DYNAMICS OF TARGET MOTION UNDER EXPOSURE OF HARD GAMMA UNDULATOR RADIATION

A. Mikhailichenko, Cornell University, CLASSE, Ithaca, NY14853, USA

Abstract

We describe a time dependent dynamics of target motion under exposure by undulator radiation in a system for positron production. We took into account inertia of material of target. Calculations carried with FlexPDE code.

OVERVIEW

For generation of polarized positrons in amounts, required by ILC (see Table 1) the undulator scheme is accepted as a baseline [1].

Table 1: Nominal ILC Undulator/ Beam Parameters

Primary beam energy, *GeV/c*	150-500
Particles per bunch	2×10^{10}
Number of bunches	2625
Bunch length, μm/sec	$300/ 10^{-12}$
Distance between bunches, *ns*(*m*)	369(110.6)
Repetition rate, Hz	5
Length of undulator, *m*	170
Period of undulator, *mm*	10
Ø of undulator aperture, *mm*	8
K factor	0.3-0.5
*E*γ @1harmonic	18
*N*γ@1 harmonic	40-95
Polarization of *e*+ (e^-)	>65%
Ratio e^+/e^-primary	1.5
Thickness of target , X_0	~0.5
X_0 for *W*. g/cm^2 (*cm*)	6.76 (0.35)
X_0 for *Ti*. g/cm^2 (*cm*)	16.6 (3.56)

Electrons or positrons could be used as primary ones. Mostly important advantage of undulator-based scheme is in its ability to generate polarized positrons (and electrons) in quantities ~3e+ per each two primary particles, i.e. ratio 1.5 positrons for each primary electron or positron. When positrons are used as primary ones, the wings of linear collider can operate independently. In last case a simple feedback system implemented in conversion collection optics could hold amount of circulating positrons steady. Small low-energy electron beam source, irradiating positron target can easily restore the amount of positrons in a loop [2].

Besides polarization, the conversion system drastically reduces average power deposited in a target if compared with traditional method of conversion of electrons in positrons. This is due to the fact that the target now is irradiated by photons in substantial amounts, so it is not necessary to convert primary electrons in bremsstrahlung photons, so the thickness of target could be much smaller. Typically in undulator scheme the target has thickness ~0.5X0. Although the average power is low, <100W typically, the power density remains high. So that is why the baseline of ILS suggests a Titanium target as with lower Z material the energy becomes deposited in larger volume. In SLAC experiment E-166 [3], where the undulator conversion system was tested experimentally, a set of Tungsten (Z=74) and Titanium (Z= 22) targets of different thickness was installed in a remotely controlled cassette, Fig.1.

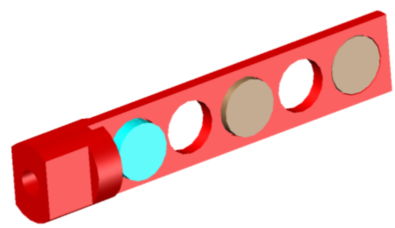

Figure 1: Gamma-target cassette (cartridge) [3].

Disks made from W and Ti separated by two empty holes for transporting the gamma ray to the gamma-table for calibration of intensity. Separation with holes helps in prevention from mistakable identification of target slot. Changing the target material was appointed for identification of best combination of material-thickness pair. The Titanium target demonstrated substantially smaller yield of positrons, so after the first test was done, it was not used at all. This low yield of positrons is in nature of mechanism of positron production. The photons generated by primary beam in undulator lose theirs energy in a target mainly by two processes: Compton scattering and positron-electron pair production. Namely the last type is interesting for us; it is dominating in region of photon energy of our interest. Really, the cross section of Compton Effect for $\omega >> m$ goes to be $\sigma_C \approx \pi r_e^2 / \gamma$, where $\gamma = \hbar\omega / mc^2$ stands for gamma factor of photon, $r_e = e^2 / m \cong 2.8 \cdot 10^{-13} cm$ is the classical electron radius. Meanwhile the cross section for the pair creation (per nuclei) is $\sigma_p \approx r_e^2 Z^2 \alpha$ (full screening). So the ratio of these cross sections per g/cm2 of media becomes $\sigma_C / \sigma_p \approx 1/ \gamma Z \alpha$ ~5% (for W, for Ti-16%)). From the other hand the ratio of cross-sections of positron production for Tungsten and Titanium is $\sigma_W / \sigma_{Ti} \approx (74/22)^2 = 11.3$ (per atom). Other reason why the Ti target is not so effective as the W one is in the fact that critical energy, which marks equalizing ionization losses to radiation ones, $E_c \approx 610/Z[MeV]$, for Tungsten is ≈8 MeV, while for Titanium it is ≈26 MeV, so while reaching this energy the electrons and positrons created by incoming gamma-quanta does not create

†One should agree, that the gamma-beam transfers its energy to electron-positron gas first and then, through this stage to the atoms.

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gammas for pairs. That is why experiment E-166 demonstrated low yield of positrons for Ti target, even for the same thickness (in terms of X0).

Namely electrons and positrons created in a target are responsible for heating the target due to ionization of atoms of target and by direct shaking atoms due to elastic scattering. While created, the e+e- pair moments separated by angle ~1/γ~1/20. This follows from the formula for angular distribution of created positrons/electrons [4]

$$n(\theta)d\theta \cong \theta\, d\theta/(\theta^2 + 1/\gamma^2)\,. \quad (1)$$

If we accepted that at the exit of target the angular spread for secondary particles~ $\theta_0 \cong 13.6/cp\sqrt{t/X_0} \cong 0.7$ for 13 MeV ones, then one should accept that the energy transferred to the atoms of target by transverse momenta are $\cong pc\cdot Cos\,\theta_0 \cong 9.6MeV$ per particle. Fortunately, the number of such particles with maximal deflection angles is not so high, following Gaussian distribution. Meanwhile the energy transferred to the media of target thru the one single act of ionization is ~few eV only, but happen more frequently.

Passage of γ-bunch through the target with thickness z_T lasts extremely short time, $\tau_P \approx z_T / c = l_{X0}/2c \approx 3\,ps$ (for W; for Ti-30*ps*), meanwhile the characteristic time for motion of target media defined by speed of sound c_s is $\tau_T \approx l_{X0}/c_s \approx 0.36\,\mu s$ i.e. $\approx 6\cdot 10^4$ times bigger. From the other hand temperature relaxation for local perturbation is defined by the distance between atoms. So the kinetic energy exchange between neighboring atoms happens with the time $\tau_T \approx a/c_s \approx 0.1\,ps$, where the distance between neighboring atoms ~5Å was substituted. Basically this time corresponds to the frequency of atomic oscillations ~10^{13}sec^{-1}. So for the processes of stress relaxation in a target, which is going with a speed of sound in material of target, all atoms involved could be considered as excited coherently and the local temperature established during passage of gamma beam (together with e^+e^- cascade).

So the picture of transferring energy from the gamma beam to the target, i.e. its heating, is the following. Gamma-bust having the same length as the primary electron (positron) bunch from Table 1 enters the target. First layers of target do not heated at all as there are no positrons and electrons yet. The pairs appear after passage some length and amount of secondary particles could be approximated by $N_{e+} \cong N_\gamma (7/9) t / X_0$, where t stands for the thickness of target material passed through measured in *g/cm*^{2} , 7/9 –is an asymptotic factor of total cross section in Bethe-Geitler formula [4]. These electron/positrons interact with atoms of target and transferring its momenta to the atoms by elastic collisions. Other component of losses of these secondary particles arisen from ionization of atoms. Acting all together these processes shift atoms from theirs equilibrium positions. Atoms oscillate around shifted positions while the gamma-beam passed through material of target[†]. Starting from shifted positions atoms began oscillation around theirs equilibrium positions, i.e. acquire the temperature bust. Time scale of these oscillations is the period of sound (shock) waves, which remains much longer, than the time of passage of gamma-bunch through the target. As the number of positrons/electrons increase to the exit of target so there is kind of bump in shifts of all atomic positions rising to the exit of target also. Then atomic forces tent to bring the atoms back to equilibrium position, but the forces acting between neighboring atoms excite oscillations around local equilibrium, what is a temperature oscillation. As we supposed that deflection of atoms increase to the exit of target, inevitably we should accept that between-atoms forces carry shifted atoms toward the body of target while energy of oscillations transferred to the atoms located apart from the gamma beam trajectory. Namely these pulling forces are responsible for appearance of *negative* pressure at the exit of target. So we have identified few time scales, Table 2.

Table 2: Time Scales

Energy exchange between neighboring atoms	0.1*ps*
Gamma bunch duty	1 *ps*
Passage of γ beam over target	3 *ps*
Thermal relaxation of target	0.36*µs*

As the time of thermal relaxation is much bigger, than the time when the heating source is acting, $\tau_T >> \tau_P$, we can talk about shock wave regime [5]. Atoms of target located at the out-surface cannot transfer theirs kinetic energy to neighboring ones, so the wave of pressure developed by deposited energy can deploy them from the surface-an analog of acoustic triggered emission.

COUPLED THERMOELASTIC PROBLEM

Pressure established along the beam trajectory is linearly increased with distance

$$P(z) \cong (\Gamma Q/V)\cdot(z/z_T)\,, \quad (2)$$

Q /V is a volume density of deposited energy, Γ stands for Grűneisen parameter, $\Gamma = \alpha c_s^2 / C_V$, where C_V is a heat capacity, $\alpha = (1/V)(\partial V/\partial T)_P$ is a coefficient of thermal expansion at constant pressure [5], [6]. Absorption length for the photon with $\hbar\omega \geq 10\,MeV$ is ~20 *g/cm*^{2}, so by passing W target each photon loses ~17% of its energy only. For Tungsten $\Gamma \approx 1.6$. If we suggest, that the total energy deposited in a target by single bunch is $Q = 0.17\cdot N_\gamma \cdot E_\gamma \approx 0.5$J, the gamma-beam size defined by collimator located in front of target $D \approx 1.5mm$, then the volume, where this energy deposited is $V \approx D^2 z_T/3 \cong 1.3mm^3 \equiv 1.3\cdot 10^{-3} cm^3$, so the energy density comes to be $Q/V \approx 380\,J/cm^3$, or ~20*J/g*, so the pressure profile comes to $P(z) \cong 6\cdot(z/z_T)kBar$, while the elastic limit for Tungsten is about $P_T \approx 1.08$ *kBar*.

For description of target behavior under exposure of undulator radiation done in the very beginning of such activity [6], parameters of VLEP were taken as initial ones. The number of particle in a bunch of VLEPP was ~10^{12}, i.e. ~100 times bigger, than in ILC. So for behavior

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of material of target a hydrodynamic approximation was used [6], as the pressure initiated by the γ-bunch was few ten times bigger, than the elastic limit of stress (1.08 *kBar*). For the primary beam with 10^{10} particles, thermoelastic behavior should be considered instead. Equations we used for modeling are well explained in [7]:

$$\Delta T + Q(\vec{r},t) - \kappa \dot{T} = (3\lambda + 2\mu)\alpha(T - T_0)/k \cdot div(\partial\vec{U}/\partial t)$$

$$(\lambda + 2\mu)\cdot\Delta\vec{U} - \rho\ddot{U} = (3\lambda + 2\mu)\alpha\cdot\vec{\nabla}T \quad , \qquad (2)$$

where $\kappa = \rho C_V / k$, ρ is a volume density, C_V is a heat capacity, k- is a heat transfer coefficient, α- is thermal expansion coefficient, Q is a source of thermal excitation of atoms of target, T-is local current temperature, T_0 is initial temperature, μ,λ- are Lamé coefficients, $\vec{U}$ is a vector of displacements, $\vec{U} = (u,v,w)$. The terms at the right side of each equations couple the local temperature (local energy of vibrations of atoms) and local displacement of atoms, associated with inertial forces. Stresses of material are defined by

$$\sigma_{xx} = (\lambda + 2\mu)\varepsilon_{xx} - (3\lambda + 2\mu)\alpha(T - T_0)\,,\ \varepsilon_{xx} = \partial u/\partial x \quad (3)$$

and similarly for other coordinates.

Results of calculations represented in Figs. 2-4.

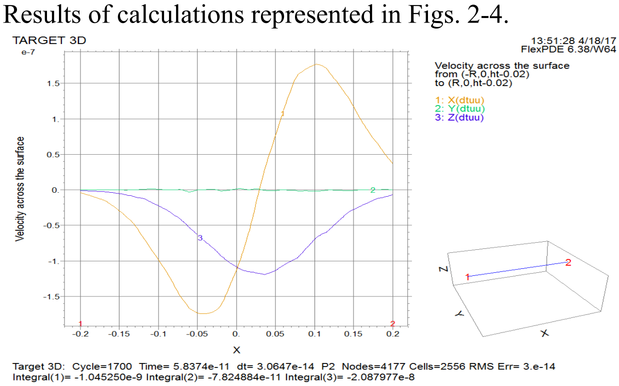

Figure 2: Velocity distribution at the out-surface.

One can see from Fig.2, that velocity of media at the exit surface directed towards the target in direction of beam passage and apart from the beam axis.

In Fig. 3 the bump at maximum coincides with the moment when the gamma-beam exits the target. So right after the gamma-beam is leaving the target the pressure wave driven by beam changed its direction. Relaxation will happen at far longer times according to Table 2. The temperature established along the gamma-beam passage remains linear, as it should be, Fig.4.

SUMMARY

Usage of Tungsten as a target has advantages compared with Titanium (ILC baseline) in larger cross section of positron production which is 11 times bigger for W; then the critical energy of Titanium is 26/8=3.25 times bigger which narrows production of quants of second and so on generations. Shock wave induced by gamma bunch provides negative pressure at the out surface of target which might be destructive for W, if not attend properly. This peculiarity is responsible for the damages in target of SLC positron conversion system. For parameters of ILC with spinning W target the parameters could be suggested within safe margins however. Calculation of heat and pressure build up in a target require taking in consideration of inertial and elastic properties of material of target.

Usage of liquid metal target [8] remains mostly attractive solution and brings calculations to hydrodynamic approximation naturally.

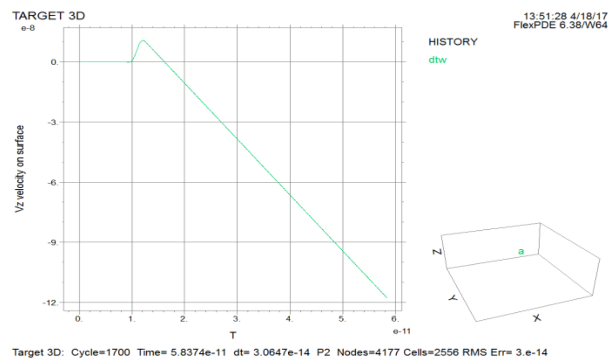

Figure 3: Velocity at center of gamma beam out-point.

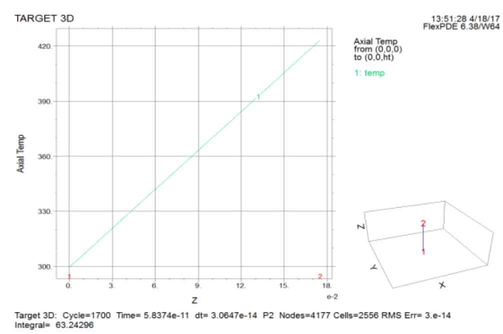

Figure 4: Elevation of axial temperature.

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