EVOLUTION OF PRESSURE IN POSITRON SOURCE FOR FUTURE LINEAR (e^+ - e^-) COLLIDER*

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Abstract

Energy deposition in the conversion targets of positron sources for future linear colliders induces an immense thermal load and creates pressure waves in the material. This stress could substantially reduce the lifetime of the target or other target materials impinged by the incident intense photon or electron beam. We have studied the evolution of pressure waves in target materials based on the parameter assumptions for the International Linear Collider (ILC) baseline source. The fluid model is employed by taking into account the target and the incident photon beam parameters. Initial results of these new simulations are presented and compared with earlier studies. Prospects for further studies are outlined.

INTRODUCTION

The International Linear Collider (ILC) is designed to explore the territory of physics up to the TeV Scale with an unprecedented precision. It expands the discoveries made by the Large Hadron Collider (LHC) and will reveal the new laws of nature at the Terascale [1].

Achieving a high luminosity is mandatory to fulfill the physics goals and for the ILC a luminosity of 2×10^{34} cm^{-2}s^{-1} is foreseen. In the baseline design of the ILC an undulator-based positron source is chosen: the relativistic electron beam from the electron main linac will pass through a long helical undulator to generate a multi-MeV (typically of order 10 MeV) photon beam which then strikes a thin metal (0.4 of radiation length, X_0) target to generate electron-positron pair that can escape from the target material and be captured and accelerated.

The choice of the target material is one of the main challenges for the positron source of any e^+e^- linear collider [2]. In case of the ILC, the positron source has to produce the required positron bunches, namely 1312 bunches per pulse [3]. The target material has to stand the huge energy deposition, radiation damages and mechanical fatigue [4] which are caused by the bombardment of the target with an energetic photon beam at a small spot size of about 1.7mm [5].

ILC parameters were compared to those of past accelerators [6]. In particular the Stanford Linear Collider (SLC) positron source comes closest to ILC requirement in terms of yield and luminosity. However, the ILC source is still a factor of 60 greater in flux and a factor of 8 in energy deposition into the target [6]. The target of the SLC positron source was decommissioned after $\sim$ 5 years in operation and its damage was attributed to a thermal fatigue due to the cyclic thermal stress imposed by the nonuniform shower energy deposition of the incident 33 GeV electron beam [6, 7]. Although positron production at SLC was generated via conventional source, it is worth investigating what is expected for the ILC target material in the positron source.

The energy deposition in target materials leads to a rise of pressure in the region where such a deposition takes place, thus inciting compressive wave propagation (compression) into the region of energy deposition from its boundary to the centre [2]. The pressure in the decompressive waves (expansion) can fall below zero and if the negative pressure exceeds the limit of material tensile strength for expansion, destruction can occur [2]. Previous simulation work indicates that the titanium solid target will not even survive a single bunch bombardment of photon beam [8].

In this study, we extend [8, 9, 10] and analyze the features of destruction by considering the material behaviour from a hydrodynamical point of view. The following sections present the analytical model, the numerical analysis of the model, the discussion of the results and finally, the summary and outlook.

THE MODEL

As a basis for our study we consider a hydrodynamical system of equations for the target material. We assume a Gaussian distribution for spatial distribution for the deposited energy in the target caused by the photon beam. The target is regarded to be practically immobile; the target immobility implies that no eddy currents occur which are typically induced by the rotating target in a magnetic field of the adjacent captive optics [11]. so far, we only considered a single bunch of the photon beam in the model and assumed that no (or negligible) radiation effects happen.

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The Fluid Equations for Target Material

We apply mass conservation,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \tag{1}$$

and momentum conservation,

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla P, \tag{2}$$

where ρ: density; u: velocity; P: Pressure.

For the equation of state, the internal energy and pressure of a solid can be written as:

$$Q = Q_c + Q_T \tag{3}$$

$$P = P_c + P_T \tag{4}$$

where Q_c and P_c are the elastic component which are also called ”cold” energy and pressure respectively. In this model both terms are neglected. The other parts, Q_T and P_T are the thermal component relating to the heating of the target material by the photon beam. Hence Eq. 3 and Eq. 4 can be reduced to: $Q = Q_T$ and $P = P_T$ respectively. The Grüneisen model describes the relationship between Q_T and P_T, which takes into the account the lattice oscillations. One obtains for the solid state of matter [12]:

$$P = \frac{\Gamma}{V} Q, \tag{5}$$

where V= Volume = $\pi\sigma_r^2 l_T$, σ_r: bunch size in (r-) radial direction, l_T= target thickness; Q: internal energy caused by thermal motion of atoms contributed by energy deposition on the target by photon beam and Γ: the Grüneisen coefficient.

Energy deposited on target by photon beam: A single bunch energy deposition is described by Gaussian distribution (see [9])

$$\dot{Q} = \frac{2cQ_{bunch}}{\sqrt{\pi}\sigma_z} \cdot \frac{z}{l_T} \exp\left(-\frac{(z-ct)^2}{{\sigma_z}^2}\right) \exp\left(-\frac{r^2}{{\sigma_r}^2}\right), \tag{6}$$

where Q_{bunch}= energy deposited per bunch, σ_r: transverse size of gamma-beam at the target and σ_z: bunch size in (z-) longitudinal direction.

Linear Pressure Waves: Small perturbation near Equilibrium

In order to investigate the effect of the energy deposited on the target by a single bunch photon beam, we first linearize Eqn. 1, 2 and 5, by putting $\rho = \rho_0 + \epsilon\rho_1$, $u = u_0 + \epsilon u_1$, $Q = Q_0 + \epsilon Q_1$, $P = P_0 + \epsilon P_1$ and applying the equilibrium conditions: $u_0 = \frac{\partial \rho_0}{\partial x} = \frac{\partial \rho_0}{\partial t} = \frac{\partial P_0}{\partial t} = \frac{\partial Q_0}{\partial t} = 0$, where $\epsilon \ll 1$ and ρ_0, P_0, u_0, Q_0 and V_0 are equilibrium values. The linearized system leads to the linear pressure equation:

$$\ddot{P} - \nabla \cdot (c_s^2 \nabla P) = \frac{\Gamma}{V_0} \ddot{Q}. \tag{7}$$

NUMERICAL ANALYSIS OF PRESSURE WAVES EQUATION

In order to investigate the pressure wave in the target, the propagation described in Eq. 7 was numerically solved by using a commercial software called **FlexPDE** [13], which is a scripted finite element model builder and numerical solver for partial differential equations. The problem was described in 2-dimensional co-ordinates (z,r). The simulation was carried out for two different target materials, Titanium (Ti) and Tungsten (W). In order to avoid a discontinuity in the simulation, the Gaussian beam was shifted backward by $0.002m$ that is, $\sim 6.67ps$ (see Table 1 below for the material parameters).

Table 1: Target Material Parameters

Parameters	**Units**	**Ti**	**W**
Target Thickness	mm	14.62	1.408
Radius	mm	5	5
Grüneisen constant	-	1.211	1.647
Sound Speed	ms^{-1}	4140	5174
Density	Kgm^{-3}	4507	19250

For the photon beam the following parameters were used: beam length ($\sigma_z = 0.0003m$); beam radius ($\sigma_r = 0.002m$) and energy deposited per bunch ($Q_{bunch} = 0.4J$)

Result and Discussion

The numerically obtained pressure wave effect on the target is presented in Figs. 1 & 2 for a Titanium and in Figs. 3 & 4 for a Tungsten target. Figs. 1 & 3 show the pressure evolution in the target just immediately after the photon beam has left the target for both Titanium and Tungsten, respectively (the beam shift of $\sim 6.67ps$ was taken into account). Only positive pressure which represents the compression of the target by the photon beam can be observed in both cases. This peak pressure is less than both material compression strengths. The peak pressure in Titanium is less than that of Tungsten. It can be inferred from the analysis that the major contribution is due to the target thickness although they are both $0.4X_0$ but the Titanium thickness is about a factor 10 bigger than the Tungsten counterpart.

In Figs. 2 & 4, the pressure evolution in the target (for Titanium and Tungsten respectively) is shown, when the photon beam has left the target already some time ago. In the case of Titanium the beam has left the target $\sim 0.94ns$ ago and for Tungsten, the beam has left $\sim 0.99ns$ ago. It was observed that the pressure continues to grow in time and in the case of Tungsten, the big negative pressure appears in the simulation when the photon beam has already left the target.

SUMMARY AND OUTLOOK

In this report of our work in progress, we simulated the pressure generated by energy deposition in positron targets at a future linear collider. The huge negative pressure shown in [8, 10] was confirmed, its magnitude depends strongly on the simulation parameters and is currently not yet fully understood.

Since the pressure propagation continues when the photon beam left the target, the results depend strongly on the time chosen to run the simulation. If this high negative pressure is real, already one single photon bunch (at 1ns) yields tensile stress at the end of the Tungsten target which the material can not cope with. For Titanium, both the compressive and expansive pressure are below the material tensile and compression strength. The cumulative effect of multiple bunches over a long run time will have great impact on the fatigue failure of the material.

So far, a Gaussian distribution was assumed for the energy deposition on the target, only one bunch and only linear wave effects have been included; a more detailed analysis is in progress. The improved model will include a realistic photon beam profile, possible non-linear wave effects, multi-bunch effects and rotation of the target.

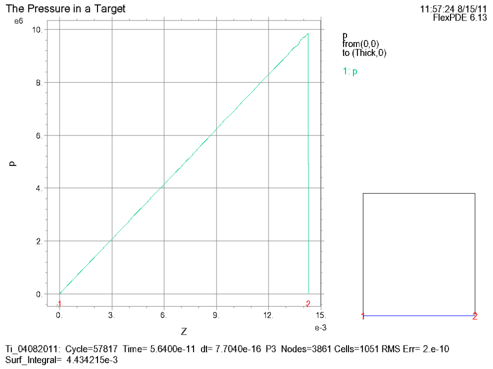

Figure 1: P (Pa) vs. z (m): Pressure evolution in titanium target immediately after photons has left the target.

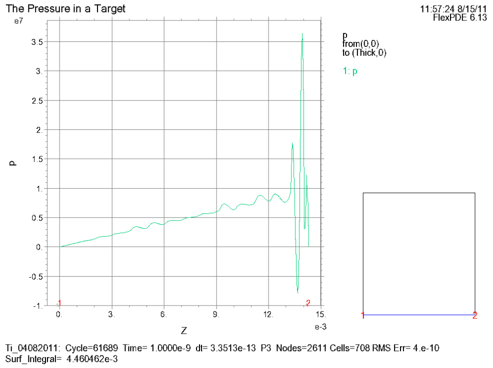

Figure 2: P (Pa) vs. z (m): Pressure evolution in Titanium target, when photons has already left target at 0.94 ns ago.

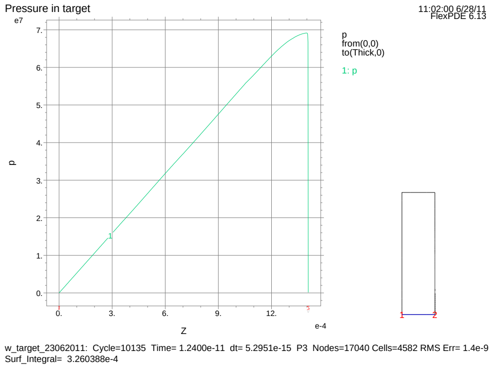

Figure 3: P (Pa) vs. z (m): Pressure evolution in Tungsten target immediately after photon has left the target.

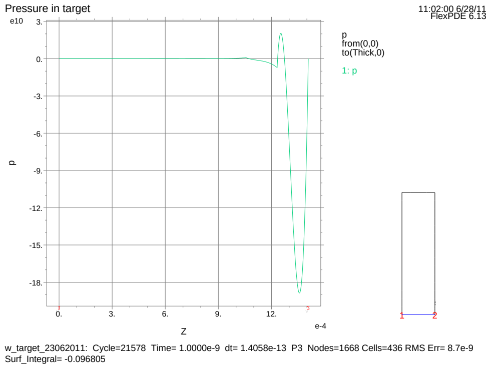

Figure 4: P(Pa) vs. z (m): Pressure evolution in Tungsten target, when photons has already left target at 0.99ns ago.

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