LIQUID METAL TARGET FOR ILC

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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 guaranteed 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 Titanum 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 target 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 $Z^2$ (per nuclei) and all these elements have highest atomic number $Z$: $^{83}\text{Bi} - ^{82}\text{Pb}$). Bi-Pb alloy composed with 55.51Mass% of Bi and 44.49 Mass% of Pb has liquid phase at 125.9°C. Phase diagram of this alloy is rather branchy with different modifications of Pb sub-phases. At 200°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

$$X_r = \frac{1}{\frac{\%\text{Bi}}{X_{\text{Bi}}} + \frac{\%\text{Pb}}{X_{\text{Pb}}}} \times \frac{0.555}{6.2} + \frac{0.445}{6.4} = \frac{1}{6.28}.$$ (1)

Corresponding geometric length is $l_{\text{geo}} = X_r / \rho_{\text{eff}} \approx 0.6$cm, 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°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 °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°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°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 $\sim$444 years.

**THERMODYNAMICS OF TARGET**

Temperature dynamics in a target governed by equation

$$\nabla(k\nabla T) + Q = \rho c_{v} \dot{T},$$

(1)

where $k$ stands for thermal conductivity, $Q$ [Watts/cm$^{2}$] – density of energy deposition, $c_{v}$ stands for the heat capacity. Calculations show that the average power deposition in a target $\sim$5 kW. So every second $Q=5kJ$ is deposited there. We created numerical model for solving (1) using FlexPDE with the moving source

$$Q_{\text{bunch}} = \sum \frac{2\pi Q_{\text{train}}}{\pi \sigma_{x} \sigma_{y} l_{T}} \exp \left( \frac{(z + z_{0} - c(t - l_{t}))^{2}}{\sigma_{x}^{2}} \right) \exp \left( \frac{r^{2}}{\sigma_{y}^{2}} \right)$$

(2)

$Q_{\text{bunch}}$ stands for the energy deposited by single bunch, $i$– numerates the bunch, $z_{0}$ initial displacement. Expression normalized so that for the single bunch

$$\int_{0}^{\text{Volume}} \int_{0}^{t_{f}} \dot{Q}(r, z, t) dV = Q_{\text{bunch}}.$$ (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.](image)

As soon as the temperature profile is known, the thermal pressure $p_{T}$ can be expressed as the following [10]

$$p_{T} = \Gamma(V) \frac{c_{v} T}{V} = \Gamma(V) \frac{e_{T}}{V},$$

(4)

where $\Gamma(V) = V / c_{v} (\partial P / \partial T_{v})$, characterizing the ratio of the thermal pressure to the specific thermal energy $e_{T} / V$ called Grüneisen coefficient. By introduction of thermal expansion coefficient $\alpha$, Grüneisen coefficient can be expressed as

$$\Gamma(V) = V \alpha K_{T} / c_{v} = V \alpha K_{L} / c_{p},$$

(5)

where $K_{L}$ is the adiabatic bulk modulus. Energy deposited in the volume defined by the gamma beam size at the target

$$\rho \sigma_{x}^{2} + \rho \sigma_{y}^{2} + \rho \gamma \beta \gamma \sigma_{x}^{2} + \rho \gamma \beta \gamma \sigma_{y}^{2}$$

(6)

where $(\gamma \beta)$ stands for invariant beam emittance, $\beta$ is envelope function in undulator, $\gamma$ 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

$$V \equiv \rho \sigma_{x}^{2} l_{T} \equiv \frac{\pi}{4} \sigma_{x}^{2} l_{x 0},$$

(7)

where $l_{T} \equiv l_{x 0}$ 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 $Q_{\text{bunch}}$ deposited by the bunch in the target is $Q \approx 0.15-0.2 J$ depending on details of focusing in undulator. So the pressure existing at the very first moments comes to [11]

$$p_{T} = \Gamma(V) \frac{e_{T}}{V} \equiv \frac{Q}{\rho \sigma_{x}^{2} l_{T}} \frac{z}{l_{T}},$$

(8)

where $z$ coordinate runs from the entrance of target. As the Grüneisen coefficient for typical case $\sim$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 oC 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

$$\sigma_{\text{Compton}} / \sigma_{\text{pair}} = 1 / \gamma \alpha \sim 8.5\%,$$

(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 $v=10\text{m/sec}$ and dimensions $S=1 \times 0.24 \text{ cm}^{2}$ in cross section. So the volume passed per second is $V \equiv 240\text{cm}^{3}$. Due to turbulence all energy is deposited evenly. The temperature gain becomes $\Delta T \equiv Q / \rho V c_{T} \equiv 12^{\circ}\text{C}$, 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 $\tau \equiv 300 \text{nsec}$ the jet will pass $L \equiv v \tau \equiv 3\mu m$ only, but for the time while the train passes, the distance will be $L \equiv v \tau = 10\text{m/sec} \times 10^{-3} \text{cm}$. Energy deposited in the target by one train will be $Q_{\text{train}} = Q / f \equiv 1000 J$ in a
volume \( V \equiv l_7S \equiv 0.24\, \text{cm}^3 \), so for the temperature gain \( \Delta T \equiv 320\, ^\circ\text{C} \) (starting from \( T=370\, ^\circ\text{C} \)) the energy absorbed will be \( Q \equiv \rho V c_t \Delta T \equiv 13.6 \times 0.24 \times 0.14 \times 320 = 146\, [J] \).

**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 °C) can be tolerated with LMJC described above. The boiling temperature of this last alloy is much higher, ~1500 °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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**REFERENCES**