SIMULATION OF STRESS IN TARGET MATERIALS INCUDED BY INTENSE PHOTON AND ELECTRON BEAMS

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The ILC is a e+e- accelerator planned for future research in particle physics. The collision of point like particles has a huge advantage for precision measurements. However, the creation of a high energy positron beam is a challenge and technical effort is required for the development of accelerator components, e.g. the positron target and capture. Since the ILC positron beam is produced using a photon created in a helical undulator, the life time of the positron production target depends on the photon beam parameters. In particular, the heat load in the target must be kept within reasonable limits. In this work, the temperature and stress evolution as well as the induced deformation of a titanium target probe is simulated using ANSYS FEM simulation software. The heat load data created by the high-energy photon beam are simulated with the FLUKA Monte-Carlo Code.

1. Introduction

A high energy linear e^+e^- collider is recommended as one major next particle physics facility. It would complement the Large Hadron Collider at CERN

Precise measurement of the Higgs boson properties are important issues for the ILC project to understand the particles mass generation mechanism which strongly related to the coupling with the Higgs boson as in Standard Model.

Particles such as electron and positron do not have an internal structure. That's why physics phenomena can be studied at an e^+e^- collider with substantially higher precision than at the LHC. The ILC project is in the planning phase, a Technical design Report will be published by end of 2012.

At a first stage is is proposed to accelerate particles to 500 GeV (in center mass system). But in future is planned to increase energy up to 1 TeV. For the study of the Higgs boson a lower energy is required,

$$126\ \text{GeV}_{\text{Higgs boson}} + 92\text{GeV}_{\text{Z-boson}} = 218\ \text{GeV} < 500\ \text{GeV}.$$

1.1. *International Linear Collider (ILC)*

The ILC is designed with two accelerator structures for the e+ and e- with a total length of about 31 km as shown in fig1.

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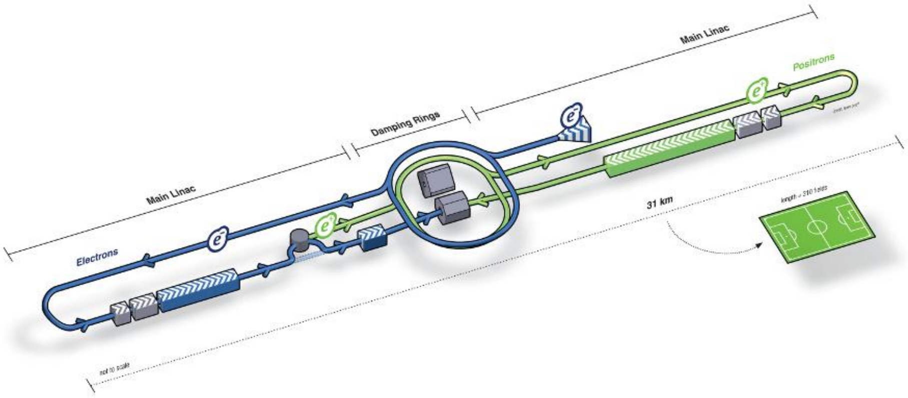

Fig.1 ILC layout with e$^-$ and e$^+$ accelerator structures and damping rings [3]. Two movable particle detectors are located at the IP.

The electron source provides polarized electrons up to 80% polarization. The electron source is based on a photocathode DC gun.

The positron production is based on a helical undulator: The high energy electrons pass a a helical undulator and emit a circularly polarized photon beam. The energy of the photons is in the range of 30 MeV, the beam spot size is σ ≈ 1 mm. By penetrating a Ti6Al4V target longitudinally polarized electron-positrons pairs are produced. The target thickness is $0.4X_0$=1.48 cm, where X_0 is the radiation length.

The positrons are captured with an optical matching device and a normal conducting L-band RF with solenoidal focusing. The setup is optimized to achieve a yield of 1.5 positrons per electron passing the undulator.

The produced electrons and the remaining photons are separated from the positrons and are dumped. The positrons are stored in a damping ring and ejected to the main linac and accelerated up to 250 GeV for the interaction.

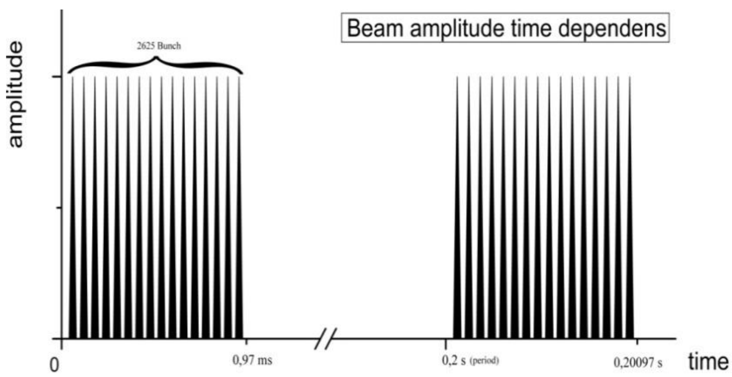

Fig.2 ILC time structure (high lumi option).

1.2. *Positron production target*

The ILC time structure is shown in Fig.3:

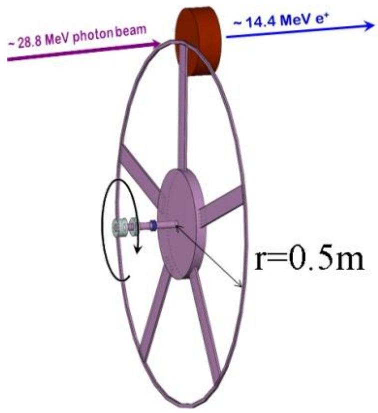

Fig.3 Positron production target. A rotating Ti wheel is used to distribute the beam heat loads over a larger volume.

In order to distribute the huge energy deposition over a larger volume, the target consists of a wheel rotating with velocity of 100 m/s at the periphery. This means that one bunch train (2625 bunches = 0.97 ms) occupies 97mm of target:

$$s = v \cdot t = 100 \frac{m}{s} \cdot 0.97\ ms = 0.097\ m = 97\ mm$$

if the photon beam size is 1mm.

2. Material science

2.1 The interaction of photons with matter

With the passage of γ-radiation through matter, there is a weakening of the intensity of the beam γ-ray, which is a result of their interaction with atoms and nuclei.

The largest contribution to the interaction of γ-rays with matter makes such phenomena as the photoelectric effect, Compton effect and pair production. The total effective cross section is the sum of the effective cross sections σ_{tot} of individual processes involved in the weakening of the primary stream

$$\sigma_{tot} = \sigma_{photoefect} + \sigma_{compton} + \sigma_{pair\ production}. \quad (1)$$

The effective cross section of each of the processes designed for a single atom of the absorber is a function of both energy gamma radiation and the atomic number Z of the absorber material [4].

$$\sigma_{photoefect} \sim \frac{Z^5}{E_\gamma^{\frac{7}{5}}} \quad (2)$$

$$\sigma_{compton} \sim \frac{Z}{E} \quad (3)$$

$$\sigma_{pair\ production} \sim Z^2 \ln(2E_\gamma) \quad (4)$$

The intensity I(x) of mono energetic gamma rays through matter decreases exponentially,

$I(x) = I(0)\, e^{-n\sigma x} = I(0)\, e^{-\tau x}$ (5)

where n is the number of absorbing atoms, σ is the total cross section and τ the linear absorption coefficient.

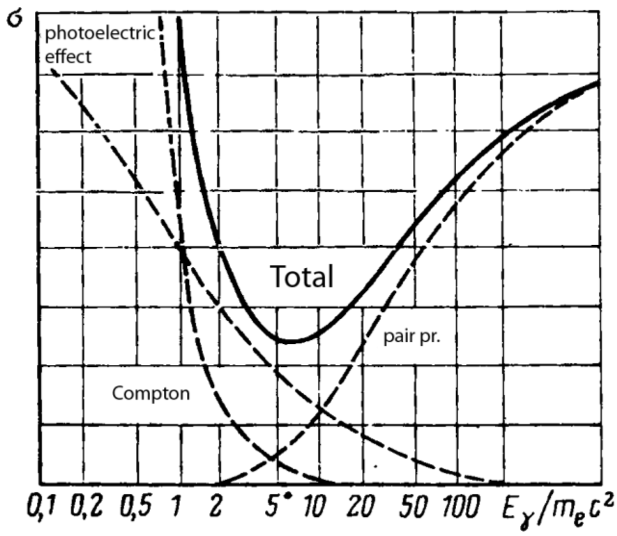

Fig.2 The individual contribution of interaction yields to a total cross section of γ-ray interaction with matter [4].

Each type of interaction contributes to the final cross section. At low energies dominates the process of photoelectric effect, at medium energies the Compton Effect dominates, and at high energies the pair production.

2.2 The interaction of electrons and positrons with matter

When electrons and positrons pass matter they interact with atoms and nuclei. For the energy range considered here, bremsstrahlungs and ionization processes are important. The bremsstrahlungs photons undergo pair production, so an electromagnetic shower develops. The radiation length, X_0, is related to the material properties and describes the shower parameters.

Due to the interaction of photons and electrons/positrons with matter energy is deposited in the material and results in a temperature increase. In production targets, the evaluation of this heat load is important since is determines the lifetime of the target.

The Bethe equation for ionization is given by [5]

$$\frac{dE}{dx} = 2\pi N_e \rho \cdot r_0^2 \cdot \frac{mc^2}{\beta^2}\ \ln \frac{E^2\ \ E+2mc^2}{2mc^2 I^2} + \frac{E^2\ \ 8-\ \ 2E+mc^2\ \ \cdot mc^2 \cdot ln2}{E+mc^2\ \ ^2} + 1 -\ \beta^2 - \ \delta \quad (6).$$

where E is the kinetic energy of the electron, r_0 classic electron radius, δ is correlating member, I the ionization potential, m the electron mass and N_e the concentration of electrons in matter.
The electron radiation loss is given by [5]

$$\frac{dE}{dx}_{\ rad} = \frac{E}{t_r} \quad (7)$$

where t_r is the radiation length.
Such processes as ionization and radiation induce heat loads in the material.

2.3 Stress and deformation

In a continuous body, a deformation field results from a stress field induced by applied forces or is due to changes in the temperature field inside the body. The relation between stresses and induced strains is expressed by constitutive equations (for example Hooke's law for linear elastic materials). Deformations which are recovered after the stress field has been removed are called elastic deformations. In this case, the continuum completely recovers its original configuration. On the other hand, irreversible deformations remain even after stresses have been removed. One type of irreversible deformation is plastic deformation, which occurs in material bodies after stresses have attained a certain threshold value known as the elastic limit or yield stress, and are the result of slip, or dislocation mechanisms at the atomic level.

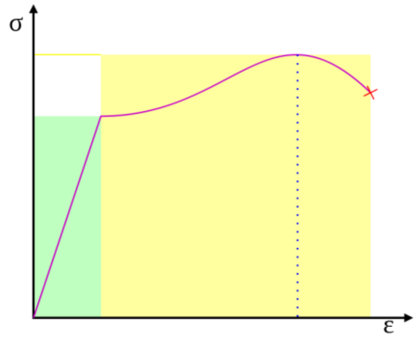

Fig.3 Graph of Hook`s law for stress (σ) and elongation (ϵ) [6].

In its simplest form the Hooke law a long thin rod the force is given by $F = -kx$ where F is the force, k is the stiffness constant of the material and x is elongation. The stress σ in the linear regime is

$$\sigma = E\frac{\Delta l}{l} = E\epsilon$$

and defined the force per unit cross section area of the body, $\epsilon = \frac{\Delta l}{l}$ the relative elongation and E is the Young's modulus.

The Hooke law for three-dimensional (complex) stress state in the case of an isotropic material can be written as a system of equations

$$\epsilon_x = \frac{1}{E}\ \sigma_x - \nu\ \sigma_y + \sigma_z$$
$$\epsilon_y = \frac{1}{E}\ \sigma_y - \nu\ \sigma_z + \sigma_x$$
$$\epsilon_z = \frac{1}{E}\ \sigma_z - \nu\ \sigma_x + \sigma_y$$

where ν is the Poisson's ratio and σ the strain tension compression.

3. Material stress simulations induced by photon beam heat loads

3.1 Ansys

The ANSYS simulation tool is a universal program system of finite-element method (FEM) analysis [1]. The program offers flexible solutions to enable the analysis of real world designs conditions on a desktop computer. Modeling and analyses are allowed avoiding costly and lengthy development cycles, such as "design - construction - testing".

The finite element method (FEM) is a numerical technique for finding approximate solutions to partial differential equations (PDE) and their systems, as well as integral equations. In simple terms, FEM is a method for dividing up a very complicated problem into small elements that can be solved in relation to each other. The solution approach is based on eliminating the spatial derivatives from the PDE.

The equation systems are linear if the underlying PDE is linear. Algebraic equation systems are solved using numerical linear algebra method. For solving ordinary differential equations usually is using standard techniques such as Euler's method or the Runge-Kutta method.

In general, the finite element method characterizes the area occupied by the body and divides it into finite elements. The grid can consist of triangles and rectangles in planar case, or tetrahedrons in the case of three-dimensional body. Within each element are setting the shape function, which allows determining the internal displacement based on element movements in the butt joint of pieces. Piecewise polynomial basis functions is common to use. As the unknown Ritz's coefficients is taken the nodal displacement. Minimizing the energy functional and taking the algebraic system of equations after this.

3.2 Geometry

We consider a rectangular form of the target which is a piece of the whole wheel. At first, we set up the geometry of our target. We create a rectangle with the desired thickness. To simulate the heater which describes the energy deposition in the target, the central region is singled out as a separate body. This is done by cutting the cylinder from the main body and replace it by a separate cylinder body.

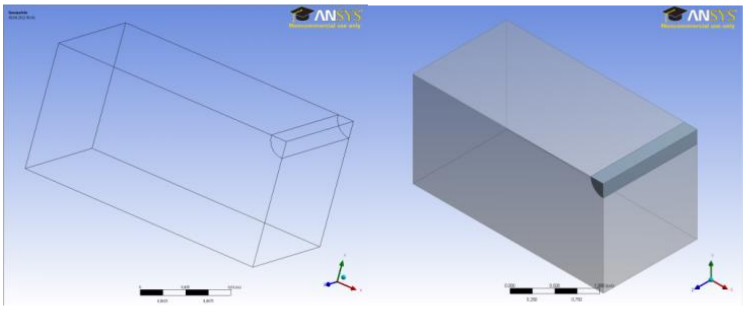

Fig.4 Rectangular geometry of the used test target. Here only two octants are shown because the figure is symmetric with respect to axis OX and OY.

The first step is the mesh generation for Finite Element Method calculations shown in Fig.5. For a better quality of the mesh every part can be divided into the required number of elements. Usually, the form of elements are default generated by the ANSYS mesh routine.

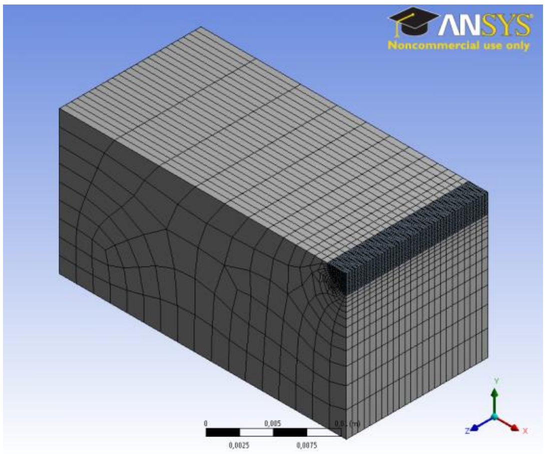

Fig.5 Generated mash of the rectangular target.

3.3 Temperature load induced by photon beam

A proper model of the target wheel is just a part of the rim hitted by 1/50 part of the photon bunch train. The time structure is shown in fig.6 with a bunch spacing of about 0.35 us and a pulse length of about 20 μs.

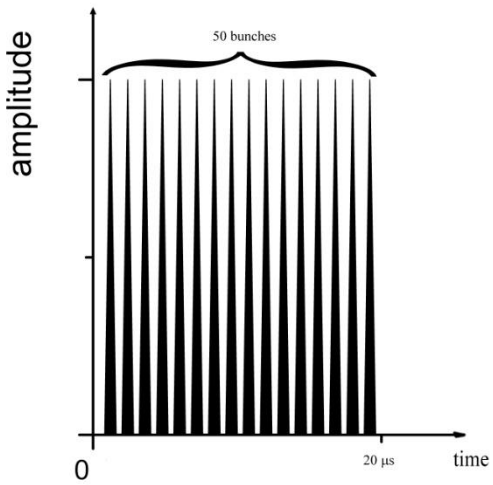

Fig.6 Time structure for the used rectangular target model.

The effective area hitted by 50 bunches is

$$a = \frac{s}{(\frac{2500}{50})} = \frac{100 * 50}{2500} = 2\ mm$$

considering the photon beam of diameter 2mm and assuming a rim velocity of about 100m/s.

The calculations are done for a titanium alloy target (Ti6Al4V) penetrated by a photon beam with energy of 30MeV. The heat load is simulated via FLUKA Monte Carlo code[2].

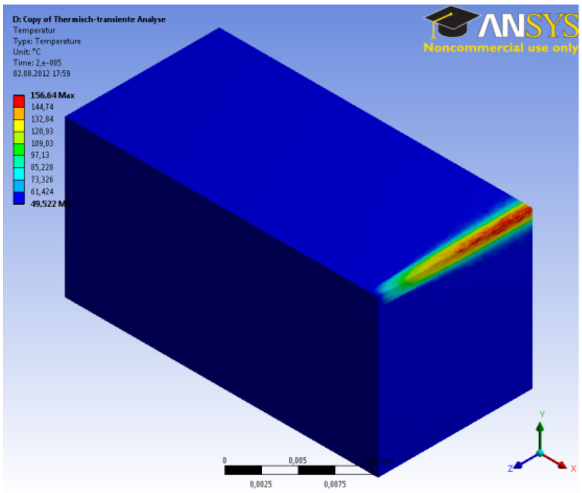

Fig.7 Color code diagram of the temperature distribution in the fixed titanium rectangular target. Without target rotation the photon beam hits 50 times the same point. The final moment of heating (after $t = 20\mu s$) is shown.

As shown in Fig.7 the heat load is not homogeneous distributed along the photon path corresponding to the development of the electromagnetic shower. The temperature is the thermodynamic quantity which is related to the scale of the kinetic motion of the atoms. The emitted bremsstrahlung and pair production processes are the major contributions to the heat load in the target material. Corresponding to the cross section of these processes, the energy deposition and the temperature grow proportional to the density of electrons and positrons.

3.4 Stress and deformation

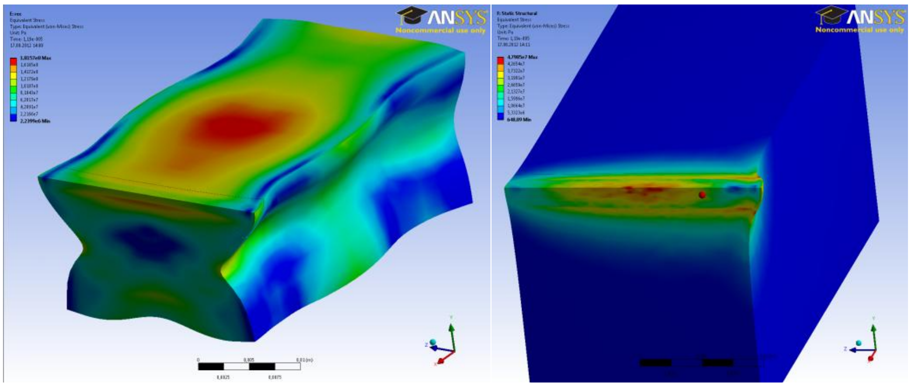

Fig.8a,b Dynamical stress and deformation evolution induced by heat load from the photon beam (left fig.). Static stress and deformation by the same present time step without dynamical previous motion (right fig.)

Fig.8a shows the stress maximum induced by wave superposition. The maximum of the stress area is close to the centre of body but not on in the maximal heated area of the target. The static stress value is about 50 MPa. This is a factor of 4 less than in the case of the dynamic stress evolution with value of about 200 MPa for 50 bunches at the same place. Fig.8a shows the stress evaluation when the maximum transversal oscillation reach the center of the body (red zone). Solids can be excited with two types of waves. The planar longitudinal stress waves usually contract and stretch the body.

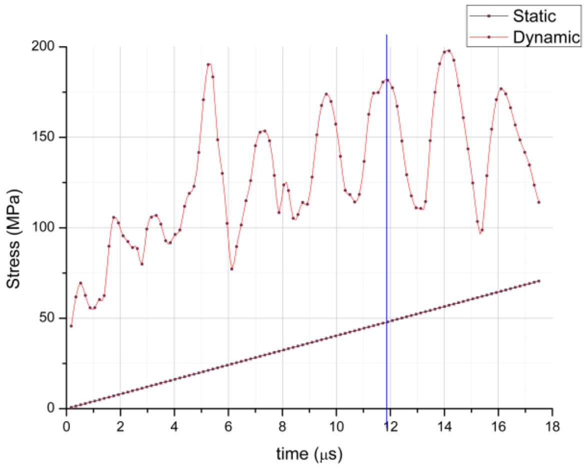

Fig.9 Graph of the time dependent and static max stress value in the target. The blue line corresponds to the time in Fig.8a and Fig.8b.

Fig.9 shows a rapid growth and decline of the stress in the dynamical case where a repeated exposure of the target by the photon beam is considered. In this case we obtain the interferences due to excited eigenmodes. The waves are accumulated until the last time step of about 17.5 μs due to continuous heating by the photon beam. The transversal waves increase their amplitude until the end of this time. Major modes spread through the longer part of the target with a long wave length. The maximum stress zone is induced by these kind of waves.

In Fig.9 the graph of the time depending maximum stress in the target is shown. The maximal stress has an oscillation nature with period approximately 2.1 μs.

This caused by longitudinal wave crossing and constructive interference in the middle of the rectangular body shown in fig.10.

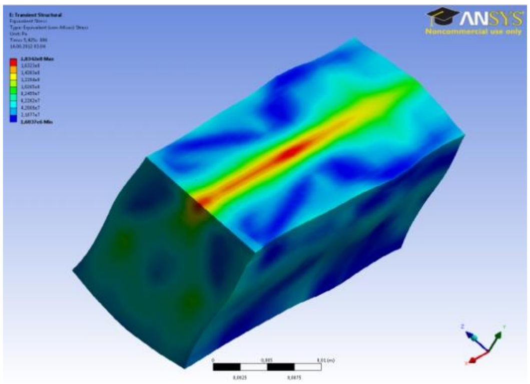

Fig.10 Stress diagram. Red zone is crossing of planar longitudinal waves.

4. Conclusion

It was shown that the solid Ti target hitted by an intense photon beam with ILC time structure behaves like liquid material.

It seems that depending on the geometry and target material properties, the periodic heat load due to an intense beam can produce strong stress waves which easily exceed the elastic limit. It could be possible that these waves build up further and could destroy the target. For a final evaluation of the long term heat load in the target both, the static and the dynamic case have to be considered and evaluated.

Acknowledgement

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