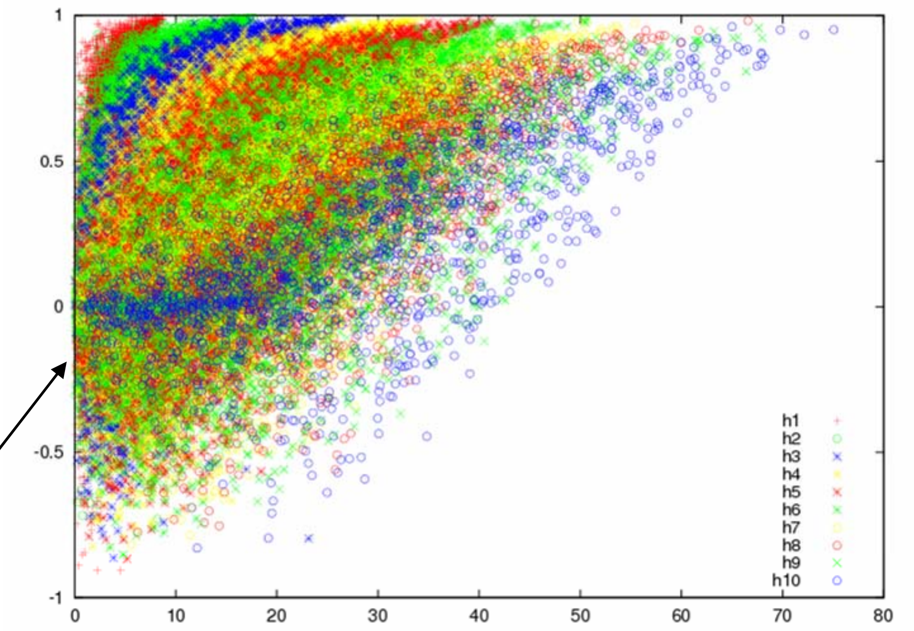
- Advantage of Geant4
  - Has a more complete model.
  - Capable of spin tracking
  - Easy to do particle tracking in RF field (comparing with EGSnrc)
  - Easy to do activation simulation (comparing with EGSnrc)
  - Open source.
- Disadvantage of Geant4
  - No space charge capability. But does not matter much for our application.

Positron polarization at target

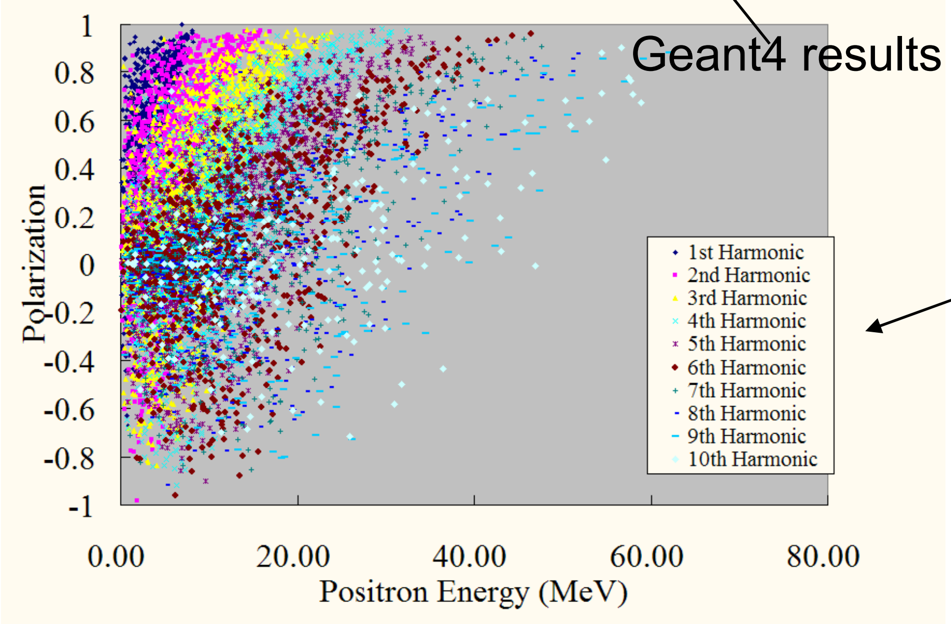


With fewer sample

Geant4 results

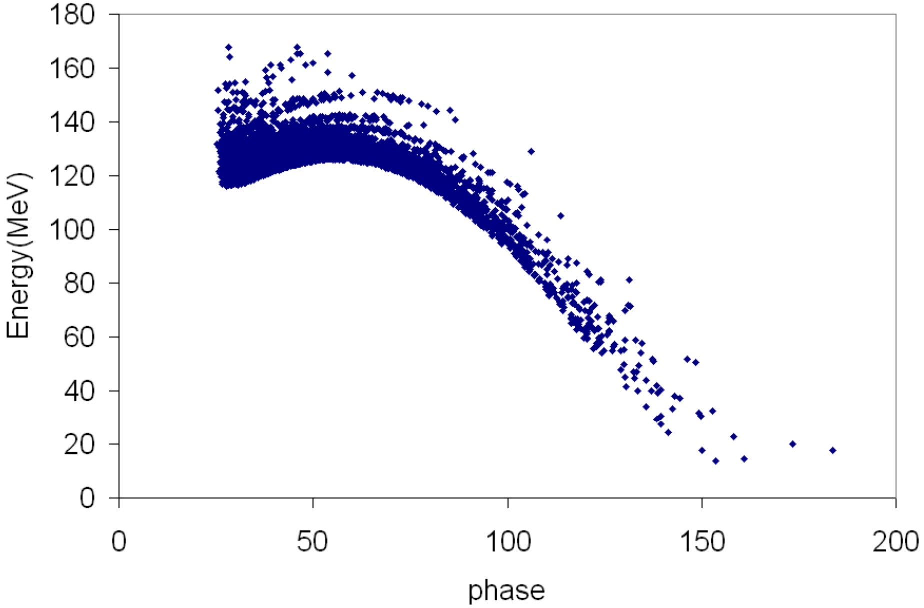


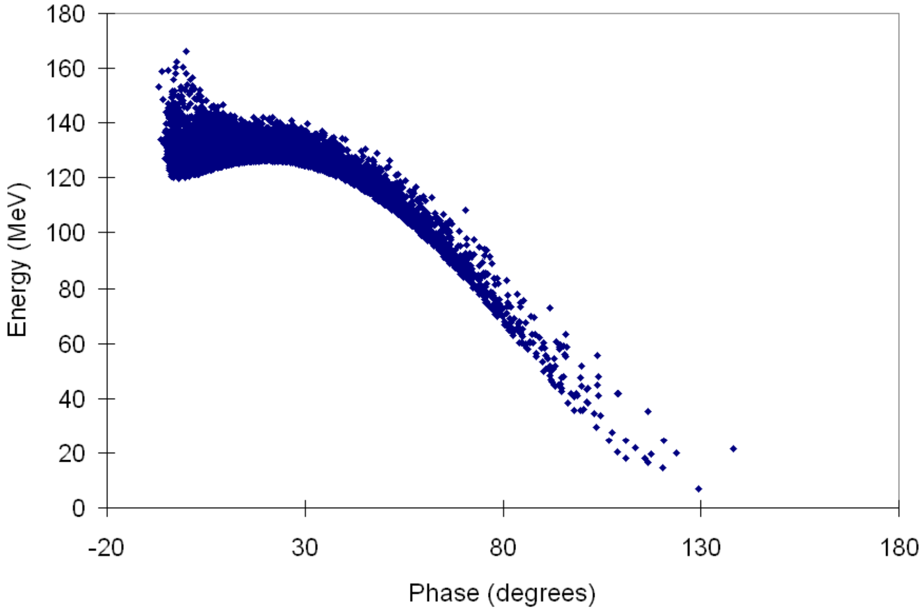
EGSnrc result



Distribution of positron polarization is about the same from both Geant and EGS4.

Comparing between Geant4 and EGSnrc + PARMELA. At 125MeV

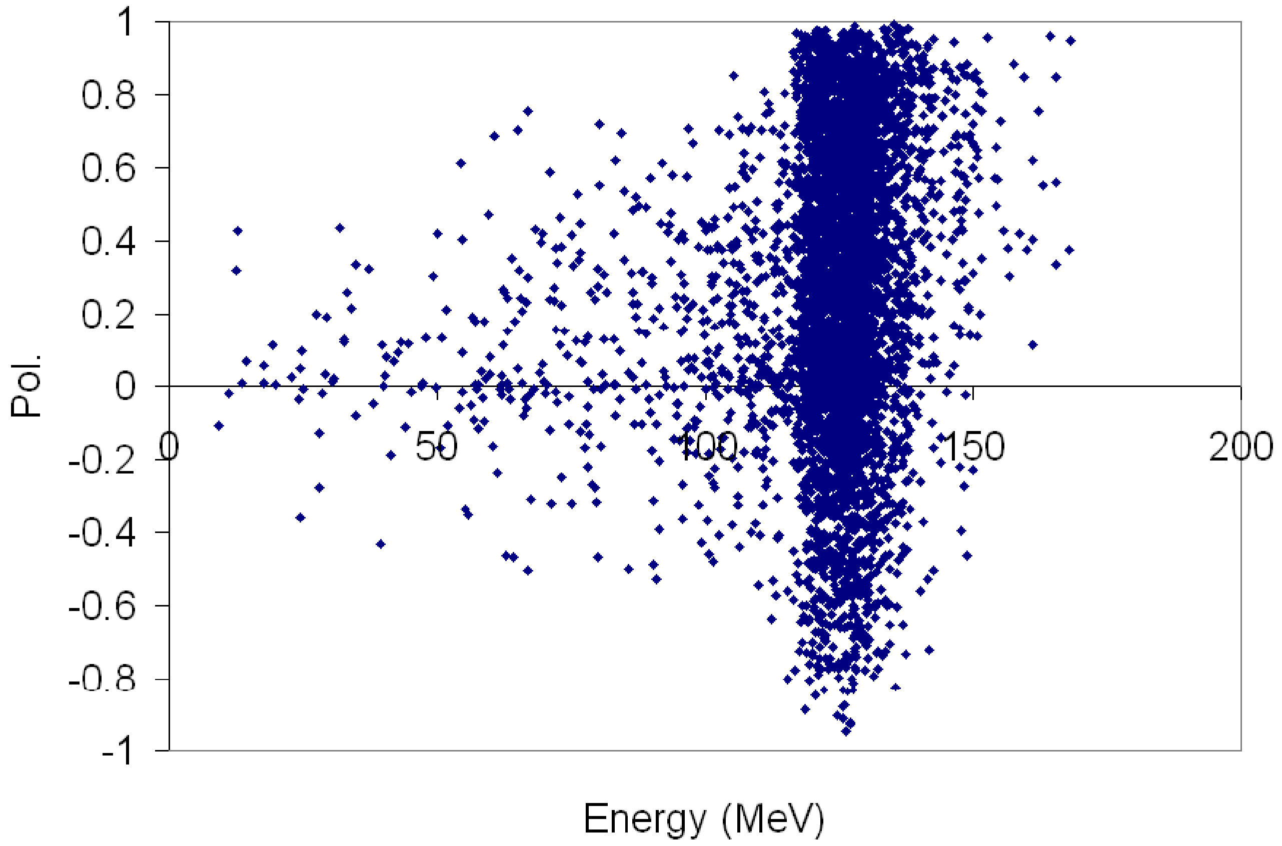




Ignore the difference of markers on x axis. The phase in PARMELA is the phase as reference to its reference particle.

Geant4 result looks more hairy and PARMELA results looks more smooth. Might need some fine tuning on tracking with Geant4.

Polarization of positrons after accelerated to 125MeV

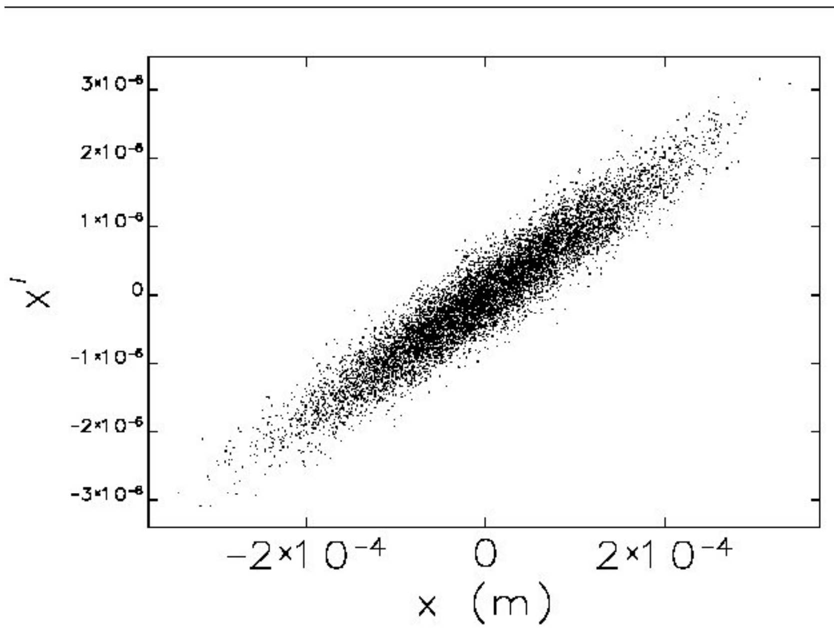


Spin tracking is included in Geant4 and activated in our program.

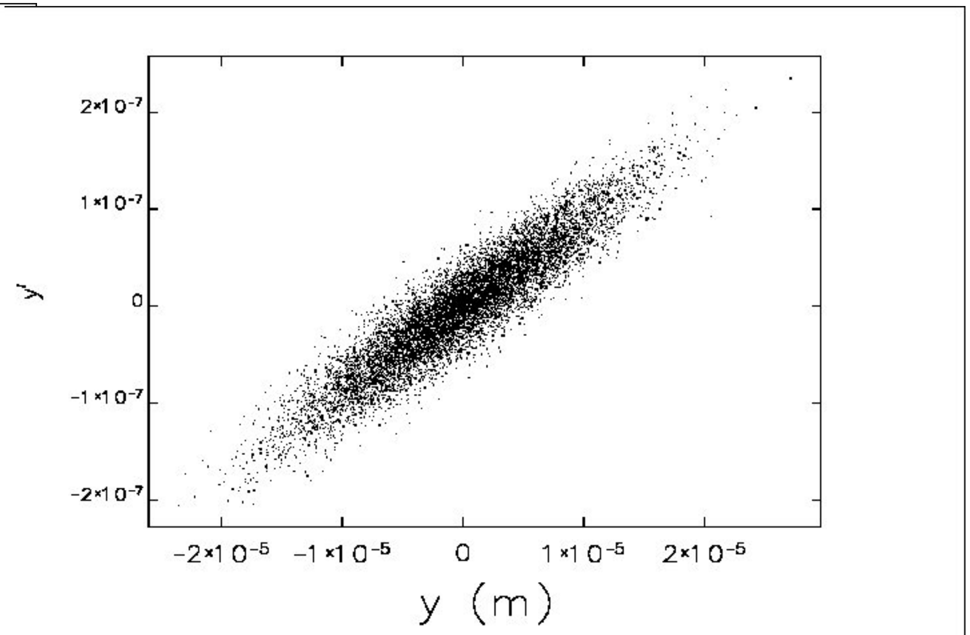
Summary

- Emittance growth due to QUAD-BPM misalignment is ~5% when rms error of misalignment is about 20um for 250m long undulator beamline.
- Due to the damping effect from undulator radiation, the emittance of drive electron beam will be damped down to the equilibrium.
- We are ready to modify/optimize the positron source beam line from target to damping ring.
- Geant4 positron production and tracking program has been developed. We need some more efforts to fine tune it and comparing with EGSnrc + PARMELA in detail.

Phase space of beam after undulator UK1



output phase space--input: UK1.ele lattice: UK1.lte



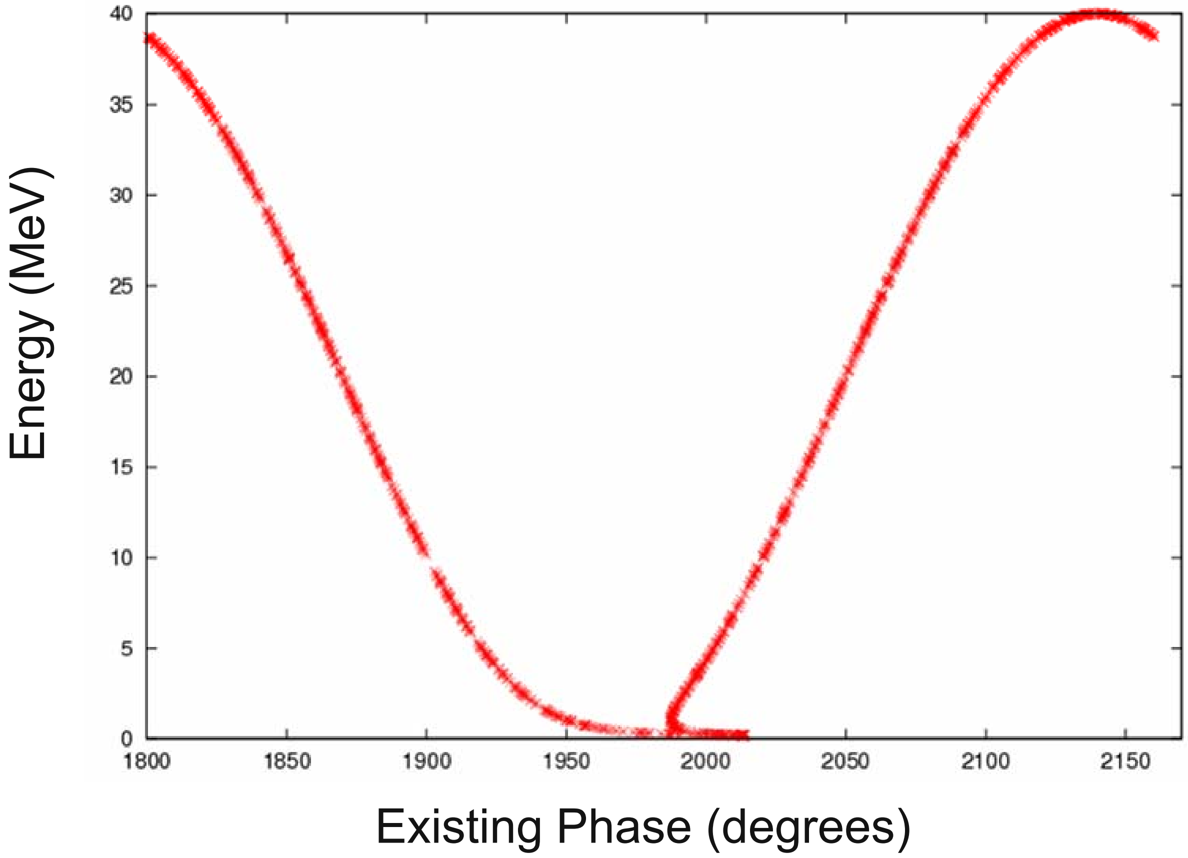
output phase space--input: UK1.ele lattice: UK1.lte

OMD studies

- K=0.92, λu=1.15cm, 100m long
- 0.4rl Ti target
- Gradient and aperture in comply with RDR
- Drift to target 450m
- OMD compared:
  - Immersed target (6T-0.5T in 20 cm)
  - Non immersed target (0-6T in 2cm, 6T-0.5T 20cm)
  - Quarter wave transformer
  - Back ground solenoid only
  - Lithium lens

Verification of G4 particle tracking inside RF field

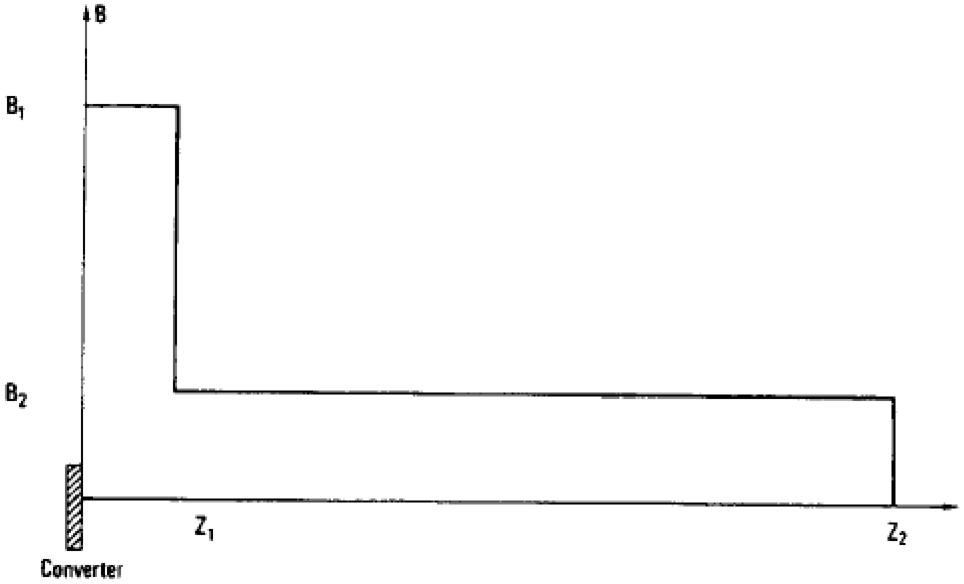
Energy of positrons passing through one 1.3GHz AWA linac with a gradient of 20MeV/m



Initial energy of positron is 20MeV, all injected on axis, randomly injected within 1 RF period. Result is as expected. This test is to make sure that our RF field is properly implemented into the program.

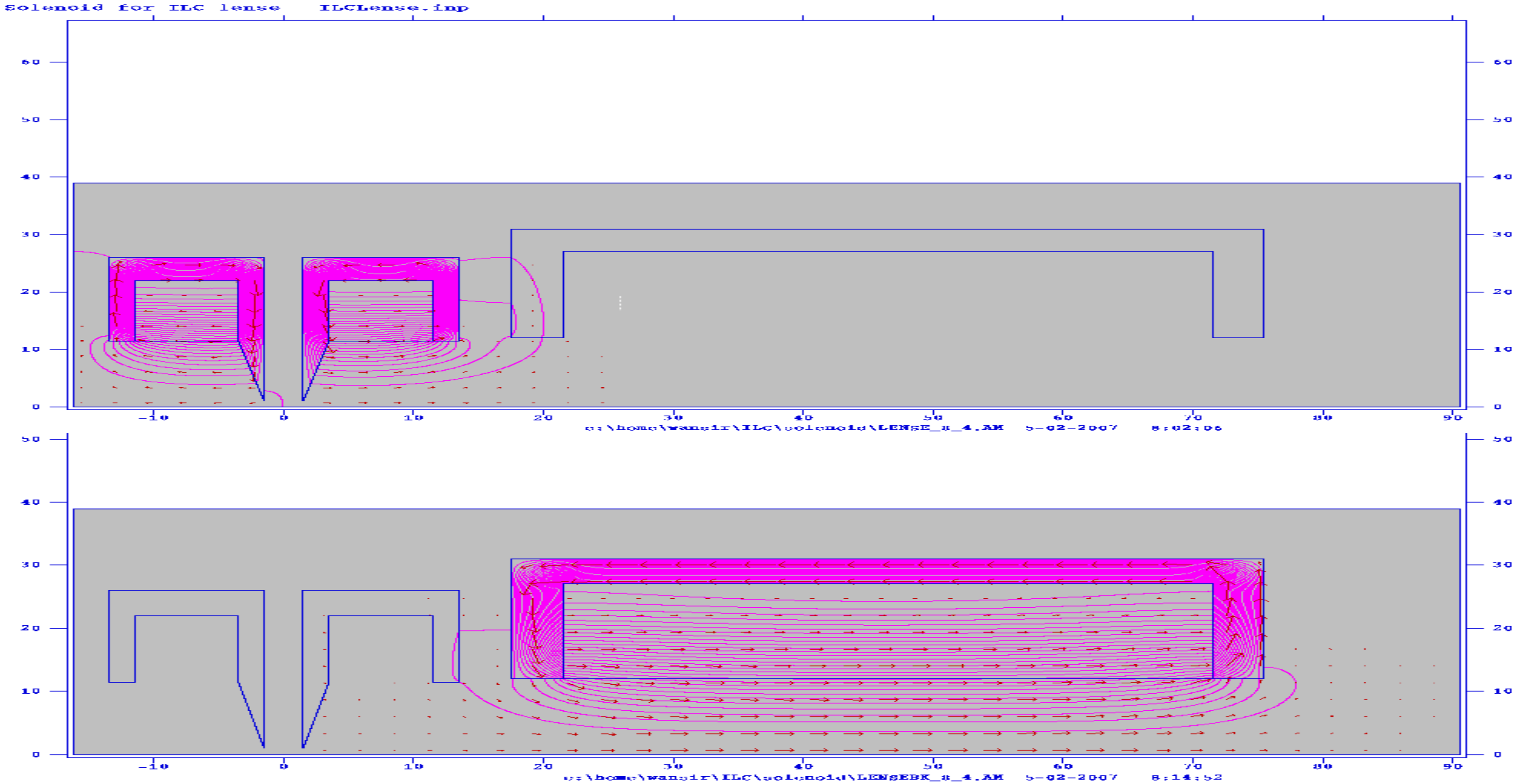
Quarter wave transformer simulation

a short lens with a high magnetic field and a long solenoidal magnetic field.

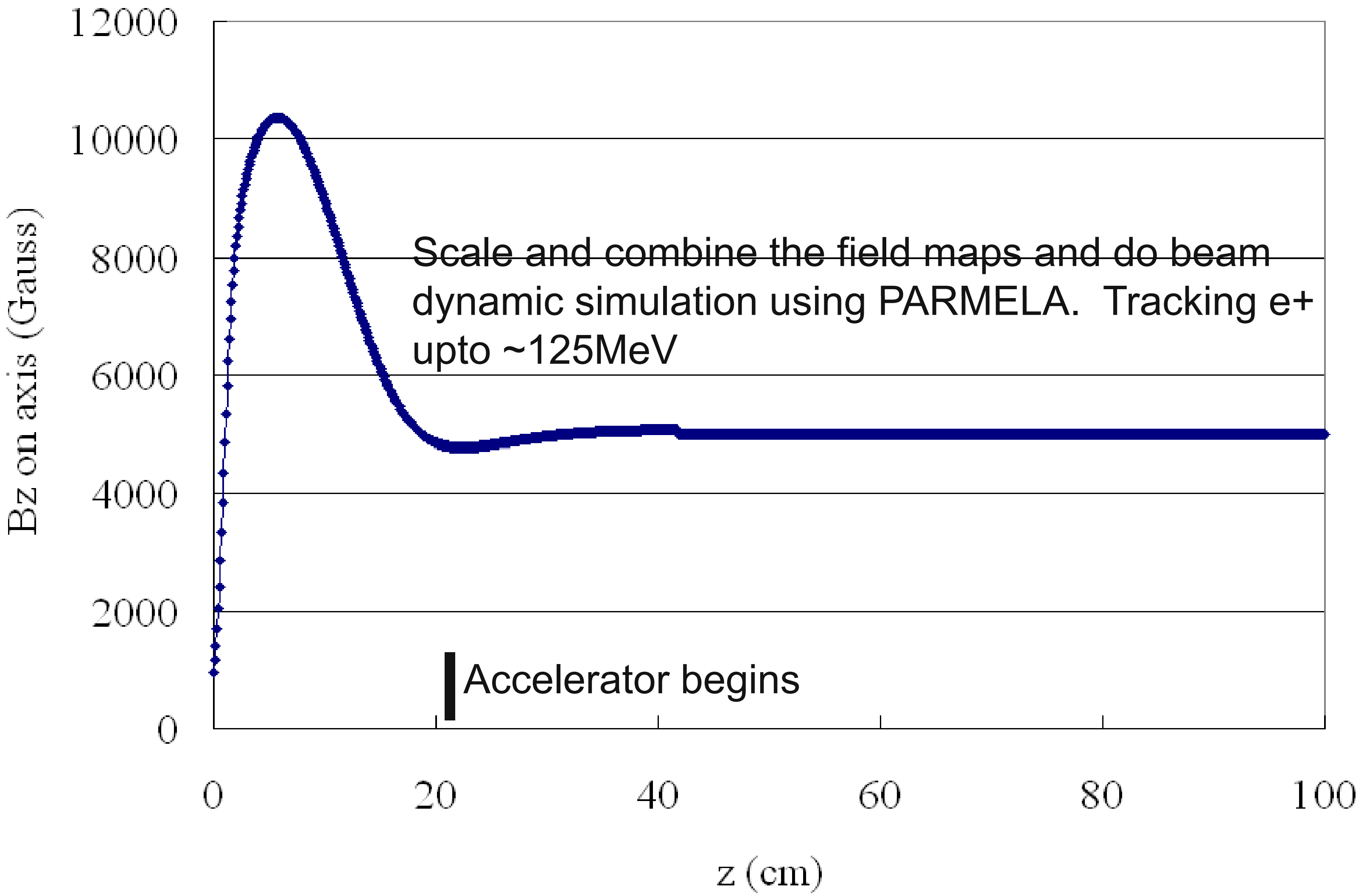


Field profile of quarter wave transformer

Magnetic field profile: Superposition of two field maps.



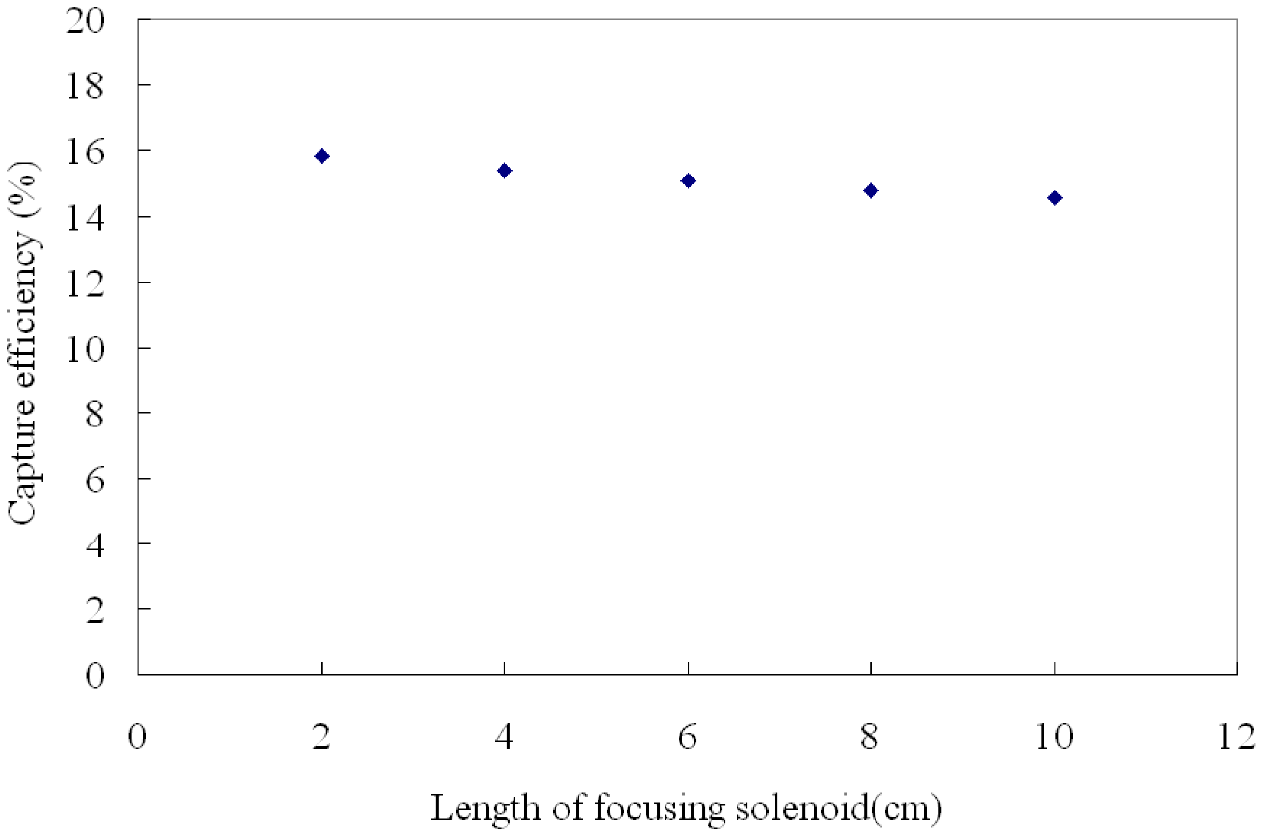
On axis Bz profile



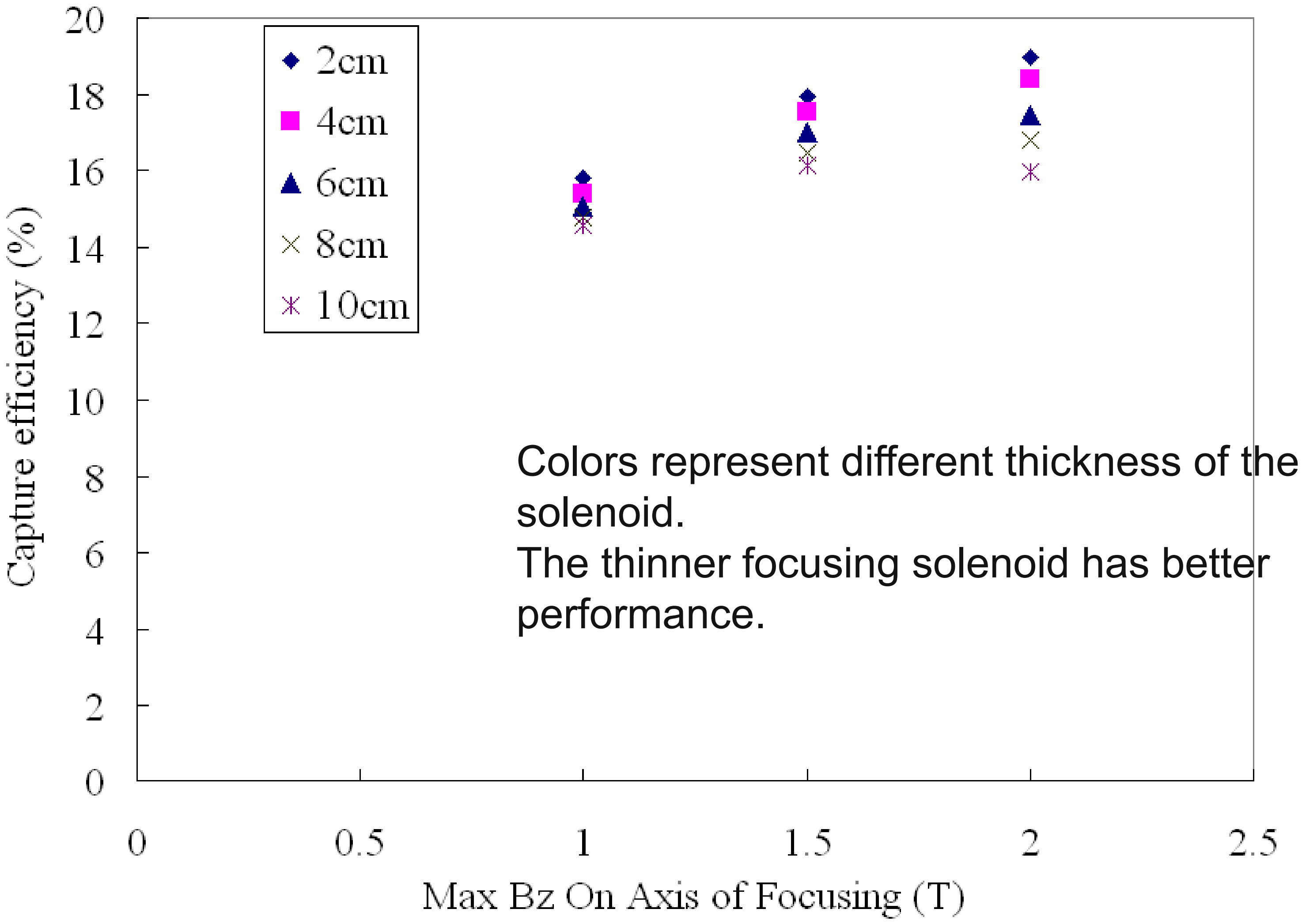
Scale and combine the field maps and do beam dynamic simulation using PARMELA. Tracking e+ upto ~125MeV

Accelerator begins

Capture efficiency as function of length of focusing solenoid. Max B field on axis is ~1T. Gap between bucking and focusing is at 2cm. Separation between focusing and matching is 0.

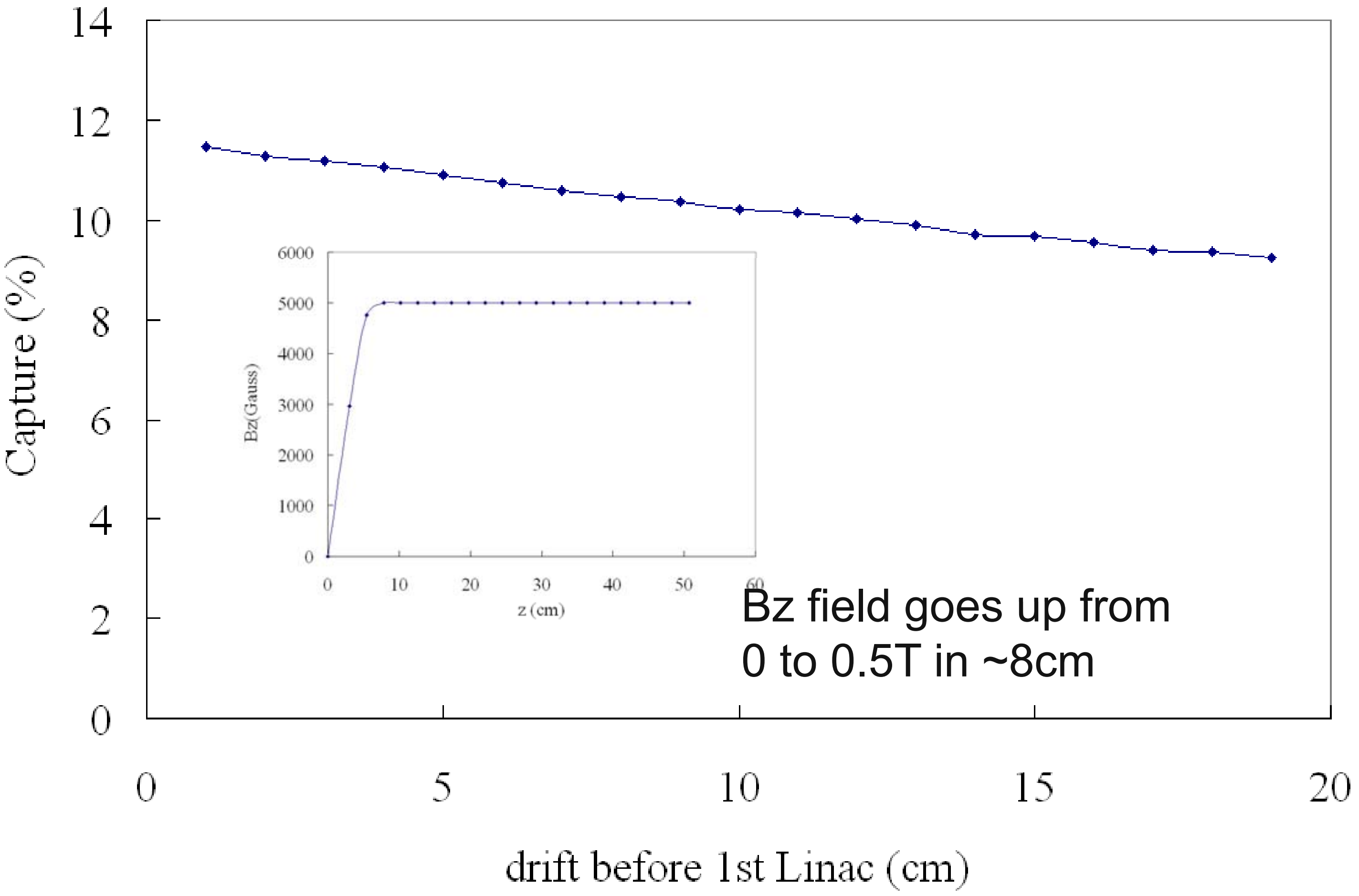


Capture as function of focusing field



Colors represent different thickness of the focusing solenoid.
The thinner focusing solenoid has better performance.

Capture efficiency with only 0.5T background solenoid

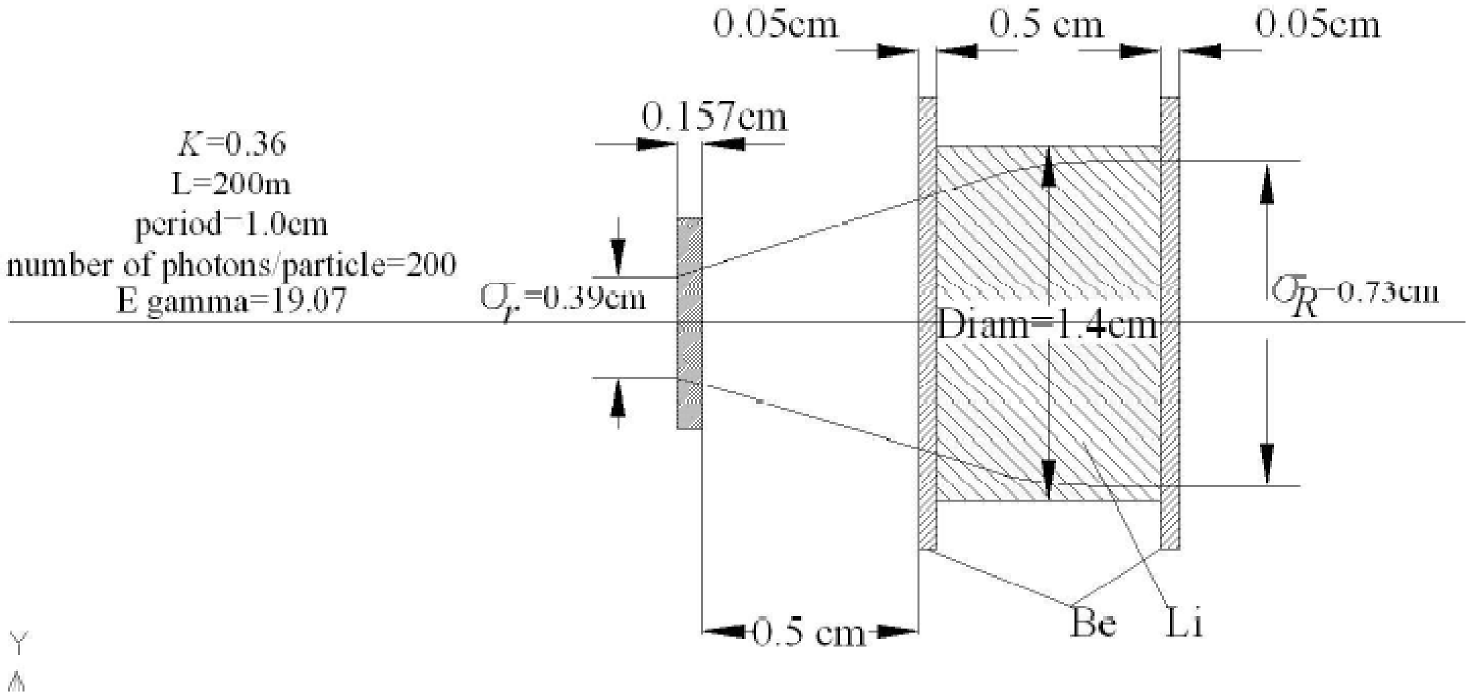


Bz field goes up from
0 to 0.5T in ~8cm

A.M. Aug 20, 2007

TARGET AND LENS

Shown below is W target



Total current in lens =156 kA. Be and Li stay in good thermal contact. Lithium is liquid and runs ~10m/sec.

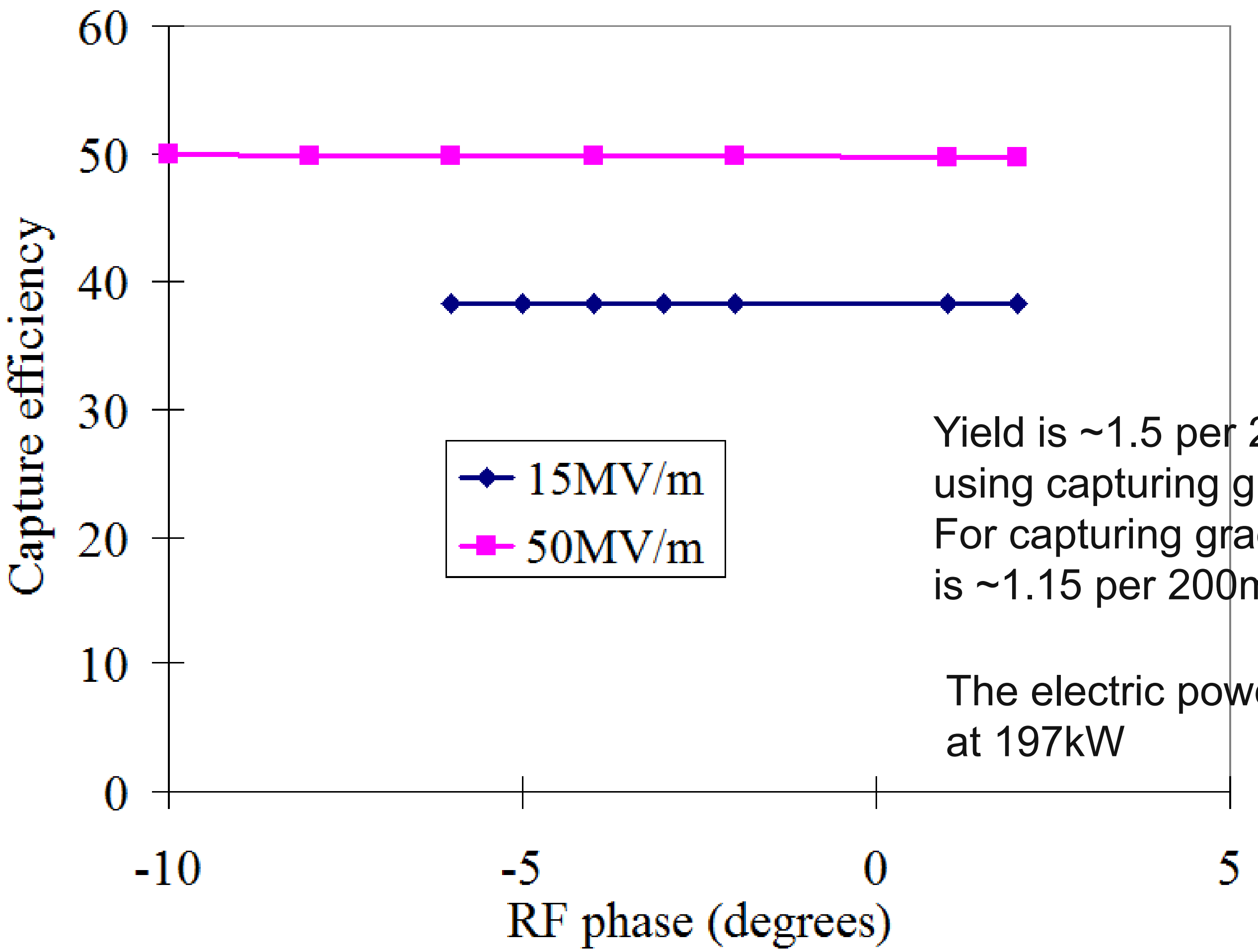
Shown is beam envelope with R.M.S. values.

Efficiency of conversion is 1.68.

Conditions:

- Undulator: $k=0.36$, $\lambda u=1.0$cm, length:200m
- Drift to target: 350m
- Drive beam energy: 150GeV
- Capture: at ~125MeV, using +/-7.5 degree phase cut, $\varepsilon x+\varepsilon y$ <0.09m.rad, energy spread +/-25MeV.
- Capturing RF gradient: 15MV/m and 50MV/m
- Assume uniform current distribution in lithium lens

Yield and capture efficiency



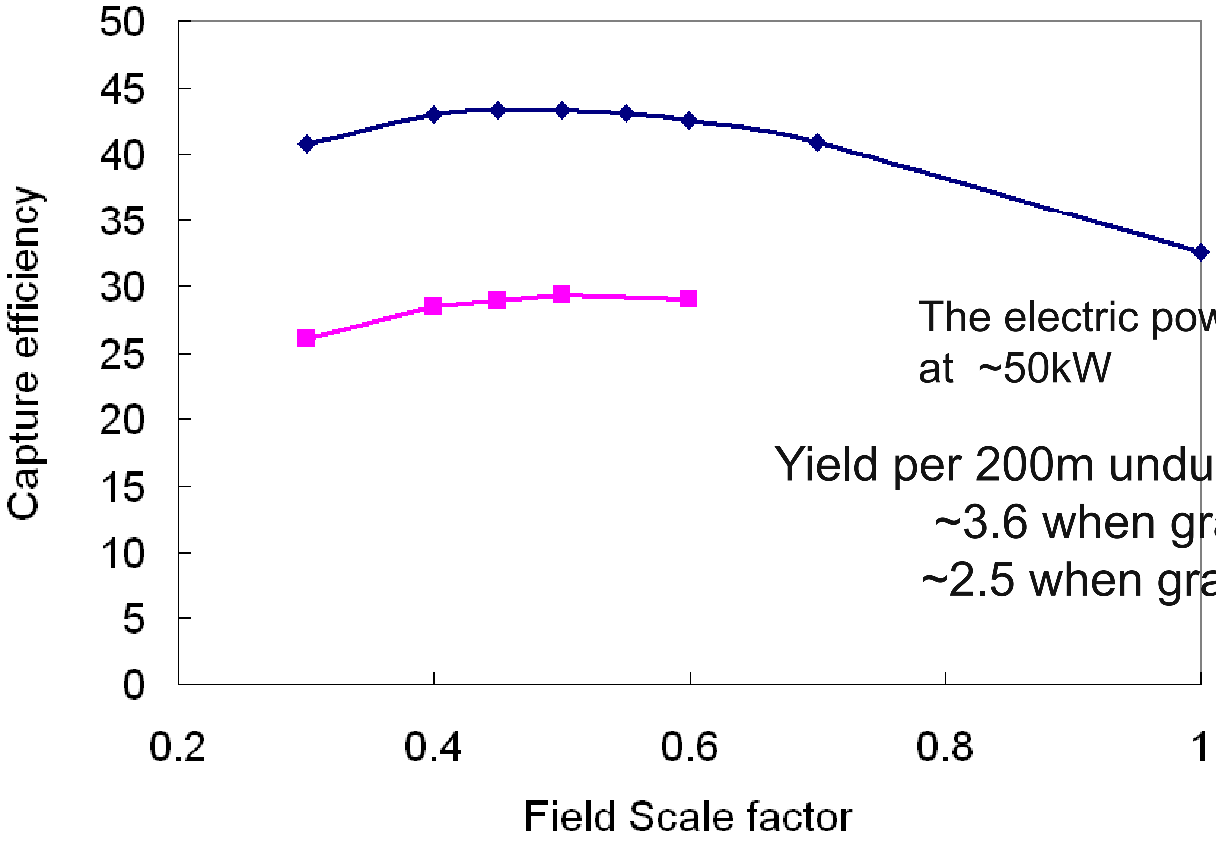
Yield is ~1.5 per 200m undulator when using capturing gradient of 50MV/m
For capturing gradient of 15MV/m, the yield is ~1.15 per 200m undulator

The electric power required is estimated at 197kW

Using baseline undulator and target with Lithium lens

- Undulator: K=0.92, λu=1.15cm, 100m
- Titanium target:0.4 rl
- Drift to target: 450m
- Drive beam energy: 150GeV
- Capture: at ~125MeV, using +/-7.5 degree phase cut, $\varepsilon x+\varepsilon y$ <0.09m.rad, energy spread +/-25MeV.
- Capturing RF gradient: 50MV/m

Yield and capture efficiency using baseline undulator and target with lithium lens



The electric power required is estimated at ~50kW

Yield per 200m undulator:
~3.6 when gradient is 50MV/m
~2.5 when gradient is 15MV/m

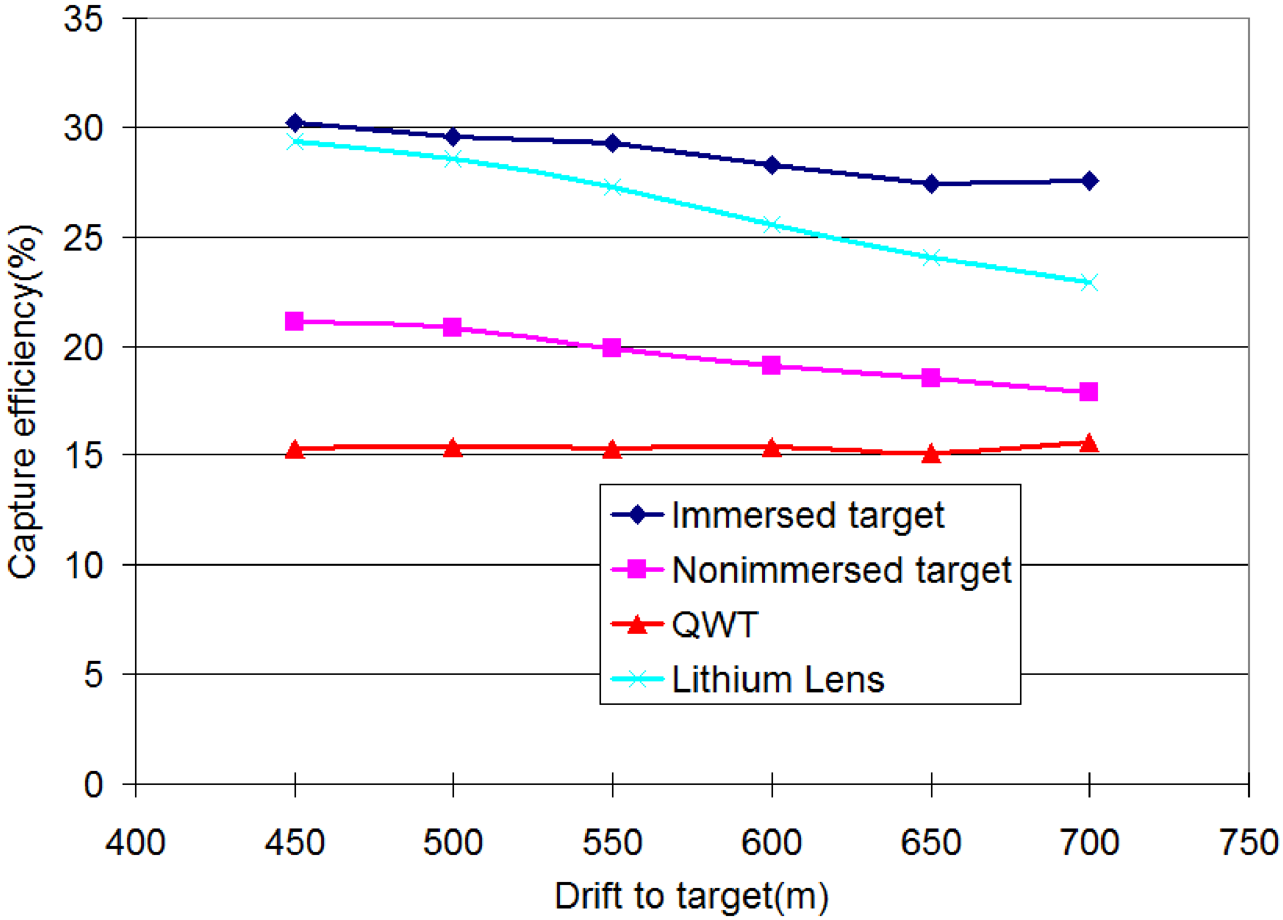
Capture Efficiency of Different OMD

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

3. The effect of spot size on positron capture efficiency

- 100m undulator, K=0.92, λu=1.15cm
- Target: Ti, 0.4 rl
- Drift to target: from 450m up to 700m(spot size: 1.5mm up to 2.3mm)
- Immersed case: 6T-0.5T, 20cm
- Non Immersed case: ramp(0-6T) 2cm, 6T-0.5T 20cm
- Quarter wave transformer: 1T-0.5T, 2cm DC coil

Capture efficiency as function of spot drift to target (spot size)



Capture efficiency lowered by 10% for immersed target when spot size increased from σ ~1.5mm up to ~2.3mm.
For non immersed case, the capture efficiency dropped by ~ 14%.
For quarter wave transformer, the capture efficiency doesn't change with spot size within the range of 1.5mm to 2.3mm
For lithium lens,

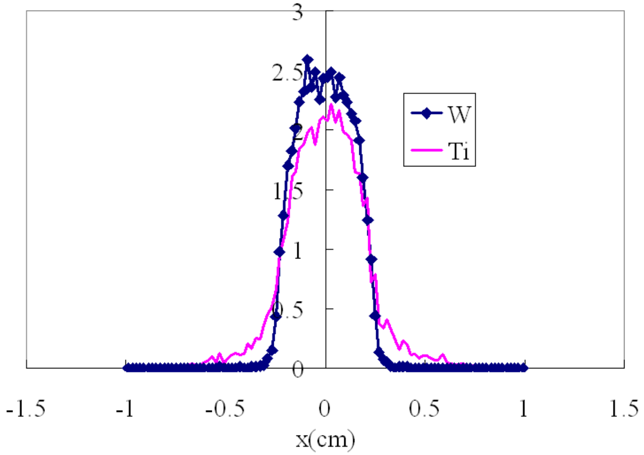
4. Comparing Tungsten target and Titanium target

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

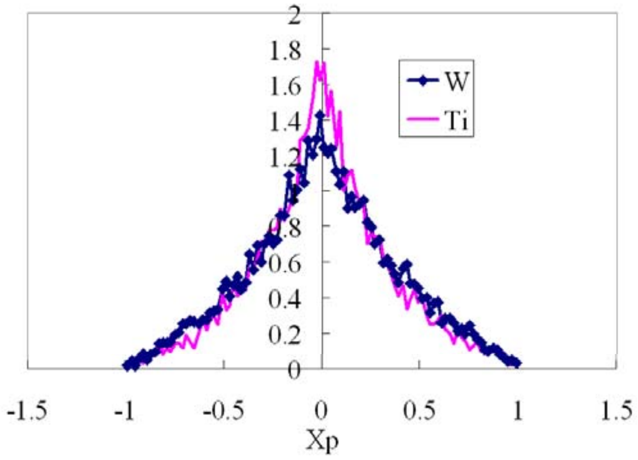
Tungsten target gives about 50% higher raw yield in positron production but the captured yield only enhanced by ~10% due to broader divergence distribution of e+ produced in tungsten target.

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

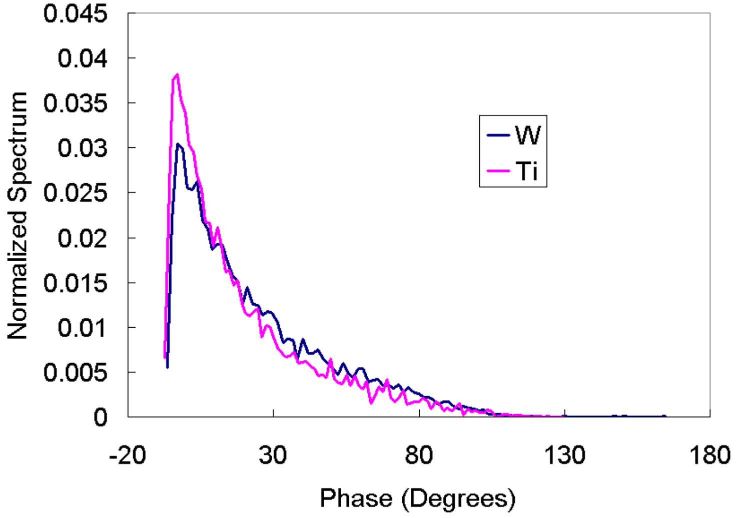
Normalized transverse distribution of e+ when exiting from target



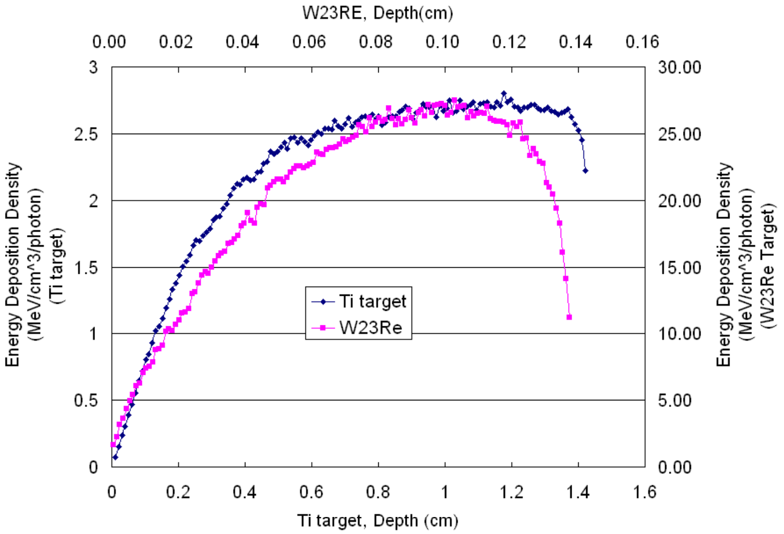
Normalized divergence distribution of e+ when exiting from target



Normalized longitudinal distribution of e+ at end of tracking



On beam axis profile of deposit energy density



Summary

- Comparing the capture efficiency, lithium lens has about the same efficiency as immersed AMD
- Increase the spot size will lower the capture efficiency except for quarter wave transformer. The exactly trade off need to be determined.
- Tungsten target can give ~50% more on raw yield. But given the same in put condition, the density of energy deposition for tungsten target is 10 times higher than for titanium target. And due to the wider divergence distribution of e+ from tungsten target, the enhancement to e+ yield will be limited
- Emittance of drive electron beam will be damped as a result of radiation. The emittance growth due to wakefield is very small and ignorable based on Duncan’s result.