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PARMELA simulation for positron source

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1 Introduction

A scheme of positron source, in which positrons are produced by using high-energy gamma rays to hit a thin target, had been proposed in [1] and investigated in [2]. The advantages of this scheme are higher positron yield and better positron beam performance. Some researches about captured optics behind target were developed [3]. Here we presented a preliminary study about positron captured optics with the aid of PARMELA. The positron captured optics behind target, as shown in Fig. 1, includes an Adiabatic Matching Device (AMD), and five Linac tanks embedded in a uniform solenoid field. AMD consists of a tapered solenoid field which has a high gradient at the starting end and tapers down adiabatically to the constant gradient at the another end of AMD.

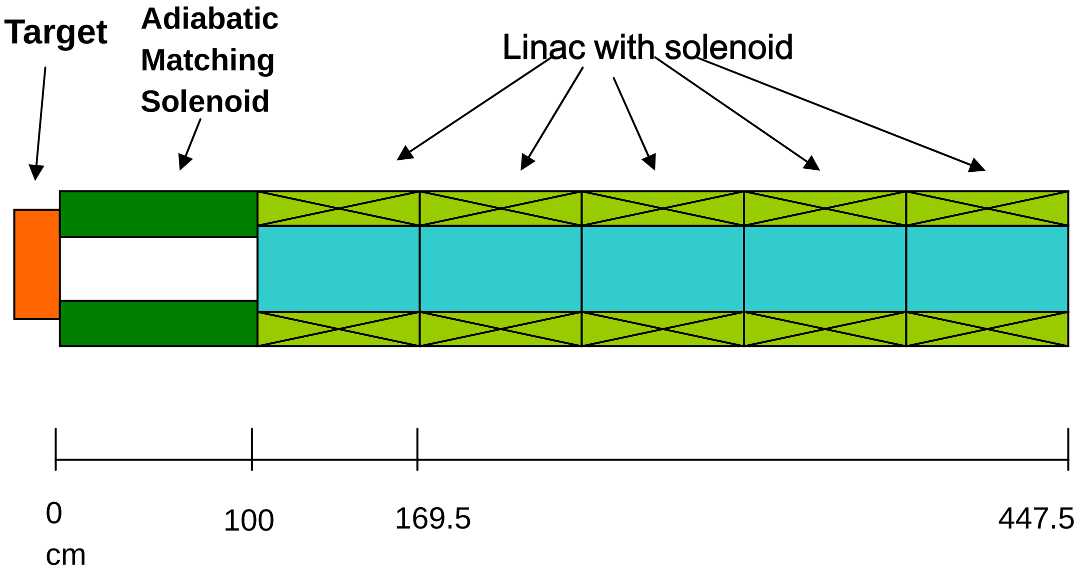


Fig.1 A schematic used in the simulation of positron source.

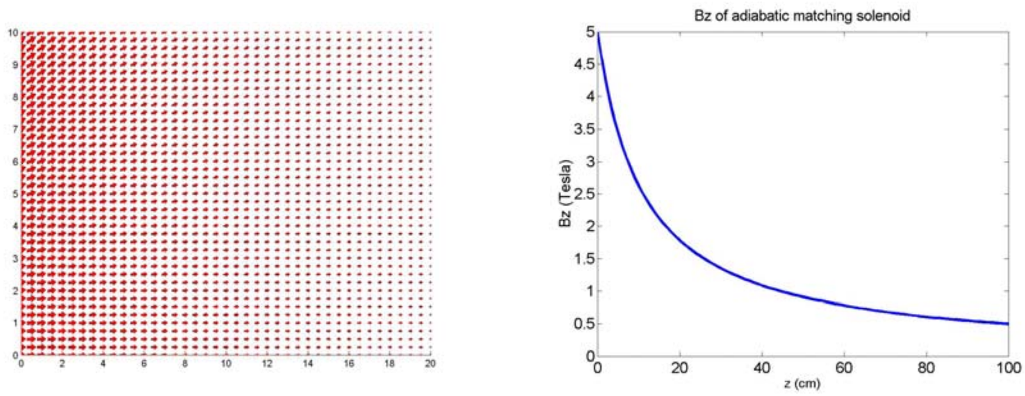
1.1 Adiabatic Matching Device (AMD)

The solenoid field in Adiabatic Matching device can be approximated by the following equations:

$$Bz(z) = \frac{B_0}{1 + g \cdot z}$$

$$Br(z,r) = \frac{gB_0}{2(1+gz)^2} r$$

The field distribution is presented in Fig. 2. This is a first order approximated field. In the later section, a complete comparison with real solenoid field will be made to confirm that it will be feasible to replace real tapered solenoid field with the first order approximated field.



(a) (b)

Fig. 2 First order approximated magnetic field of Adiabatic Matching Device.

1.2 Linac tank

Five 5-cell π mode iris loaded L band Linac tanks are used in the study. The Linac geometric and RF parameters are listed below, and the field distribution is shown in Fig. 3.

The radius of aperture = 2.5 cm,

Transit-time factor, T = 0.74,

Average gradient on axis, E0= 16MV/m,

Input Power, P = 4.4MW.

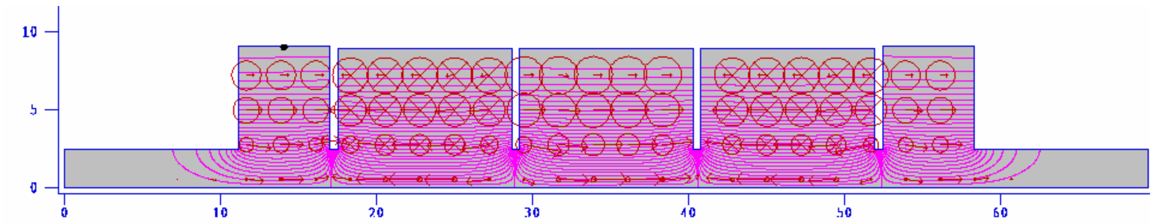


Fig. 3 Electromagnetic field distribution in the L -band Linac tank.

In the following sections, some preliminary study results about positron beam dynamics in the captured optics are presented. Two types of initial particle distribution are used in the study, one is random distribution in six-dimensional phase space, and another is real beam distribution produced by EGS4.

2 Random particle distribution

In the section a random particle distribution in six-dimensional phase space is used to simulate the positrons yield from a target. An approximated adiabatic matching solenoid field is used in the simulation.

2.1 Some typical plots

Some typical simulation results are plotted at Fig. 4 to Fig. 9. The followed is a list.

- Initial phase spectrum of beam,
- Initial beam longitudinal phase distribution,
- Phase spectrum before the entrance of 1st Linac,
- Longitudinal phase distribution before the entrance of 1st Linac,
- Phase spectrum at the exit of 5th Linac,
- Longitudinal phase distribution at the exit of 5th Linac.

The conditions used in this set of simulations are

Initial beam energy range: 2-8 MeV,
Initial beam spot radius: 2 mm,
Due to strong correlation between initial beam divergence and beam quality, for each plot, four sub-figures are plotted with different beam divergence (X’=0.25, 0.5, 0.75, 1 rad).
The solenoid field setting for Adiabatic matching device is 2.5 Testla at the position of target (Z=0), and 0.25 Tesla at the entrance of the first Linac (Z=100cm).

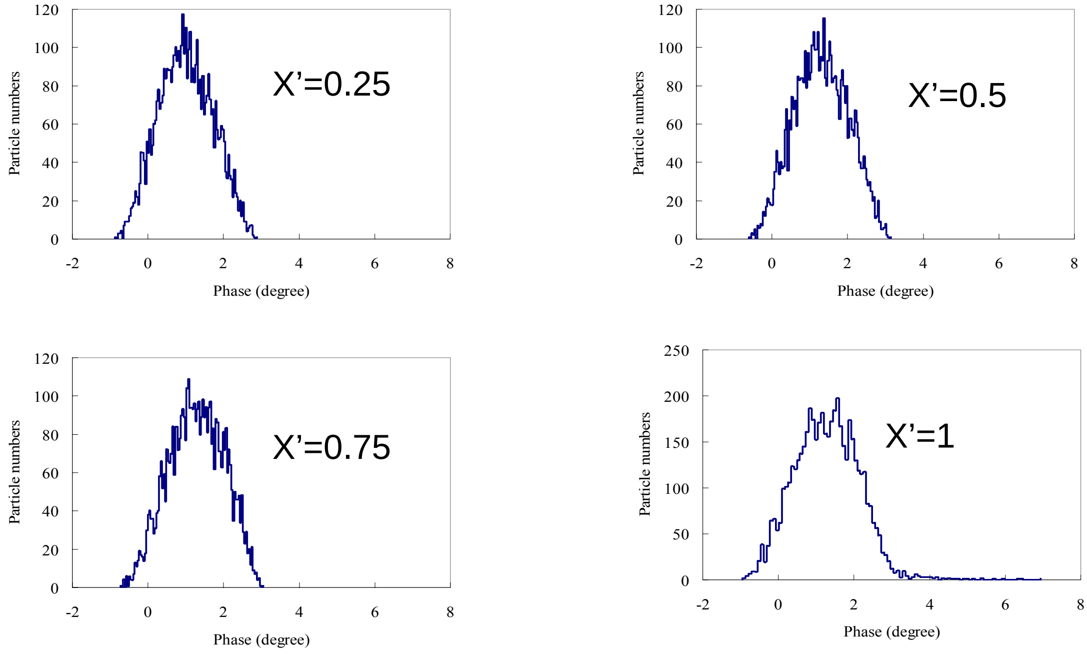


Fig. 4 Initial phase spectrum of beam with different initial beam divergence.

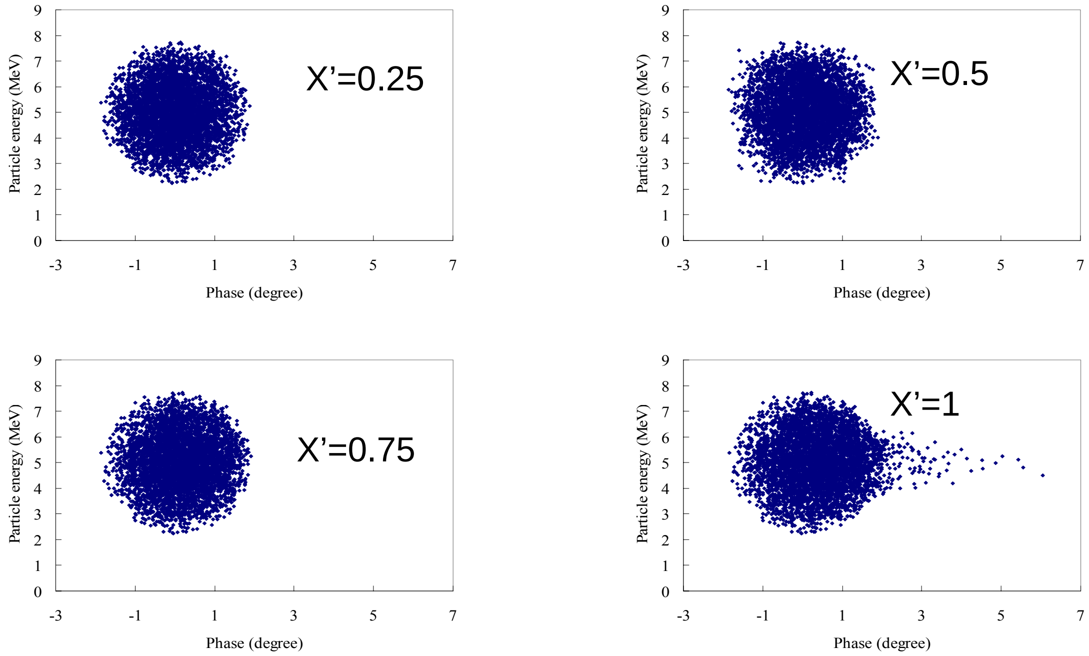


Fig. 5 Initial longitudinal phase distribution of beam.

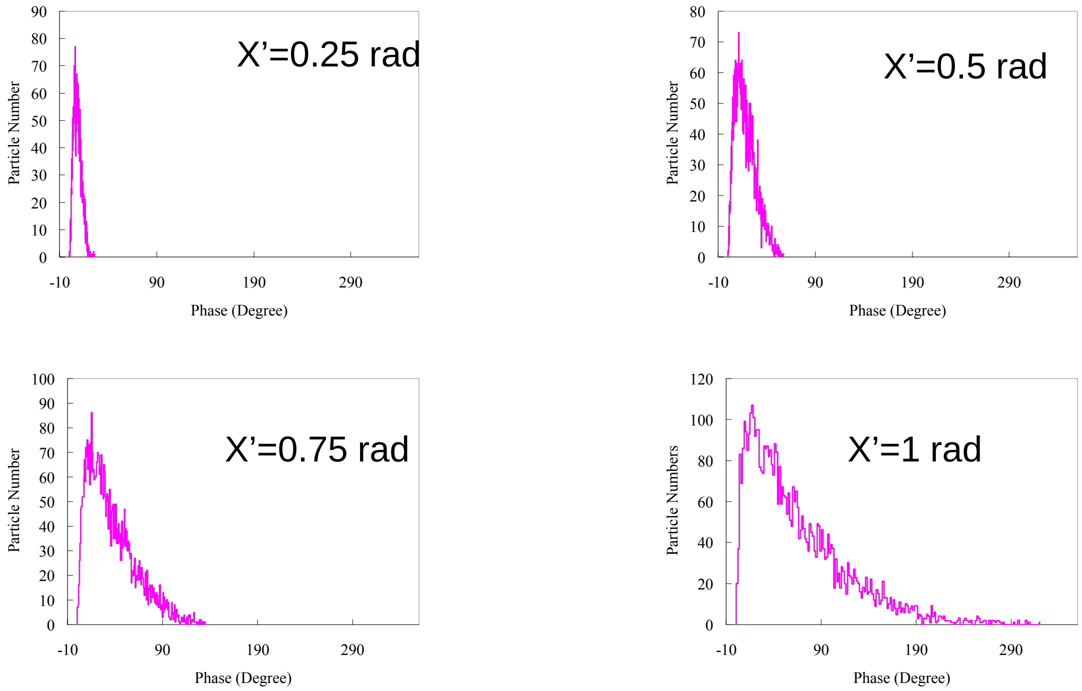


Fig. 6 Phase spectrum before the entrance of 1st Linac.

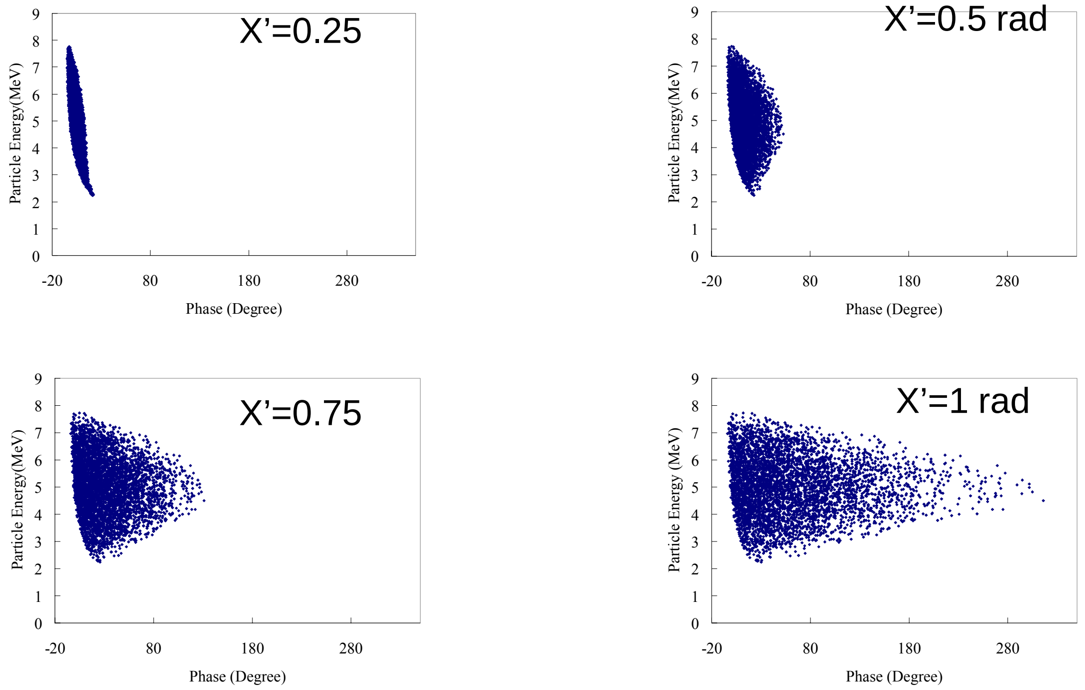


Fig. 7 Longitudinal phase distribution before the entrance of 1st Linac.

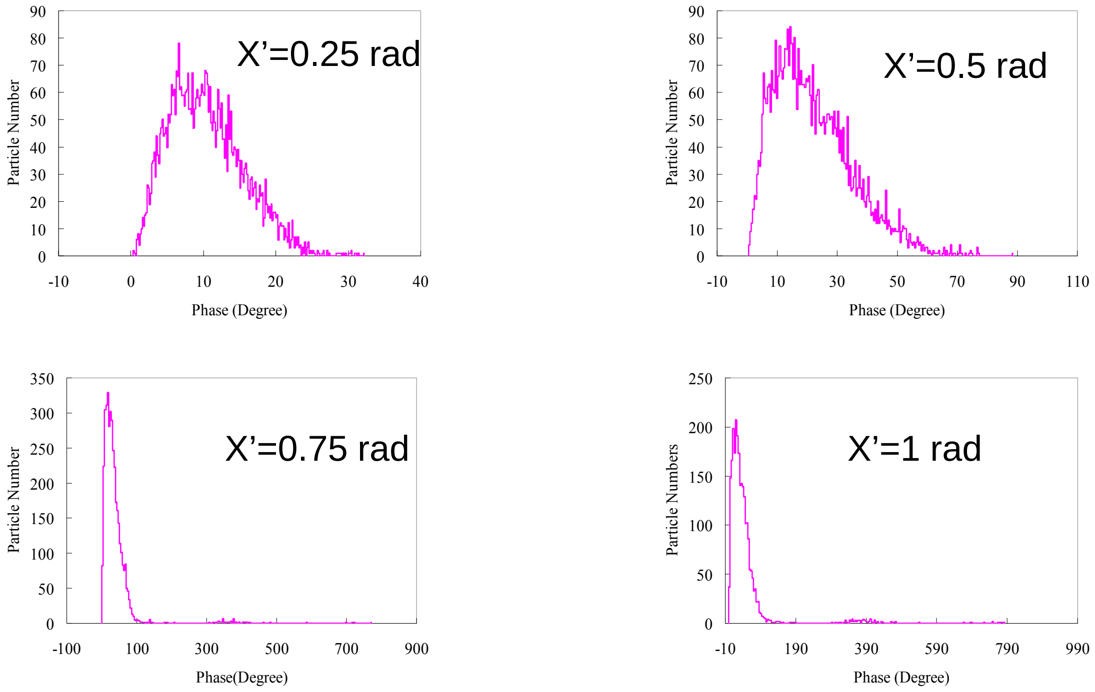


Fig. 8 Phase spectrum after the exit of 5th Linac.

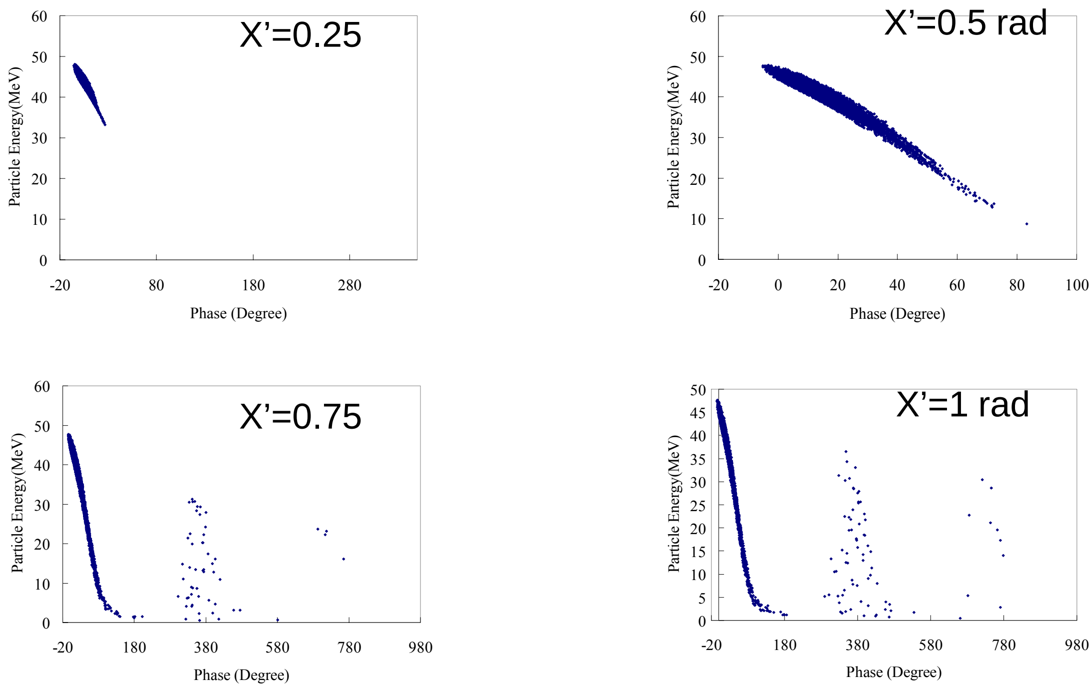


Fig. 9 Longitudinal phase distribution after the exit of 5th Linac.

2.2 Study of beam quality

In this subsection, the effects of initial beam distribution and magnetic field on beam qualities, such as beam loss and bunch length, have been studied. Here beam loss is defined as (Nt-N1)/Nt*100%. Nt means the number of particles injected from target, and N1 is the number of particles in the 1st micro-bunch. Bunch length is defined as the width of longitudinal window which contains the given percentage of total particle number.

2.2.1 Effects of initial beam divergence

Fig. 10 and Fig. 11 show the effects of initial beam divergence on beam loss and bunch length. The conditions used in this set of simulations are listed below.

Initial beam energy range: 2-8 MeV,

Initial beam spot radius: 2 mm,

Initial beam divergence X': 0.25 rad, 0.5 rad, 0.75 rad, and 1 rad,

The solenoid field setting for Adiabatic matching device is 2.5 Testla at the position of target (Z=0), and 0.25 Tesla at the entrance of first Linac (Z=100cm).

Beam loss is calculated at the exit of 5th Linac. Bunch length data are obtained at the location Z=95cm (before the entrance of 1st Linac).

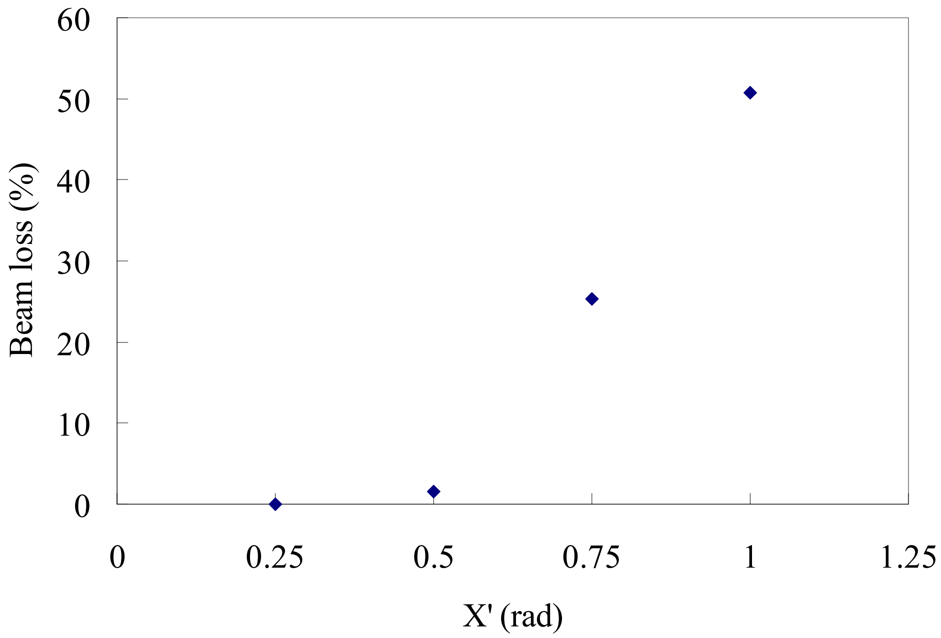


Fig. 10 The effect of the initial beam divergence to beam loss.

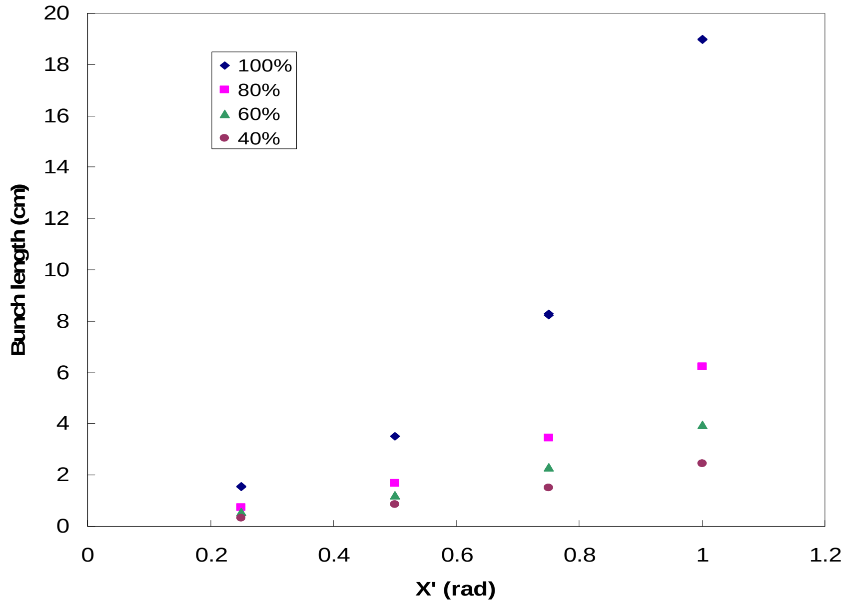


Fig. 11 The effect of the initial divergence to bunch length.

2.2.2 The effects of initial beam size

Fig. 12 shows the effect of initial beam size on bunch length. Compared to the previous case, only the initial beam size is adjusted from 2mm to 1mm. Both results don't have big difference.

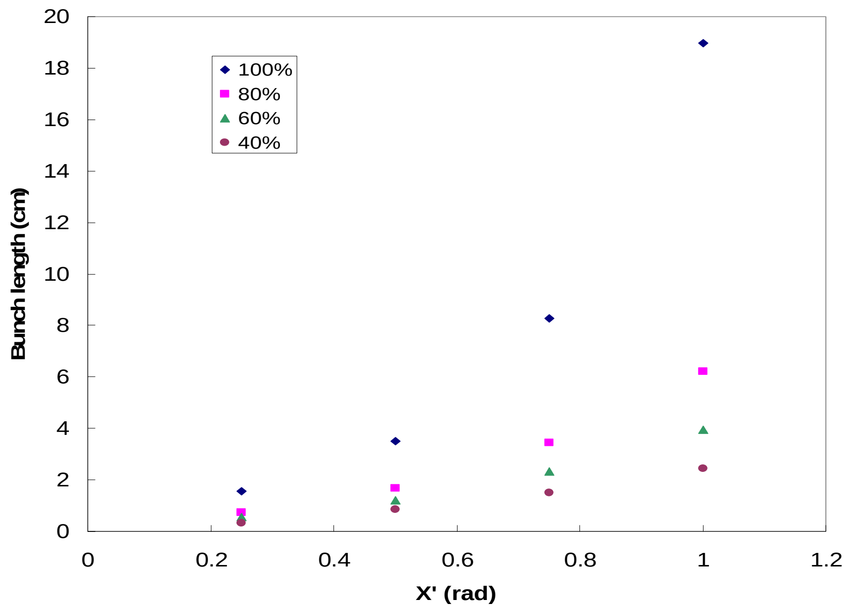


Fig. 12 The effect of the initial beam size to bunch length.

2.2.3 Effects of AMD length and initial strength of magnetic field to beam qualities

In this subsection, the length and initial field strength of Adiabatic Matching device are adjusted. Their effects to beam loss and bunch length are studied. Four cases are simulated. Detailed simulation conditions for the four cased are presented below.

Common conditions:

Initial beam energy range: 2-8 MeV,

Initial beam spot radius: 2 mm,

Initial beam divergence X’:1 rad.

Case 1:

The length of AMD, L=100cm,

Variation of solenoid field in AMD: 2.5 Testla – 0.25 Testla.

Case 2:

The length of AMD, L=100cm,

Variation of solenoid field in AMD: 5.0 Testla – 0.25 Testla.

Case 3:

The length of AMD, L=50cm,

Variation of solenoid field in AMD: 2.5 Testla – 0.25 Testla.

Case 4:

The length of AMD, L=50cm,

Variation of solenoid field in AMD: 5.0 Testla – 0.25 Testla.

PARMELA simulation results are shown in Fig. 13-15.

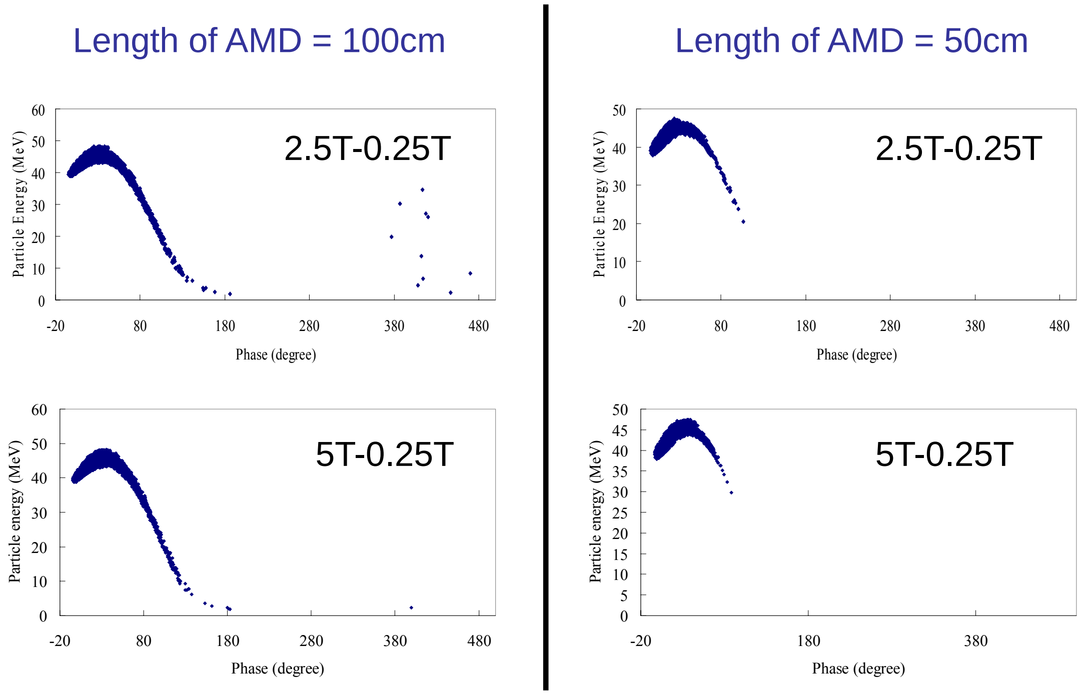


Fig. 13 Longitudinal phase distribution after the exit of 5th Linac.

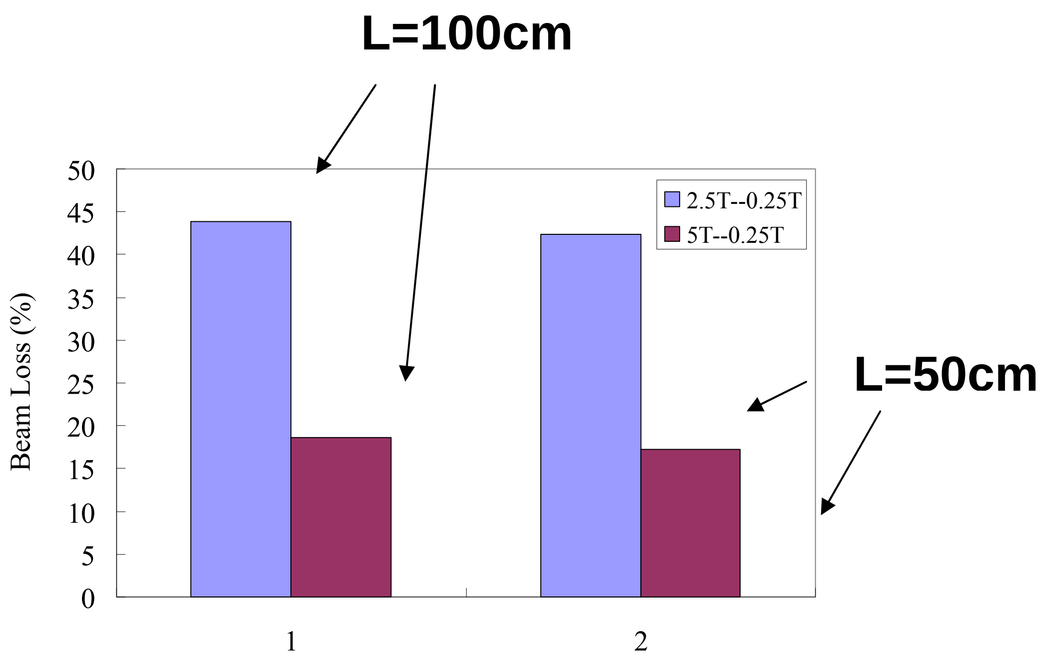


Fig. 14 The effect of AMD length and strength to beam loss. (Beam loss is calculated after the exit of 5^{th} Linac.)

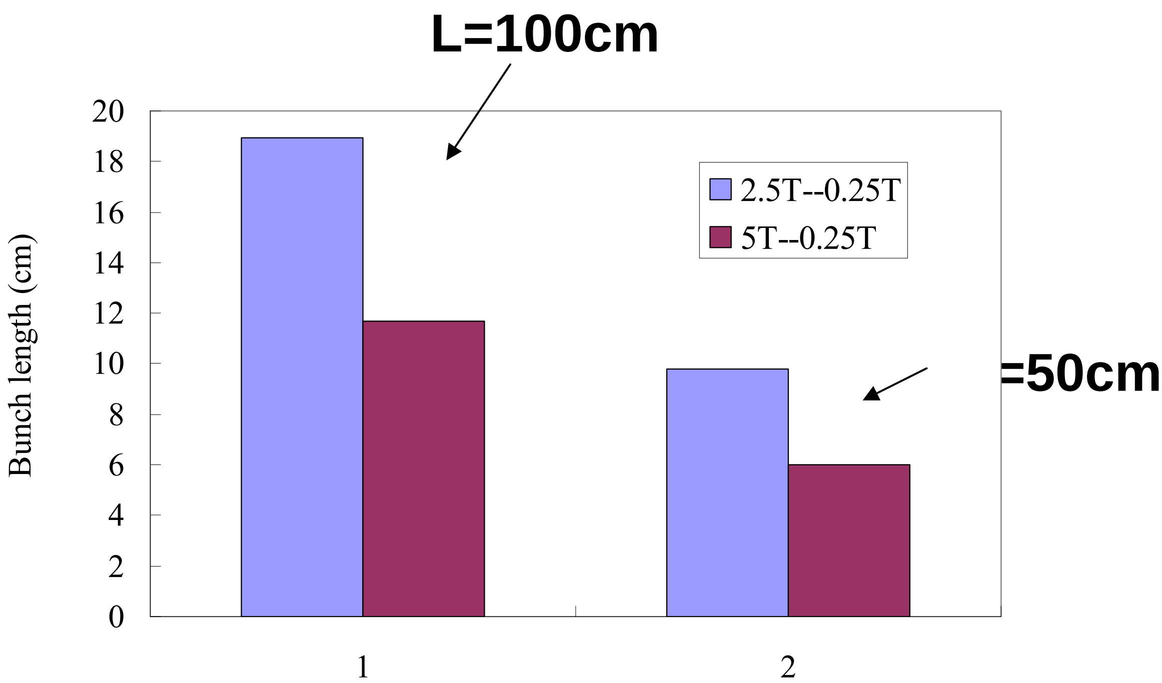


Fig. 15 The effect of AMD length and strength to bunch length. (Bunch length is calculated before the entrance of 1st Linac.)

The simulation results shown above indicate that increasing the gradient of solenoid field in AMD and reducing the length of AMD will decrease beam loss and bunch length, and finally increase positron captured rate. However, this process is not unlimited. It is hard to build an AMD which has a short length, and can support a very high gradient in practice. There exists an optimized AMD design.

2.3 Other beam quality parameters

Fig. 16 shows typical normalized transverse emittance evolution at different initial beam divergence, in which 99% particles are included. Positron beam horizontal trajectories are shown in Fig. 17. The simulation conditions for this set of data are listed below.

Initial beam energy range: 2-8 MeV,
Initial beam spot radius: 2 mm,
Initial beam divergence X':1 rad,
Length of AMD: 50 cm,
Solenoid field strength in AMD: 5 Testla – 0.25 Tesla,
Solenoid field at Linac tank region: 0.25 Tesla,
Average gradient in Linac tank: 16MV/m,
Launch phase of Linac: 154 degree.

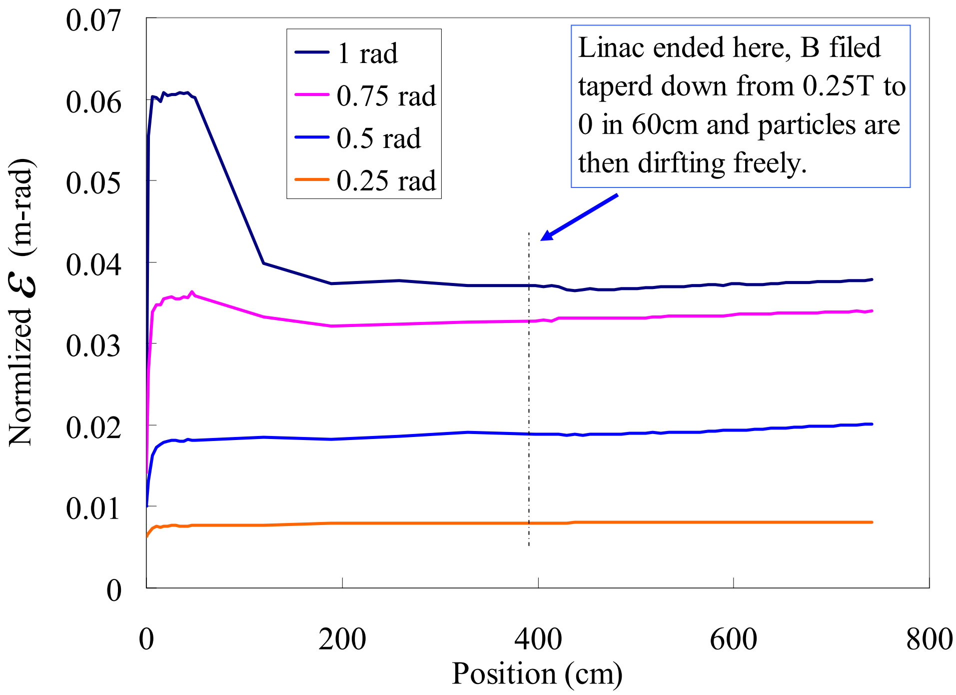


Fig. 16 Normalized transverse emittance evolution (including 99% particles).

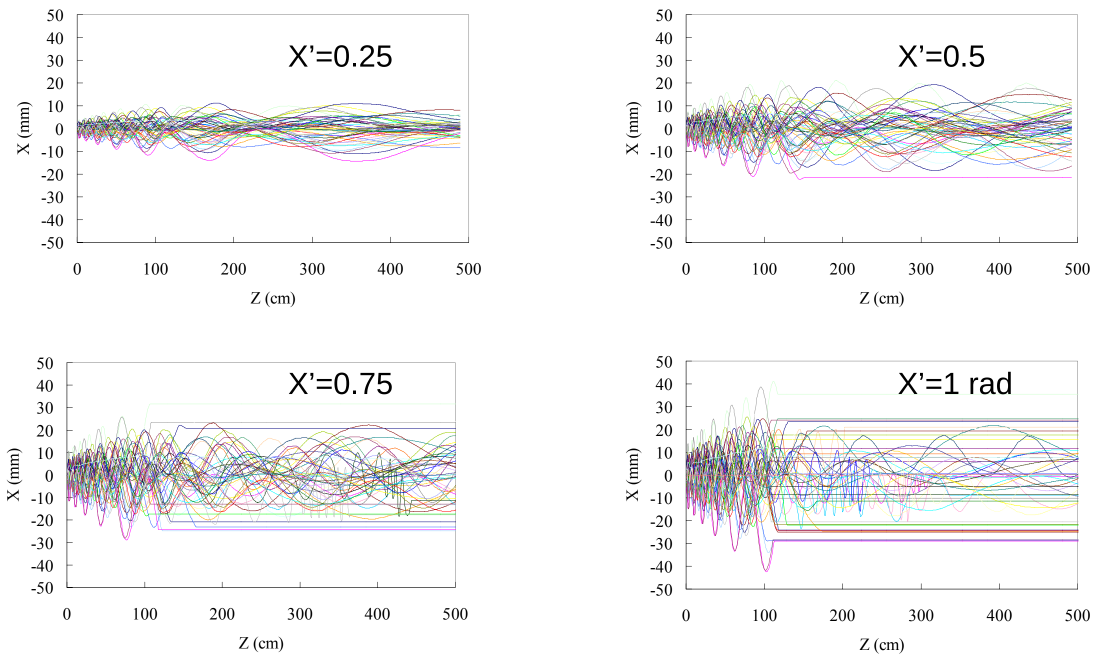


Fig. 17 Horizontal particle trajectory.

2.4 Does 1st order approximate tapered magnetic field in AMD affect simulation results?

For all the simulations presented above, we applied 1st order approximated tapered magnetic field to replace real solenoid field in AMD. To verify its feasibility, a real solenoid field produced by SUPERFISH is used in PARMELA simulation. The results will be compared to ones of 1st order approximate field.

Fig. 18 shows a real AMD solenoid field map produced by SUPERFISH. Fig. 19 shows the comparison of magnetic field produced by the two approaches. Fig. 20 and 21 show the comparison of beam qualities.

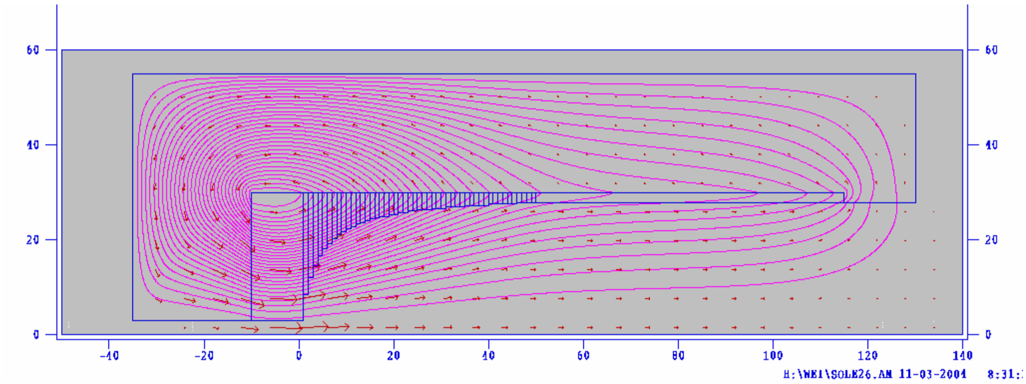


Fig. 18 A real AMD solenoid field map produced by SUPERFISH.

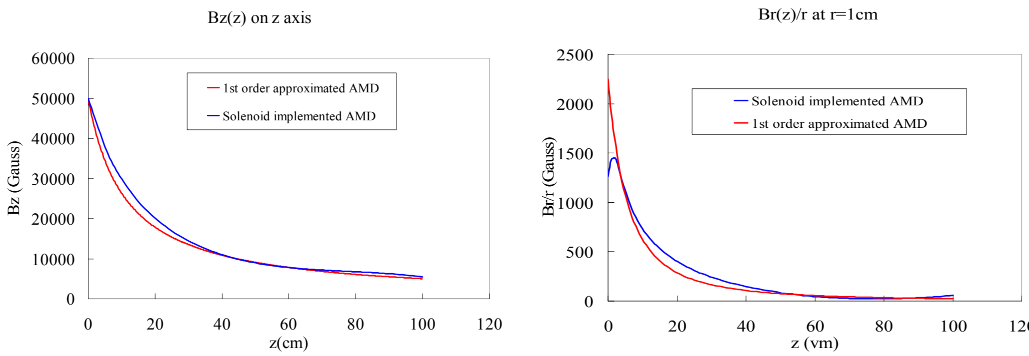


Fig. 19 Comparison of magnetic fields.

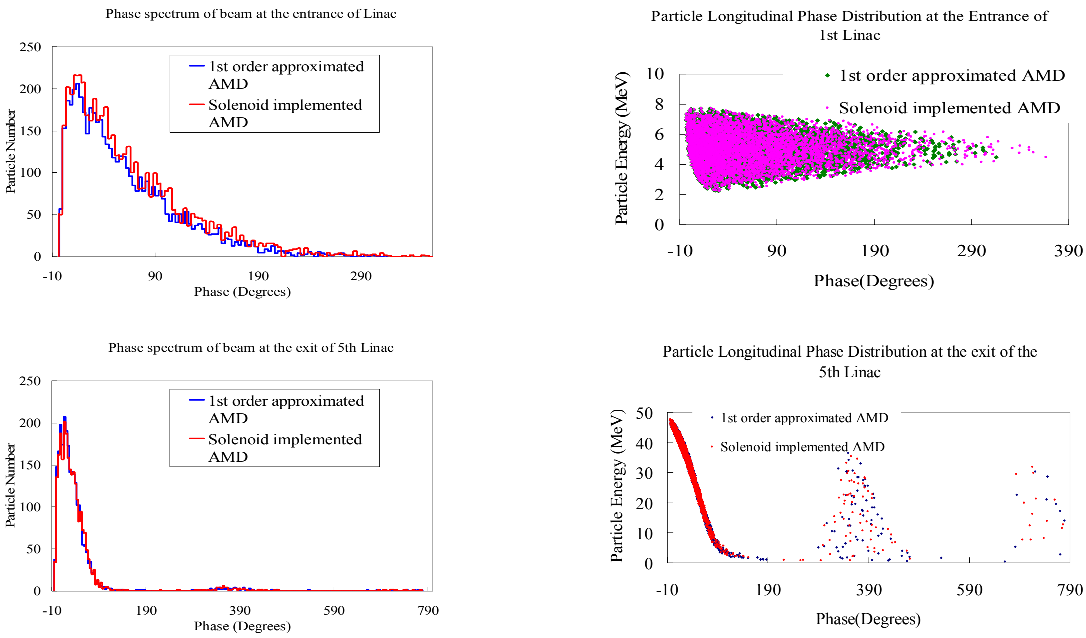


Fig. 20 Comparison of beam spectrum and longitudinal particle phase distribution.

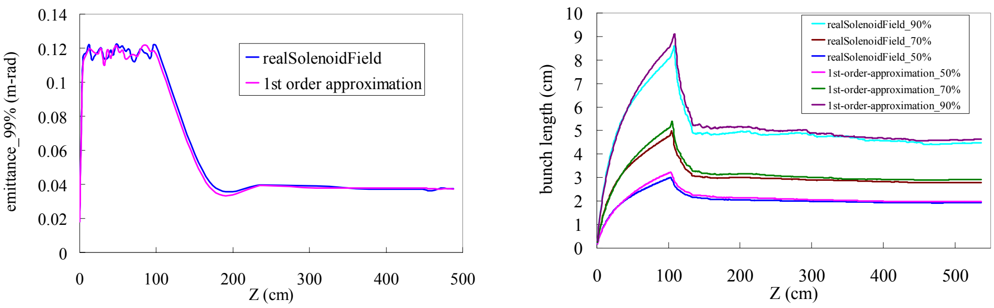


Fig. 21 Comparisons of emittance and bunch length.

From the comparisons of field and beam qualities presented above, we can conclude that 1st order approximated magnetic field for AMD can get satisfactory simulation results with negligible error. So in the later simulation, if not to be pointed out specially, the field for AMD is 1st order approximation.

3 Initial positron distribution produced by EGS4

Initial positron distribution produced by EGS4 is used in PARMELA simulation. The followed are the initial beam parameters.

Energy of Gamma ray hitting target: 12 MeV,
Number of positron produced: 2310,
Initial beam energy range: 0.5-10.7 MeV,
Initial beam spot radius: 2 mm,
Maximum initial beam divergence X': 82 degree.

AMD and Linac parameter setting:

Length of AMD: 50 cm,
Solenoid field strength in AMD: 5 Testla – 0.25 Tesla,
Solenoid field at Linac tank region: 0.25 Tesla,
Average gradient in Linac tank: 16MV/m,
Launch phase of Linac: 174 degree.

Fig. 22-24 show longitudinal phase distribution, emittance, and bunch length evolution.

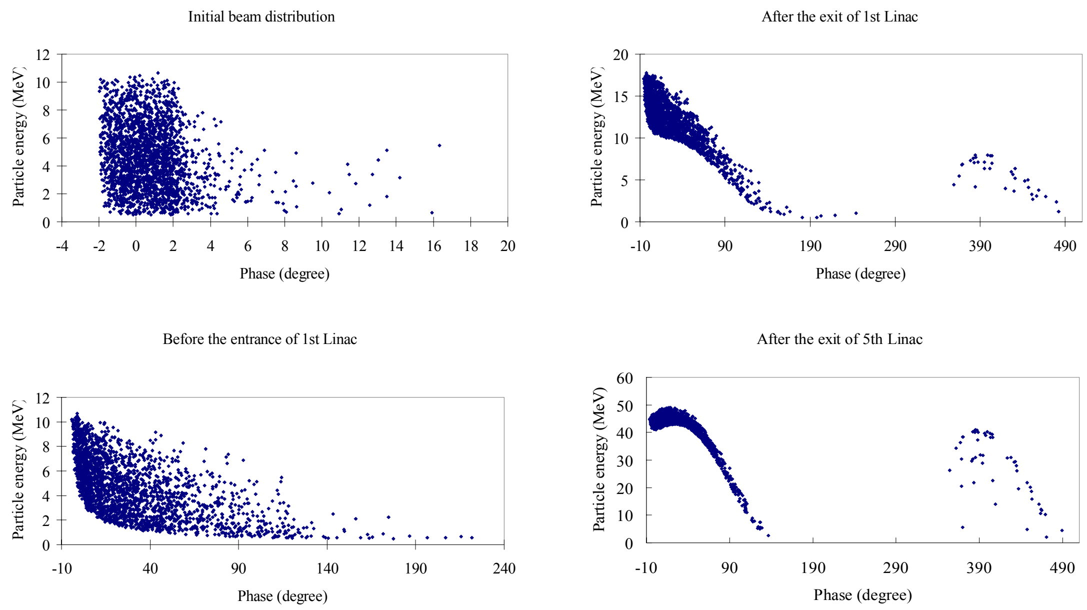


Fig. 22 Longitudinal particle phase distribution at different position.

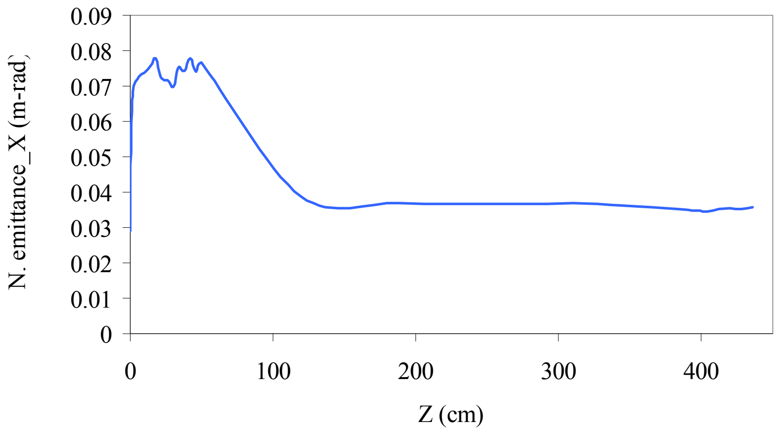


Fig. 23 Norm. horizontal emittance evolution (99% Particles).

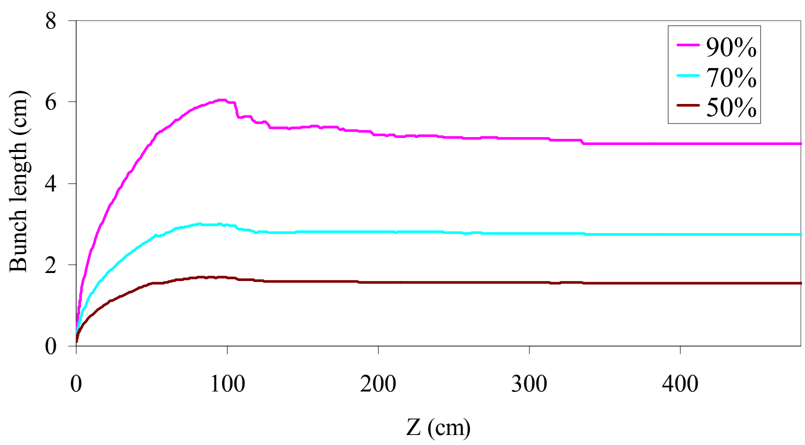


Fig. 24 Bunch length evolution.

The followed is a brief summary of simulation results:

- 78% particles stay at 1st micro-bunch after passing through 5 Linac,
- Captured efficiency is 25.4% with captured window =+/- 7.5º and εx+εy <=0.048m-rad,
- Captured efficiency is 35.8% with captured window =+/- 12º and εx+εy <=0.048m-rad.

4 Conclusion

A preliminary study of positron captured optics was done with the aid of PARMELA. The simulations from a random particle distribution in six-dimensional phase space indicate that beam loss and bunch length have a strong correlation with the initial beam divergence x', and finally this will result in deceased positron captured rate. The simulations also show that reducing the length of adiabatic matching device and increase field gradient of AMD will reduce bunch length and beam loss, and captured rate can be improved. However, this process is not unlimited. It is hard to build an AMD which has a short length, and can support a very high gradient in practice. There exists an optimized AMD design.

The simulations from real beam distribution produced by EGS4 show that 25.4% Captured efficiency can be obtained by assuming captured window =+/- 7.5º and εx+εy <=0.048m-rad, and 35.8% captured efficiency with captured window =+/- 12º and εx+εy <=0.048m-rad.

References

[1] V. E. Balakin, A. A. Mikhailichenko, The conversion system for obtaining high polarized electrons and positrons. Preprint INP 79-85, 1979.

[2] K. Flottmann, Investigations toward the development of polarized and unpolarized high intensity positron sources for linear colliders. DESY 93-161, 1993.

[3] V. V. Balandin, et al., Conceptual Design of a Positron Pre-Accelerator for the TESLA Linear Collider, Moscow-Hamburg, 1999.