LABORATOIRE DE L'ACCELERATEUR LINEAIRE, IN2P3-CNRS

Simulation of positron production for SuperB collider

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Abstract

The study of the positron production using a conventional scheme is presented here. Properties of the positrons at the exit of the material target and the capture section have been studied.

The impact on the material choice and the type of incident particles had been considered. Comparison between the positron production efficiencies of incident electron and photon had been done.

The capture section based on the adiabatic matching device had been introduced, and then its benefits to the positron beam had been studied.

The LAL

The Laboratory of the Linear Accelerator (LAL) is under the joint supervision of the Université Paris-Sud XI and the Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) of the CNRS **(UMR8607)**.

The research activity of the LAL is centered on particles physics, supplemented by a strong component in cosmology and astrophysics. The laboratory ensures its mission of knowledge transmission by teaching and communication activities. To carry out their experiments, the physicists rest on the various engineering and administrative services.

Two statutory authorities govern the laboratory:

- **The Laboratory Council :**

It has an advisory role and gives an opinion on all the relative questions with the scientific policy, the stock management, the organization and the operation of the Unit. It is chaired by the Director of the laboratory.

- **The Scientific Council:**

He has an advisory role and gives an opinion on all the relative questions with the programs and the coordination of the scientific research. He is requested for all new experiment. He is chaired by the Director of the Laboratory.

Introduction

The SuperB collider is a high-luminosity electron-positron accelerator that will be dedicated to elucidating new physics through precision studies of rare or suppressed decays. The title SuperB refers to the fact that the collider is expected to produce very large quantities of B mesons.

The SuperB is intended to give further information about any new physics expected to be found by the Large Hadron Collider at CERN.

The injection system for SuperB must provide electrons and positrons with an injection rate of about 10^{12} particles per second in order to compensate for beam losses due to the short beam lifetimes. This requirement is particularly demanding for the positron source **[1]**.

For the SuperB collider the conventional source is considered as the base line for positron production. It requires a high energy and intense electron beam impinging on a converter target. Then the photon produced from the Bremstrahlung process is converted into an e-e+ pair inside the target itself.

At the exit of the target the positrons produced are captured, collected and accelerated before being injected into the damping ring where their transverse size is reduced. Where the positrons are accelerated up to the main ring, where the collision with the electron bunch will occur.

In the section 2, an introduction of the physical processes occurring in an amorphous target with a high energy electron impinging the target converter will presented. Concepts such as energy losses, radiation length and critical energy are introduced. In the section 3 the simulation used for positron production simulation is briefly presented.

The last part of this work is devoted to the results concerning the positron production with a target material and also when the target is associated with an optical matching device and the influence of this capture section is studied.

Positron production processes

There are two different processes that could be used for positron production the β+ decay and the e-e+ pair creation:

1) The radioactive β+: consists into the conversion of a proton into a neutron inside a nucleus. It results a release of a positron and a neutrino. The produced positrons have a large energy distribution and are emitted over 4π. It is one the reason why it is difficult to use this process for a collider where it is necessary to have an intense narrow energy and angular divergence beam.
2) The e-e+ pair production consists on a high energy electron impinging on a material target. The energy loss by Bremstrahlung process is used to create an e-e+ pair. The positrons should be collected after the target. The advantage of the pair production process is that positrons produced are collimated and have a better distribution.

A. Interaction of an electron with a target material

When a high energy electron crosses a medium (material target) it results a cascade of electromagnetic processes (cascade shower) which lead to the production of positrons (Figure:1). The electron impinging the target material can lose its energy by Bremstrahlung radiation, collisions with nucleus and/or with the electrons of the medium. The collisions with electron are responsible of the excitation or ionization of atoms.

One can note that the energy dissipated by the collisions is responsible for the target thermal heating. The photons which are emitted by the Bremstrahlung process can produce positron via e-e+ pair creation (If its energy is above **2x me c^2** where **me** is the electron mass).

The energy lost by Bremstrahlung radiation is distributed among the secondary photons. The created photons interacting with the nucleus and in a weaker manner with the peripheral electrons, undergo materialization with subsequent pair creation. The electron pairs radiate photons and can be transformed into other pairs. The energy of the created electrons is decreasing at each step. Such a process is called cascade shower (Figure: 1).

*Electromagnetic radiation produced by the deceleration of a charged particle when deflected by another charged particle, typically an electron by an atomic nucleus.

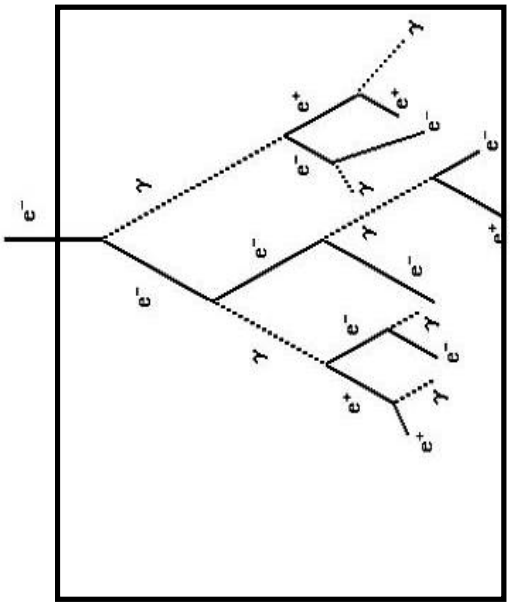

Figure 1: cascade shower through material target

B. Energy losses by ionization and Bremstrahlung

An electron loses energy by Bremstrahlung at a rate nearly proportional to its energy, while the ionization loss rate varies only logarithmically with electron energy.

For high energy electrons (> 10MeV for Tungsten, depending on the material) predominantly lose energy in matter by Bremsstrahlung and high photons by e-e+ pair production. The characteristic amount of matter traversed for these related interactions is called the radiation length X0, usually measured in ($g \cdot cm^{-2}$).

It is the mean distance over which a high-energy electron loses all but $\frac{1}{e}$ of its energy by Bremstrahlung. It is also the appropriate scale length for describing high-energy electromagnetic cascades.

The critical energy Ec is sometimes defined as the energy at which the two loss rates are equal. Among alternate definitions is that of Rossi **[4]**, who defines the critical energy as the energy which the ionization loss per radiation length (introduced later) is equal to the electron energy. Equivalently, it is the same as the first definition with the approximation:

$$\frac{dE}{dx} \sim \frac{E}{X0} \; .$$

C. Positron yield

The positron yield is defined by the ratio of the number of positron divided by the number of incident particles (e- or photon) which impinges the target.

This positron yield is highly depending on the impinging particle energy and the target material. It is preferable to use high energy particles, and a material with a high atomic number such as the Tungsten (Z=74).

For positron production process a target with many radiation lengths is required, to allow a full development of cascade shower phenomenon. Hence materials with short radiation length such as Titanium or Tungsten are more suitable.

In order to calculate the radiation length there are several formulas:

Formula by Y.S Tsai **[2]**:

$$\mathbf{\frac{1}{X0} = 4\alpha r_e^{\,2}\, \frac{NA}{A}\, \{Z^2\, [\, L_{rad} - f(Z) + Z\, L'_{rad}\, \}}$$

For :

$\mathbf{A}$= 1 g.mol^{-1}

$\mathbf{4\alpha r_e^{\,2}\, \frac{NA}{A}}$ = (716,408 g.cm^{-2})$^{-1}$

$\mathbf{L_{rad}}$ and $\mathbf{L'_{rad}}$ are given by tables

Element	**Z**	$\mathbf{L_{rad}}$	$\mathbf{L'_{rad}}$
H	1	5.31	6.144
He	2	4.79	5.621
Li	3	4.74	5.805
Be	4	4.71	5.924
Others	>4	Ln(184.15 $Z^{-1/3}$)	Ln(1194 $Z^{-2/3}$)

Table 1:Lrad for different target materials

Dahl provides a compact fit to the data **[2]**:

$$X_0 = \frac{716.4\ A}{Z\,(Z+1)\ln(\frac{287}{\sqrt{Z}})}$$. Where "A" is the nucleon number and "Z" the atomic number.

Results using this formula agree with Tsai's values to better than 2.5% for all elements except helium, where the results are about 5% lower **[2].**

The unit of X0 given by Dahl formula is **g.cm^{-2}** , in order to have a X_0 in conventional unit , it is necessary to apply this formula:

$$X_0\,(\mathrm{cm}) = \frac{X0\ (\mathrm{g.cm}-2\ )}{\rho(g.cm-3)}$$.

Where ρ is the density of the considered material, this value can be calculated or determined with different tables.

Material	Z	A	X_0 (g.cm^{-2})	ρ (g.cm^{-3})	X_0 (cm)
W	74	183,84	6,77	19,3	0,35
Ti	22	47,867	16,47	4,54	3,63
Li	3	6,941	81,09	0.543	149,33

Table 2: Radiation Length for different target materials

For electrons at lower energies (≤ 10MeV) the energy loss by ionization is predominant.

D. High atomic number target material , relevance for pair production

For pair production the maximum of the positron yield is obtained at a certain thickness so called optimum thickness which can be calculated by **[4]**:

$\mathbf{T_{max} = 1.01\ (\ln\ (\frac{E0}{Ec})\ -1)}$, for e- incident particle and expressed in number of radiation length (X0).

Where E0 is the incident particle energy and Ec is the critical energy as defined by Rossi **[4],**

and:

$$\mathbf{E_c} = \frac{610\ MeV}{Z+1.24}$$, for solids and liquids.

$$E_c = \frac{710\ MeV}{Z+0.92}$$, for gases.

Therefore the optimum thickness depends on the atomic number Z.

When the target material has a high Z, the critical energy is decreasing and the optimal thickness increasing. Moreover the optimal thickness is increasing with the energy of the electron (Figure: 2).

Since for the Tungsten $T_{max} = T_{optimal}/X0$.

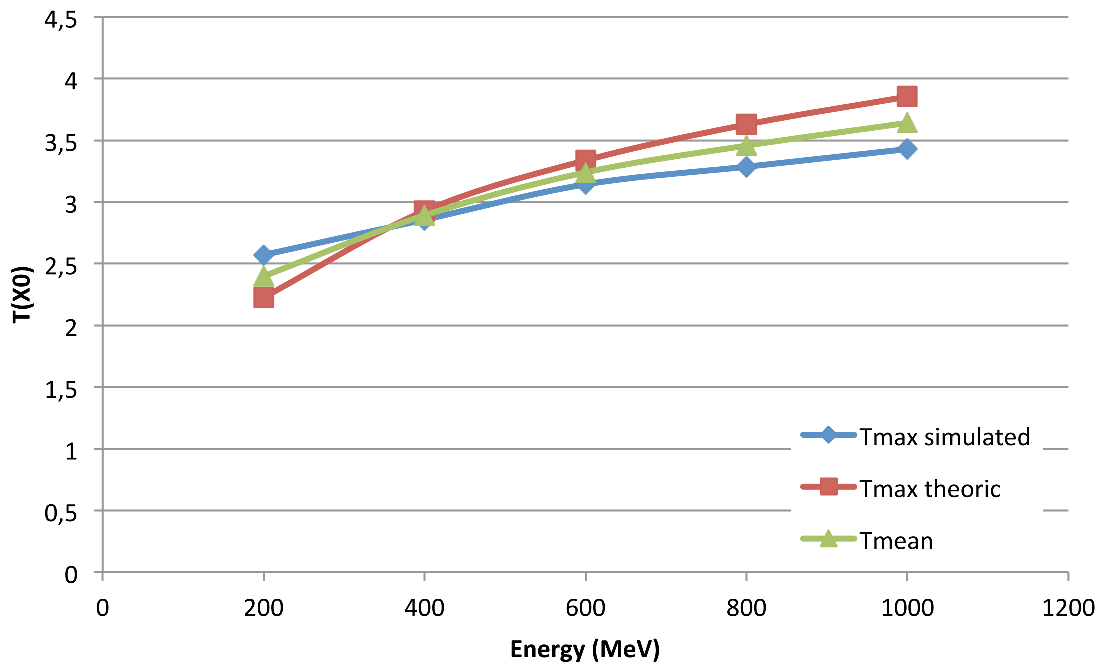

Figure 2: optimal thickness versus electron energy

A comparison between the values of optimal thickness simulated and calculated, it appears that there a little between these values estimated to a maximum of 11 % (Figure: 2).

Simulation

A. GEANT 4

GEANT4 (for GEometry ANd Tracking) is a platform for "the simulation of the passage of particles through matter," using Monte Carlo methods. It is the successor of the GEANT series of software toolkits developed by CERN, and the first to use Object oriented programming (in C++) **[3]**.

B. Simulations

In order to make the systematic studies a script has been made. In this scripts different properties of the simulations can be modified, beam settings (Annex: 1):

- Beam settings:

- Particle type: electron or photon.

- Incident energy beam values.

- Beam dimensions (RMS etc..).

- Target settings:

Material settings can be chosen (Lithium, Tungsten, Cupper...).

Target dimensions (Thickness, Radius…).

The program delivers an output file with all the statistics concerning the positrons, the electron and the photon yield. Information concerning energy deposition inside the target is also given.

But also a file allowing to know the space parameters (x, y, px, py, pz) and also the energy distribution at the exit of the target material or at the exit of the OMD (optical matching device).

C. Implementing a bash loop

The purpose of this work is to implement a bash loop in order to simplify the process of simulation. In fact without a bash loop we can only do one simulation at the same time and then operate the results.

This solution allows the user to collect easily all the needed information concerning:

- ✓ The Yield: positron, electron, photon
- ✓ The value of deposited energy
- ✓ Etc…

(Details in Annex: 2)

Results

A. The target

In order to study the positron properties at the converter target, 10^4 electrons or photons at 1GeV energy are used to impinge on a tungsten target (ρ= 19.3 g.cm^{-3}). There is no divergence of the incident electron beam considered.

The beam spot size is a Gaussian with 2.5 mm RMS radius. The target is a cylinder of 2cm radius. The optimal thickness for this target is determined by several simulations at different thickness values.

B. Optimal thickness

After having done several simulations with both incident electron and photon beams impinging on a material target and this with different energy values.

It was determined that, the optimal thickness is approximately equal to 14 mm for an electron beam.

Knowing that the Tungsten's radiation length is ~3.5mm, that means that the maximum yield is reached at 4 times the radiation length X0.

As for an incident photon beam, the optimal thickness is approximately equal to 12 mm (~3.4 times the tungsten's radiation length).

One can notice the difference between the two cases concerning the optimal thickness. This difference is due the fact that when impinging with a photon, the first step consisting in emitting a photon by Bremstrahlung process is skipped. Therefore the shower cascade has more space develop and the maximum position yield is reached at a lower thickness than for an incident electron.

C. Distribution of energy at the optimal thickness

The Figure 3 shows the distribution of the position energy at the exit of the tungsten target, the mean positron energy produced is approximately equal to 34.5 MeV, for an incident photon beam.

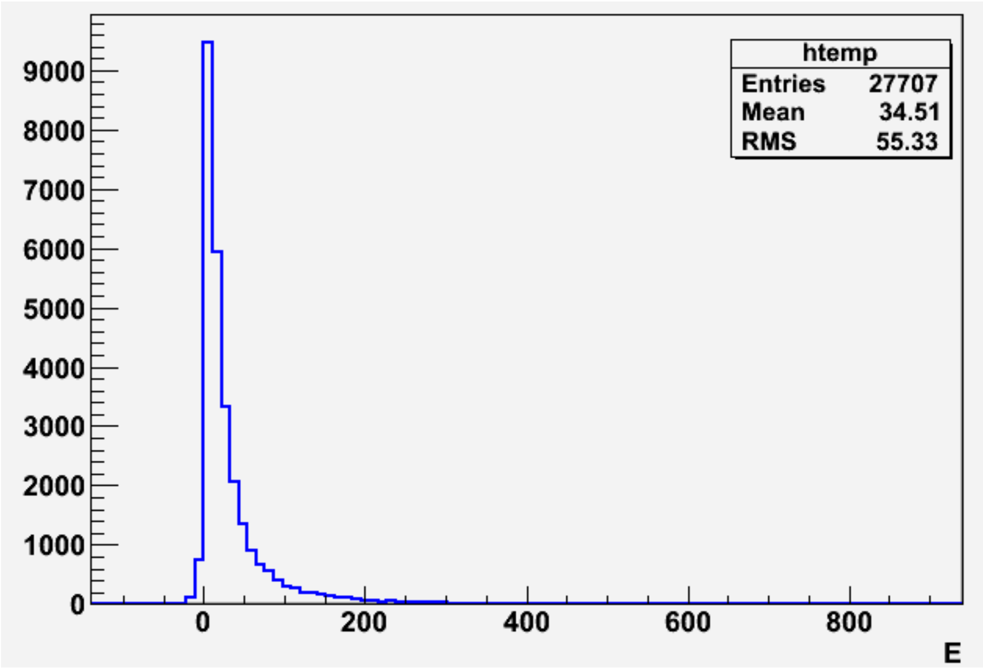

Figure 3: positron energy distribution for incident photon beam of 1GeV

The figure 4 shows the distribution of the position energy at the exit of the Tungsten target, the mean positron energy produced is 52.2 MeV, for an incident electron beam.

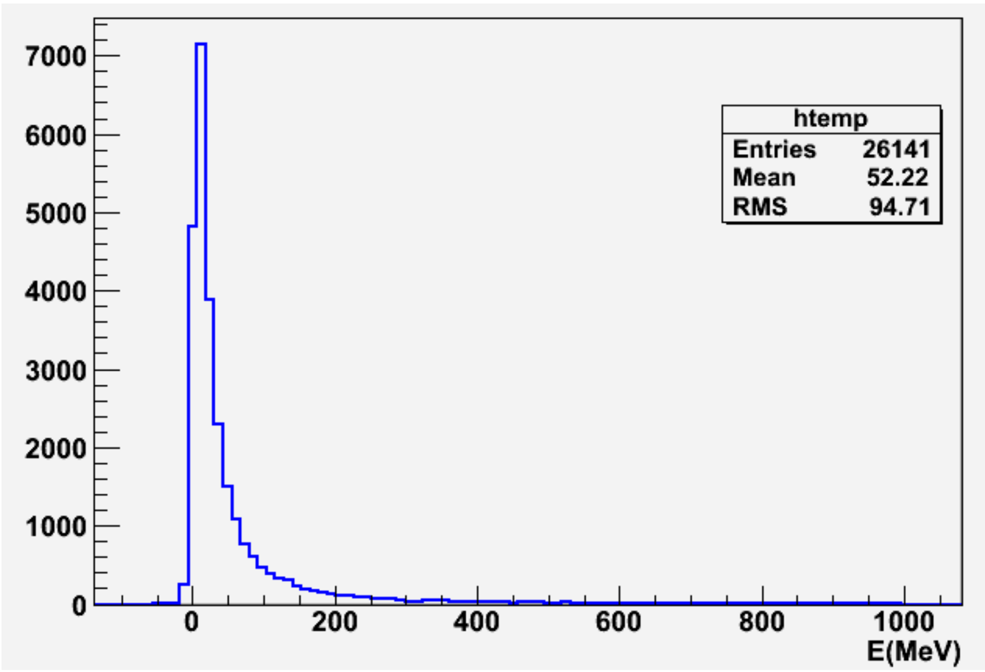

Figure 4 : positron energy distribution for incident electron beam of 1GeV

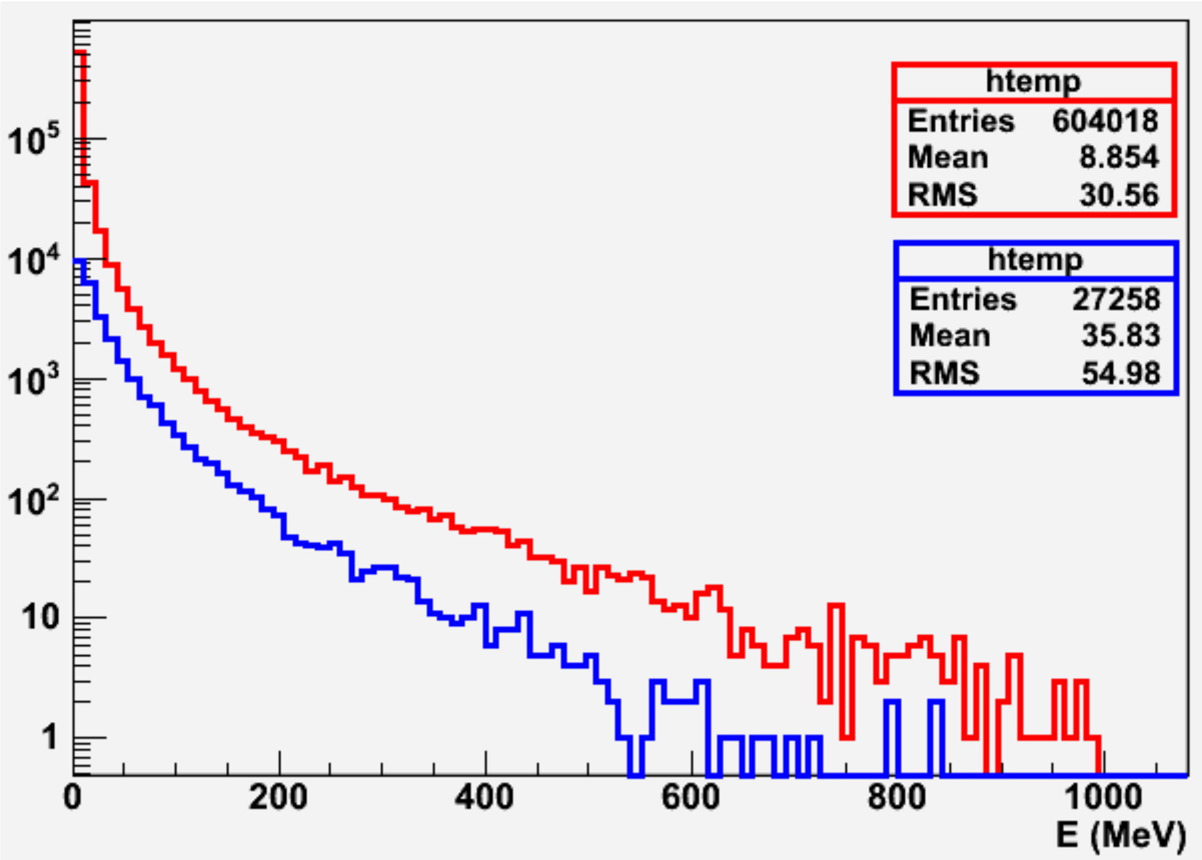

Figure 5 : comparison between positron (blue curve) and Bremstrahlung (red curve) energy distribution

The energy distribution for positron (blue curve) and photons (red curve) are very similar (figure 5). The differences coming from several factors like energy losses by ionization.

D. Angular positron distribution

The angular positron distribution is presented in (Figure: 6).The mean value is around 0.48 rad. This divergence is due to pair creation and the multiple scattering of the positron inside the target.

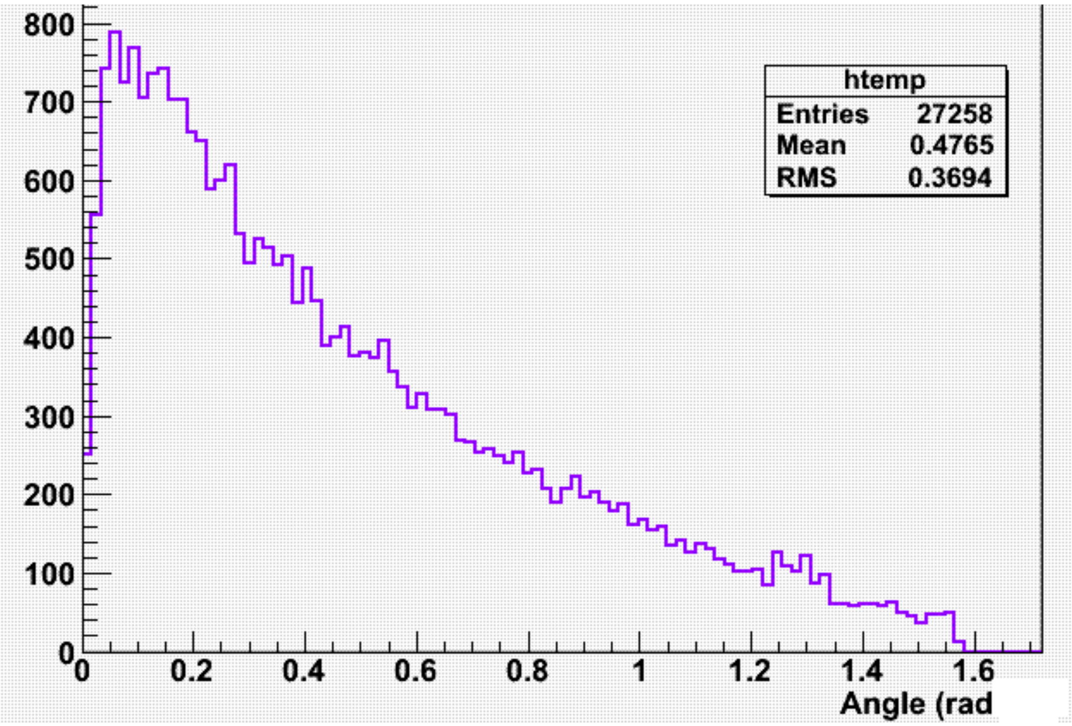

Figure 6: angular positron distribution

E. Relevance of the use of high energy incident particles

Two quantities are relevant to positron production in the longitudinal direction: The position of the shower maximum and the number of secondary particles.

For a primary electron, the number of secondary particles at shower maximum is given by **[4]**:

$$\Pi^{e-}{}_{max} = \frac{0.31}{\sqrt{\left[ln\left(\frac{E0}{Ec}\right) -0.18\right]}} \cdot \frac{E0}{Ec} \cdot$$

For a primary photon, the number of secondary particles at shower maximum given by **[4]**:

$$\Pi^{\gamma}{}_{max} = \frac{0.31}{\sqrt{\left[ln\left(\frac{E0}{Ec}\right) -0.18\right]}} \cdot \frac{E0}{Ec} \cdot$$

These formulas clearly show the importance of using high energy incident particles.

F. Comparison between electron and photon beam at 1GeV energy

Two simulations have been done, , but different incident particles:

- ✓ Incident electron
- ✓ Incident photon

The positron yields for an electron and a photon are quite similar (Figure: 7) in fact with a 1 GeV beam there is for:

- An incident electron: the positron yield is approximately equal to 2.7 and the optimal thickness is reached at T= 14 mm
- An incident photon : the positron yield is approximately equal 2.8 and the optimal thickness is reached at T= 12 mm

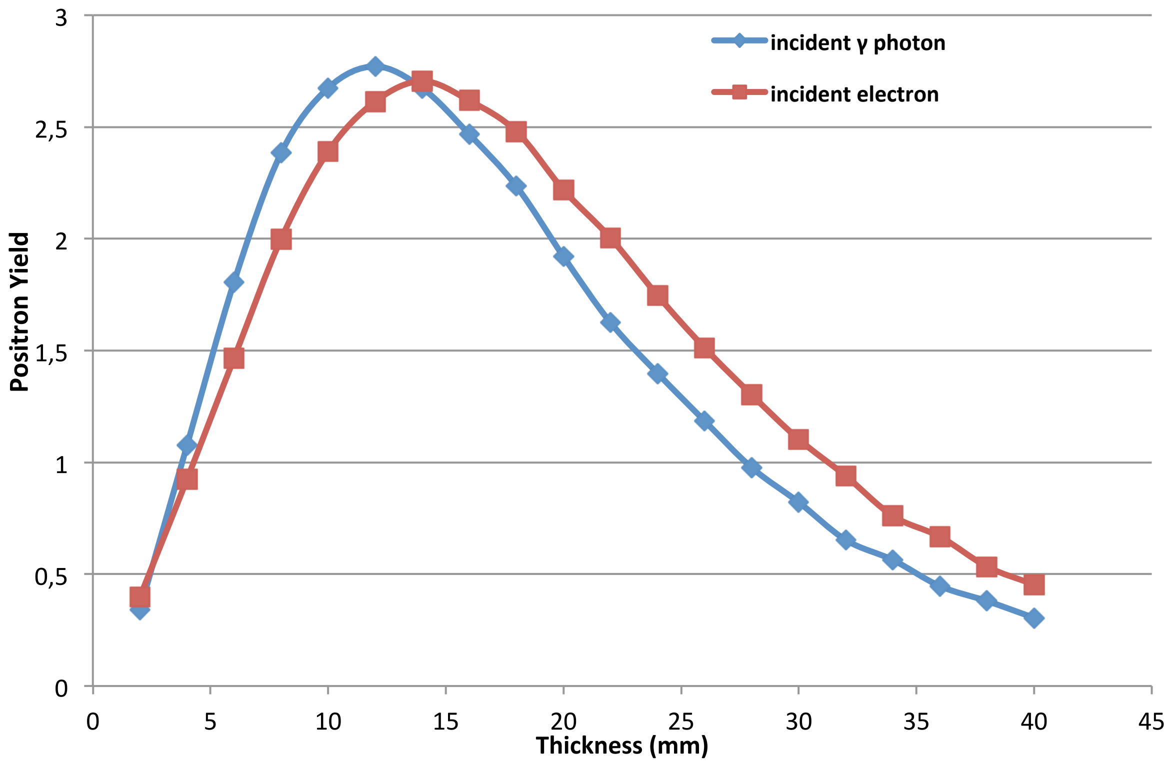

Figure 7: positron yield versus thickness for two different incident particles

As for the deposited energy there is no impact due to the type of incident particle used, since the maximum energy deposited is about 94 % (Figure: 8).

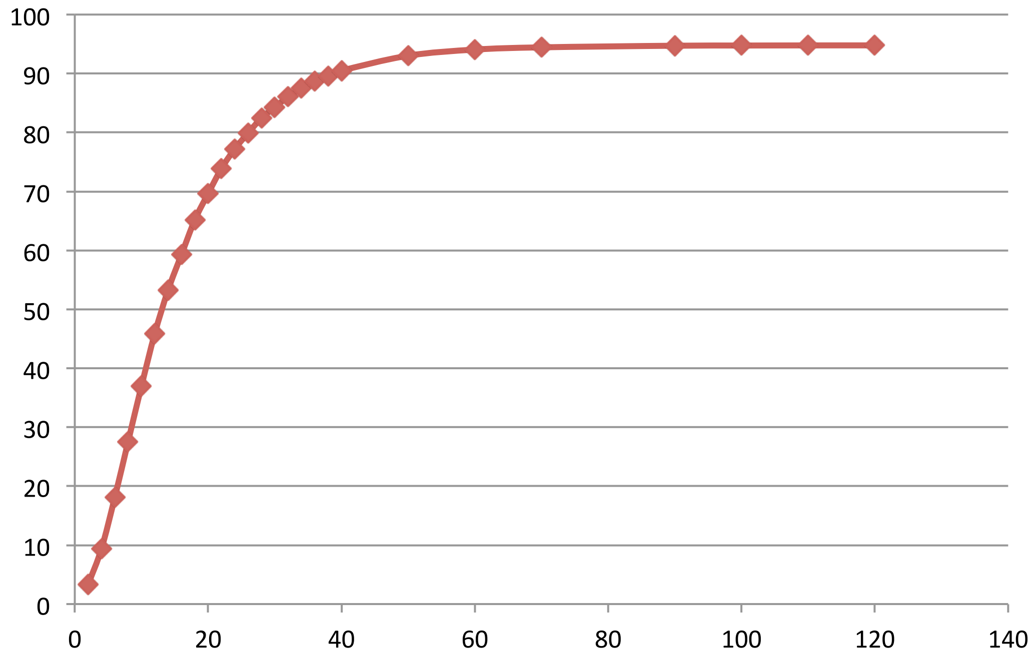

Figure 8: deposited energy versus thickness

The reason why there is not a 100% of energy deposited is due to the fact that there are some losses:

- Back scattering particle.
- Particles exiting from the target material without deposing all their energy.

Optical matching device (OMD)

The positron beam emittance coming out from the converter has large angles. In order to fit the accelerator acceptance, it is needed to transform it into small angles. The choice of the matching device is therefore dependent on two kinds of matching devices are now mainly used on positron accelerators:

- Narrow-band systems such as the quarter-wave transformer (QWT)
- Large-band systems such as the adiabatic device (AMD : subject of this section)

✓ **AMD (adiabatic matching device)**

The AMD uses a slowly varying magnetic field followed by a long solenoidal magnetic field extending over some accelerating sections. Between the maximum (B_0) and the minimum (Bs) , the field tapers adiabatically (like shown in Figure: 9).

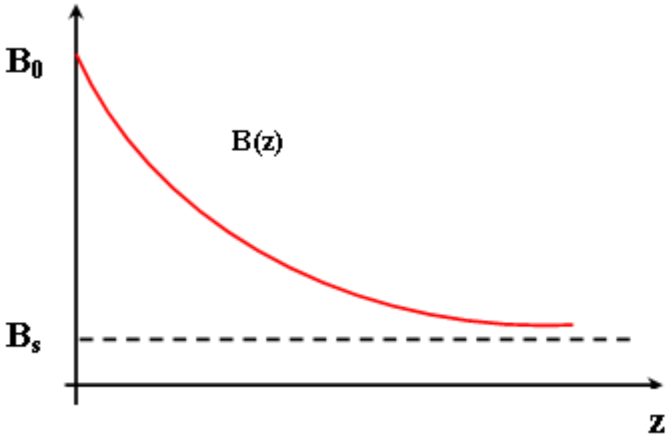

Figure 9: magnetic field profile

The longitudinal magnetic field law is represented by:

$$\mathbf{B_z = \frac{B0}{1+\alpha z}}$$

where B_0 is the maximum field

α (in m^{-1}) in such :

$$\boldsymbol{\alpha = \frac{\varepsilon B0}{P0}}$$

where P_0 a "central" momentum value

and ε smallness parameter :

$$\boldsymbol{\varepsilon = \frac{P}{eB^2} * \frac{dB}{dz}}$$

✓ Impact of AMD

To determine the impact of the AMD on the positron divergence, it is placed just after the target (distance between target and AMD equal to 0 shown in figure 10). The AMD has a radius of 2cm and a length equal to 20 cm, his initial magnetic field is quite high B0= 6T.

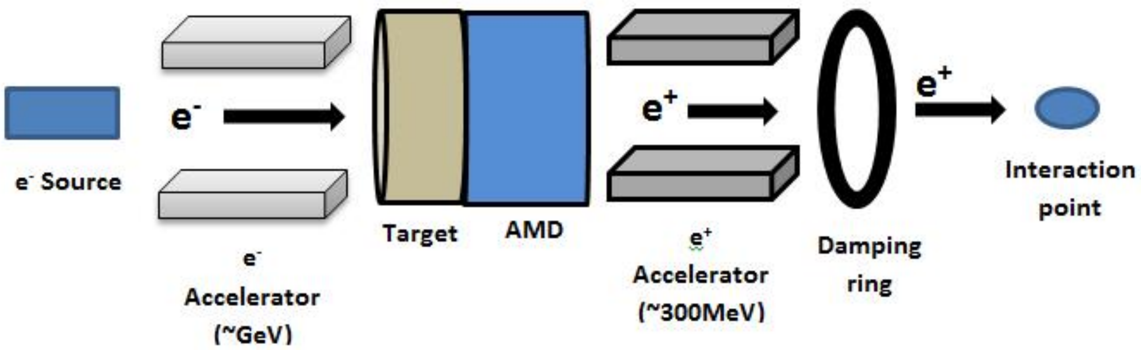

Figure 10:schematic sketch of conventional design with associated capture and acceleration section for SuperB collider

The field is decreased down to B0=0.5T over 20 cm length. At the exit of the adiabatic matching device the lateral dimensions of the positron beam are increasing while the transverse momentum is decreasing (Figures: 11 and 12).

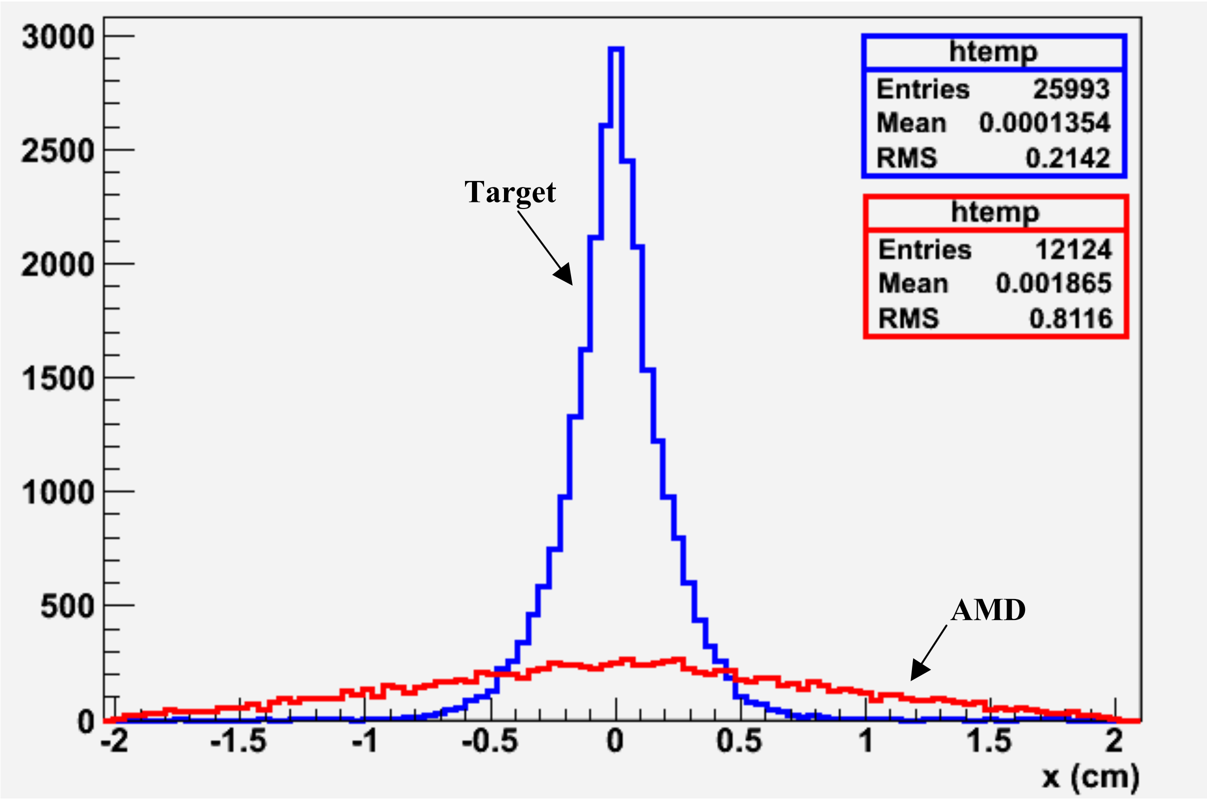

Figure 11: x distribution at the exit of the target in blue and at the exit of the AMD in red

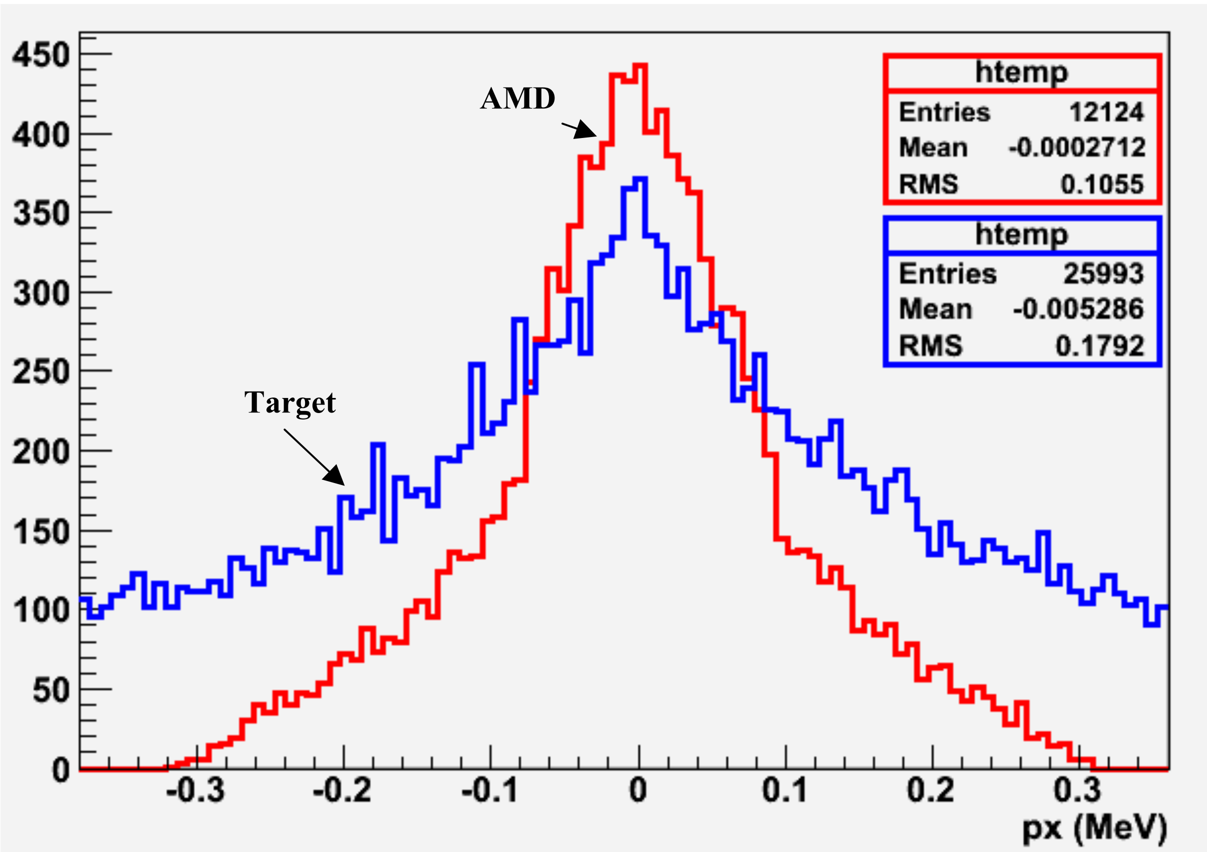

Figure 12: px distribution at the exit of the target in blue and at the exit of the AMD in red

This figure below (Figure: 13) illustrate the phenomenon described earlier, there a real impact of the AMD concerning the lateral dimension of the positron beam and his transverse momentum px.

Indeed the lateral dimension of has increased from 5 to 20 mm and his momentum px has decreased from 30 MeV to 5 MeV.

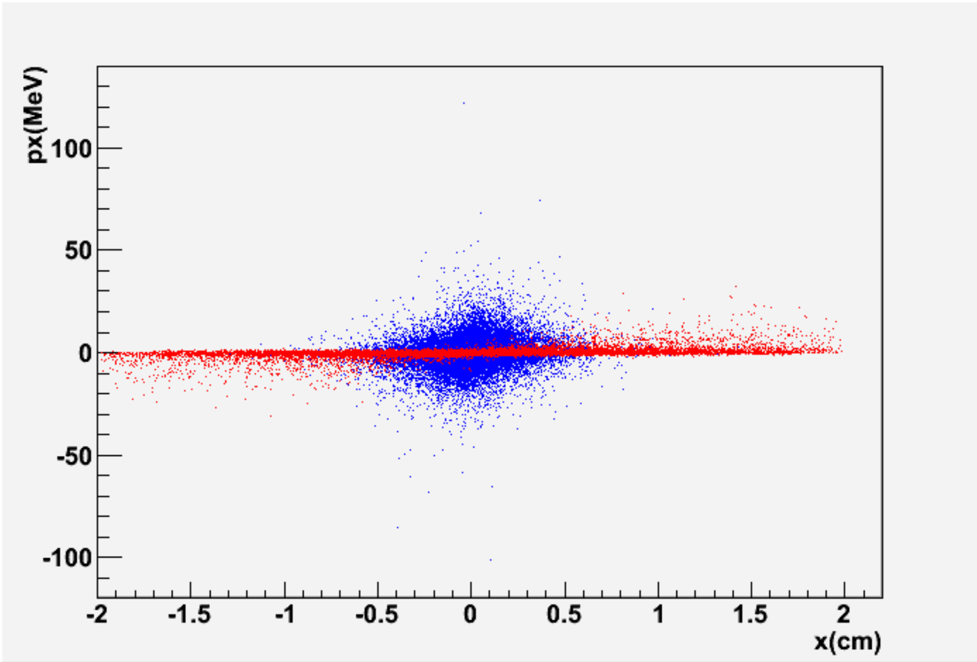

Figure 13 : Emittance of positron beam at the exit of the target (in blue) and at the exit of the AMD (in red)

Conclusion

For SuperB collider conventional scheme is considered, with amorphous Tungsten converter of multi-radiation length thickness in order to maximize the positron Yield.

Nevertheless, the atomic number of the target material (Z) and the incident particles energy have actually an impact on this positron yield.

The positron beam obtained is divergent, with large angles (transverse momentum important) A solution is to use a optical matching device, in order to decrease it.

The positron yield obtained with a Tungsten target associated with an adiabatic matching device will have small divergence.

Key words

Emittance: a property of a charged particle beam in a particle accelerator. It is a measure for the average spread of particle coordinates in position-and-momentum

Bash: Bash is the shell, or command language interpreter, for the GNU operating system. The name is an acronym for the ‘`Bourne-Again SHell`’

C++: one of the most popular programming languages and is implemented on a wide variety of hardware and operating system platforms. As an efficient compiler to native code

GNU: Unix-like computer operating system developed by the GNU Project, ultimately aiming to be a "complete Unix-compatible software system" Composed of free software. Development of GNU was initiated by Richard Stallman in 1983

Toolkit: piece of software which is usually built on the top of an operating system, windowing system, or window manager and provides programs with an application programming interface (API)

Bash loop: A loop is a block of code that iterates (repeats) a list of commands as long as the loop control condition is true.

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