LIQUID METAL TARGET FOR ILC

A.Mikhailichenko, Cornell University, LEPP, Ithaca, NY 14853, U.S.A.

Abstract

We considered the Hg/Bi-Pb target for gamma/positron conversion suitable for usage in ILC project. Positron scheme generation with undulator allows usage thin Hg/Bi-Pb jet confined in profiled duct with rectangular cross-section.

INTRODUCTION

Positron production for ILC is rather challenging problem. Power dissipated in a target with traditional method by direct electron/positron conversion becomes so big, that it is not practical for ILC. That is why positron production scheme with undulator was chosen as a baseline for ILC. Even so the target problem remains serious. The baseline for the target at the moment is a Titanium wheel having diameter ~1m, 1.42 cm thick, spinning at 500 rpm [1]. This satisfies request for the target, but we are looking for more guarantied schemes, however, see [2]. There are numerous investigations in the field of high power density targeting actual due to requirements of muon collider project; see [3]. Solid Titanium and Tungsten targets of different shapes were investigated in [4], [5]. Calculation of conversion efficiency was carried with numerical code CONVER [6] and by trajectory tracking. It was found that the *needle type* Titanium target has the yield few times higher than the wide target [5]; positrons allowed to escape the target from the sides. We would like to underline here that such enhancement allowable only for Ti target while using with gamma radiation. It is possible neither for W target, nor for usual electron-positron conversion.

In addition to this option, we are considering some other possibilities for the targets. One other concept is a *liquid metal target*. Liquid metal targets have been considered in many publications; see for example [3], [7]–[9], [11]. Here we represent our latest design for such system [2]. Liquid target has few advantages: it does not accumulate fatigue, easy to cool, with proper arrangement of flow it is less affected by shock waves; it is rather compact. That is why we investigated this approach for the ILC target system and found it feasible and attractive.

LIQUID METAL

One peculiarity associated with target business with undulator is that the target is rather thin, ~0.5 radiation length, what makes the problem much easier. High Z metals could be used, such as Lead (Pb) [8], Bismuth-Lead (Bi-Pb) eutectic alloy, Mercury (Hg) and even Wood's metal. In-Ga alloy filled with W powder can be used as a target also.

Mostly effective material from point of efficiency is Bi-Pb alloy, as the cross-section of positron production is proportional to $\sim Z^2$ (per nuclei) and all these elements have highest atomic number Z: ^{83}Bi—^{82}Pb.). Bi-Pb alloy composed with 55.51Mass% of Bi and 44.49 Mass% of Pb has liquid phase at 125.9^{o}C. Phase diagram of this alloy is rather branchy with different modifications of Pb sub-phases. At 200^{o}C this eutectic has liquid phase for wide percentage of mass ratio. This alloy is broadly in use as a coolant for transportable Nuclear Power Installations. It is also in use as a target at SINQ [9]. We would like to mention here, that these elements (Pb and Bi) have lot of isotopes, numbered by few tens, which have broad rage of lifetimes. *Anyway Bi-Pb as a coolant is very suitable for positron production and can be considered as the main candidate for this purpose*.

Effective radiation length calculated as

$$\frac{1}{X_{eff}[g/cm^2]} \cong \frac{\%Bi_W}{X_{Bi}} + \frac{\%Pb}{X_{Pb}} \cong \frac{0.555}{6.2} + \frac{0.445}{6.4} \cong \frac{1}{6.28}. \quad (1)$$

Corresponding geometric length is $l_{X0} \cong X_{eff} / \rho_{eff} \cong$ 0.6cm, and the thickness of the target~3mm.

Liquid metal jet chamber (LMJC), see Fig.2, designed so it can work at temperature up to 450^{o}C, so it can accommodate even pure liquid Pb. One peculiarity here is that the liquid metal duct has profiled extension, so the overheated metal expands in this extension practically without developing pressure in the system. The liquid located at the bottom of the chamber effectively absorbs the droplets, moving with high speed. For Bi-Pb alloy the one minor negative fact is its operational average temperature ~150 ^{o}C. Once again, operation of this alloy as a coolant in nuclear power plants is rather developed industry. Compared with the technique in use in accelerator engineering, it is not a problem to accommodate this technique. As we just mentioned, our LMJC can work with such temperature without any problem. So the other elements of the counter such as gear pump, heat exchanger, filing and filtering systems can work at this temperature as well.

Other material for the target is Mercury (Hg). One peculiarity in usage of Hg is its low boiling temperature ~356^{o}C. That means, when the heat absorbed brings Hg to the boiling point the *latent heat of vaporization* comes on scene, which allows absorbing significant amount of heat energy having moderate temperature (~356^{o}C). We considering the Mercury (Hg), confined in Titanium tube duct, as another candidate for ILC target. One negative property of Mercury, what may strictly influence to the choice – is its toxicity. Hg considered as one of mostly toxic materials; it could be handled properly, however. In some installations the Mercury is in use in turbine circle, instead of water, what give assurance of success of its implementation for our purposes. Total amount of Mercury in circulation is about ~1-1.5 liters only and there will be not a problem to handle it. Let us mention here that Mercury target is under consideration for test at CERN [12] as a proton beam target for generation of muons. So the formalities can be resolved, if necessary. Isotopes of Mercury are stable, except artificially created ^{194}Hg, which decays $^{194}Hg \rightarrow ^{194}Au$ in ~444 years.

THERMODYNAMICS OF TARGET

Temperature dynamics in a target governed by equation

$$\nabla(k\nabla T) + \dot{Q} = \rho c_V \dot{T}\,, \qquad (1)$$

where k stands for thermal conductivity, $\dot{Q}[Watts/cm^3]$ – density of energy deposition, c_V stands for the heat capacity. Calculations show that the average power deposition in a target ~5 kW. So every second Q=5kJ is deposited there. We created numerical model for solving (1) using FlexPDE with the moving source

$$\dot{Q} = \sum_i \frac{2cQ_{bunch}}{\pi\sqrt{\pi}\sigma_z\sigma^2_{\perp\gamma} l_T}\frac{z}{l_T}\exp\left(-\frac{(z+z_0-c(t-i\cdot t_0))^2}{\sigma_z^2}\right)\cdot\exp\left(-\frac{r^2}{\sigma^2_{\perp\gamma}}\right) \qquad (2)$$

Q_{bunch} stands for the energy deposited by single bunch, i – numerates the bunch, z_0 initial displacement. Expression normalized so that for the single bunch

$$\int_0^{\infty} dt \int_0^{Volume} \dot{Q}(r,z,t)dV = Q_{bunch}\,. \qquad (3)$$

Some results of this modeling are represented in Fig. 1 below.

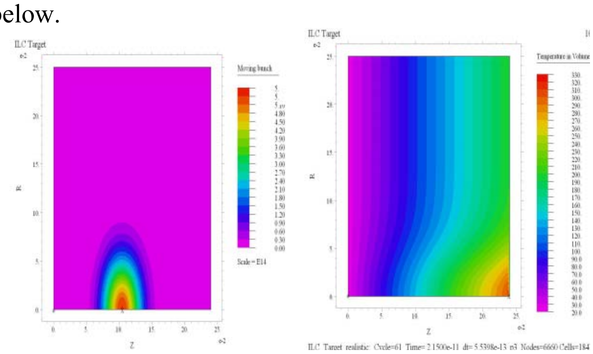

Figure 1: Instant position of the bunch moving in the target, at the left. Isotherms right after the bunch passage, at the right.

As soon as the temperature profile is known, the thermal pressure p_T can be expressed as the following [10]

$$p_T = \Gamma(V)\frac{c_V T}{V} = \Gamma(V)\frac{\varepsilon_T}{V}\,, \qquad (4)$$

where $\Gamma(V) = V / c_V(\partial P/\partial T_V)$ characterizing the ratio of the thermal pressure to the specific thermal energy ε_T / V called Grüneisen coefficient. By introduction of thermal expansion coefficient α, Grüneisen coefficient can be expressed as

$$\Gamma(V) = V\alpha K_T / c_v = V\alpha K_S / c_P\,, \qquad (5)$$

where K_S is the adiabatic bulk modulus. Energy deposited in the volume defined by the gamma beam size at the target

$$\pi\sigma^2_{\perp\gamma} \cong \pi\sigma^2_{\perp\mu} + \frac{(\gamma\varepsilon)\beta}{\gamma} \cong \pi L\cdot\left[\frac{1+K^2}{\gamma^2} + \frac{(\gamma\varepsilon)}{\gamma\beta}\right] + \frac{(\gamma\varepsilon)\beta}{\gamma} \qquad (6)$$

where $(\gamma\varepsilon)$ stands for invariant beam emittance, β is envelope function in undulator, γ is a gamma factor of the beam. By introduction of focusing and/or some steering of beam in undulator, one can artificially increase the gamma-spot size on the target. So the total volume involved comes to

$$V \cong \pi\sigma^2_{\perp\gamma} L l_T \cong \tfrac{\pi}{2}\sigma^2_{\perp\gamma} L l_{X_0}\,, \qquad (7)$$

where $l_T \cong l_{X_0}$ is the thickness of the target. For consideration of target conditions during a single bunch pass, one can accept that the beam energy deposited in this volume instantly, linearly increasing to exit of target. The energy Q_{bunch} deposited by the bunch in the target is $Q \cong 0.15-0.2$ J depending on details of focusing in undulator. So the pressure existing at the very first moments comes to [11]

$$p_T = \Gamma(V)\frac{\varepsilon_T}{V} \cong \Gamma(V)\frac{Q}{\pi\sigma^2_{\perp\gamma} l_T}\cdot\frac{z}{l_T}\,, \qquad (8)$$

where z coordinate runs from the entrance of target. As the Grüneisen coefficient for typical case ~1.5-2 then the thermal pressure at the first moment comes to *kbar* level.

In numerical model the flanges supported at different temperatures (20 and 250 ^{o}C respectively) and the properties of Mercury were substituted here. This model, showing dynamics of heating indicate good agreement with analytical estimations.

The heating of target is carried by electrons (Compton and from pairs) and by positrons. As the ratio of Compton cross section to pair creation (per g/cm^2) is

$$\sigma_{Compton} / \sigma_{pair} \cong 1/\gamma Z\alpha \sim 8.5\%, \qquad (9)$$

Compton electrons practically do not input to the heating; indeed, positrons and electrons from pairs generated in equal quantities and, hence, heat the target equally.

LIQUID METAL JET CHAMBER

Let the Mercury jet have a velocity of v=10m/sec and dimensions S=1×0.24 cm^2 in cross section. So the volume passed per second is $V \cong 240cm^3$. Due to turbulence all energy is deposited evenly. The temperature gain becomes $\Delta T \cong Q/\rho V c_V \cong 12^o$C, so from the point of average power deposition everything is acceptable.

Profile of the jet chamber chosen so, that it allows expansion of liquid in transverse direction. Target unit is shown in Fig. 2. Here the Hg or Bi-Pb at conversion point is running in the channel with rectangular cross-section in profiled Titanium duct. At the bottom of extension there is the Mercury surface as the flow is interrupted by profiled extension.

For $\tau \cong$ 300 nsec the jet will pass $L \cong v\tau \cong 3\mu m$ only, but for the time while the train passes, the distance will be $L \cong v\tau = 10m/\sec\times 10^{-3}\,1cm$. Energy deposited in the target *by one train* will be $Q_{train} = Q/f \cong 1000J$ in a volume $V \cong l_T S \cong 0.24 cm^3$, so for the temperature gain $\Delta T \cong 320^o C$ (starting from T=37^{0}C) the energy absorbed will be $Q \cong \rho V c_V \Delta T \cong 13.6 \times 0.24 \times 0.14 \times 320 = 146[J]$.

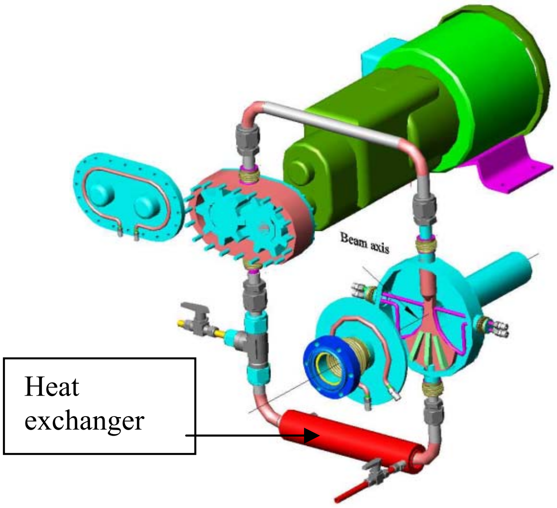

Figure 2: Scheme of liquid target. Diameter of the chamber is ~10 cm.

While becoming a vapor, the latent heat of vaporization needs to be applied to the liquid. Specific latent heat of vaporization for Mercury at 357 ^{o}C is C_L=294 *J/g*, so the energy absorbed by volume V=0.24cm^3 will be $Q_L \cong \rho V C_L \cong 959 J$. So the total energy absorbed by this volume will be $Q_{tot} \cong$ 959+146=1105[J]. This number means that Mercury *will remain liquid* at boiling temperature, however. For the single bunch, one can estimate the energy deposition ~$Q_{bunch} \cong Q / n_b \cong 0.18$ *J.* The transverse size of gamma-beam at the target defined by angular divergence ant the distance $L \cong 150 m$ from undulator to the target, see (6). Substitute there $\gamma \cong 3 \cdot 10^5$, $K^2 \cong 0.15$ one can obtain, $\sigma_{\perp\gamma} \cong 0.036 cm$, so the temperature of the volume $V \cong \pi \sigma^2_{\perp\gamma} l_{X_o} / 2$ giving density of energy deposition $Q_{bunch} / \rho V \cong$ 14 *J/g* and the temperature gain

$$\Delta T \cong \frac{Q_{bunch}}{\rho \cdot \pi \sigma^2_{\perp\gamma} 0.24 \cdot c_V} \cong 125^o \cdot$$

The temperate distributed linearly from zero at the entrance of the jet to double of this at the exit. So for the single bunch the conditions are acceptable, what means that average values we took for the train are allowable here. So, this target is able to absorb ~5 kW under the parameters specified. For velocity of jet we have a formula $v \cong \sqrt{P / \rho}$, where P stands for the pressure at the entrance of jet chamber. For moderate pressure P=30 kg/cm^2 (30 atm), one can expect the velocity 21m/s, which is two times higher, that we took for our estimations. So that is the real resource here. We would like to say, that the metal flow in other parts of the loop, outside the LMJC, is slow due to extended diameter of tubes.

CONCLUSIONS

So the basic conclusion here is that Mercury satisfies requirements. Its toxicity however can make its implementation and usage in converter more difficult, so the Bi-Pb alloy is the best candidate under this circumstance for conversion of gammas into positrons. Its moderate melting temperature (~125 ^{o}C) can be tolerated with LMJC described above. The boiling temperature of this last alloy is much higher, ~1500 ^{o}C , what makes utilization of latent heat practically impossible, so the temperature raise of liquid is higher and all defined by heat capacity of Bi-Pb alloy. One additional advantage of Bi-Pb Targetry is its low thermal neutron cross-section (0.11 *barn*, compare with 389 *barn* for Hg).

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