ILC Positron Source Based on Liquid Metal Target

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Abstract

Positron generation is one of the most difficult technical challenges among ILC (International Linear Collider) subsystems. In Conventional method, the positrons are generated, via the pair-creation process in Electro-magnetic shower induced by electron beam in a target. In ILC, a pulse train contains 2625 (5120 for low Q parameter) 3.2 nC (1.6 nC) bunches and a fixed solid metal as the positron production target can not survive and a fast rotating target (more than 100 m/s tangential speed) is required. The current baseline design is based on Undulator radiation, which mitigates the thermal stress slightly, but not dramatically; 90 m/s tangential speed is still necessary. In this article, I propose an ILC positron source based on Conventional method with a liquid metal target system under development in Budkha Institute for Nuclear Physics, Novosibirsk, Russia. This concept resolves not only the technical difficulty on the target, but also issues on system complexity introduced by the Undulator method: path length condition, inter-system dependency, commissioning scenario, problems associated with electron deceleration, etc. This scheme makes the whole ILC system much simpler and the system availability higher.

INTRODUCTION

Basic concept of all existing positron sources[1] is called as Conventional or Electron Driven from a technical point of view. A high energy electron beam, which is typically up to several GeVs, is injected on a thick target made of high Z and dense material, generating Electromagnetic shower in it. A part of positrons in the shower is focused and captured by magnetic matching device and RF field.

ILC (International Linear Collider) is aiming at electron-positron collisions at 500 GeV - 1 TeV center of mass energy. Because ILC is based on the super-conducting accelerator, a long pulse of 0.97 ms with 10mA average beam current must be implemented. In the baseline design of ILC[2][3], one train contains 2625 (5120 for low Q parameter set) 3.2 nC (1.6 nC) bunches with 369.2 ns (189.2 ns) spacing, resulting 0.97 ms train length. ILC DR (Damping Ring) has approximately 6.7 km circumference and has to store all bunches in one pulse-train, because the damping time is much longer than 1 ms. As a solution, the beam bunch is stored in DR with shorter bunch spacing, 6.2 ns (3.1 ns). This pulse train is repeated in 5 Hz. For simplicity, we discuss only the nominal parameter set in this article. Average beam current is almost same for each parameter set and the detail of the train structure is not essential for the positron production.

According to the positron source designs for Linear Colliders[4][5], 10 or 6.2 GeV driving electron beam with 4 radiation length W (Tungsten) or W-Rh (Tungsten Rhenium alloy) target yields one positron per incident electron with AMD (Adiabatic Matching Device) and S-band or L-band normal conducting capture RF section. To produce 2625 3.2 nC positron bunches, same amount of 6.2 GeV electron beam is needed and the total energy of one pulse is 50400 J. This energy is mostly deposited in a small area of target (typically several mm^2) in 0.97 ms and the peak power density becomes $13.0\mathrm{MW}/\mathrm{mm}^2$, which is obviously beyond the melting point of any metal.

To avoid any damage on the production target, a fast rotating target is proposed[5]. The rotation cycle was decided to be 360 m/s in tangential speed, so that thermal stress is below the fatigue limit[6]. An experiment to examine an actual limit of the incident power density to W-Rh alloy was carried out at KEKB[7] and it has suggested that the actual limit on the thermal stress possibly higher than the expected and the tangential speed can be lowered down to 132 m/s without any serious damage on target[8].

Liquid metal target[9] is another approach to mitigate the target thermal damage. In the liquid metal, there is no fundamental limit on the beam power density determined by the thermal stress. A large potential of this technology is pointed out by P. Logachev [10], who leads the development of the liquid metal target system at BINP, Russia.

ILC POSITRON SOURCE BASED ON LIQUID METAL TARGET

Shorter Bunch Spacing

ILC requires a long pulse train, which contains 2625 3.2 nC bunches. Before the acceleration in the main linac, those bunches stored in DR more than 100 ms for damping. Extraction kicker[11] manipulates positron bunches in DR independently and extracts in every 369.2 ns. Therefore, the train structure is determined via the extraction process and, in the positron source, it is not necessary identical to that in the main linac.

In the previous studies[5], the positron generation is assumed in the same train format, i.e. more than 2600 3.2 nC bunches with 350 ns spacing. In this scheme, bottle necks are the power density in the target and the field gradient of the first L-band accelerating tube, which works as a capture RF. This capture L-band accelerating tube should be NC because a high thermal deposition is expected and it should be placed in focusing solenoid field. Then, a powerful RF source and L-band NC RF structure should be viable in 1 ms pulse duration. 10 MW multi-beam klystron, which is operable up to 1 ms pulse duration, is developed[12][13][14] and L-band NC accelerating tube is now studied by J. Wang[15], which is capable up to 15 MV/m field gradient.

However, higher field gradient is always desirable from capture efficiency point of view. If the bunch spacing is set to 6.2 ns, the total pulse length becomes 16.3 μs instead of

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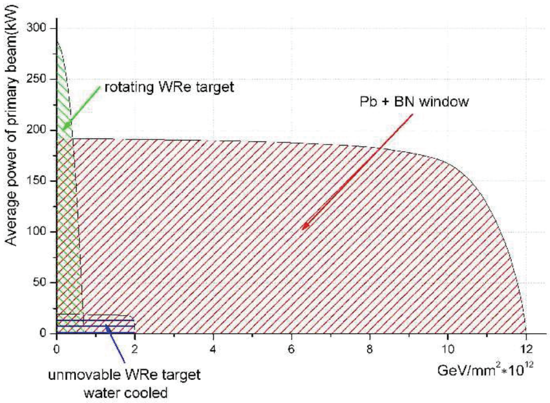

Figure 1: Areas available for different kinds of positron production targets. It is reprinted from Ref. [10] with permission.

0.97 ms. The field gradient can be higher than 15 MV/m. A L-band klystron (Thales, TV-2022E) provides 30 MW peak power with 4μs flat top and 25 MW peak power with 8μs flat top [16]. With further optimization, 20 MW peak power with 16.3 μs flat top is likely to be possible. If 20 MV/m gradient is available with 16.3 μs pulse length, the capture efficiency is improved and positron yield per incident electron becomes more than 2.0[10].

Liquid Metal Target

In the short pulse mode, another bottle neck, the target power density, becomes higher, but it is manageable with Liquid metal target. Liquid metal target is described in Ref.[9]. Heated Pb-Sn alloy is circulated with flow speed of 10 m/s. A test bench of the liquid metal circulating system has been operated more than 15000 hours long without any troubles[17]. It shows the liquid metal system is technically reliable and mature. In the real system, the liquid metal can not be operated without a vacuum isolation window from the beam line to prevent any dilutions. An actual limit of the liquid metal target is determined by the destruction of the isolation window (BN) as shown in Fig. 1, which shows ability of positron generation of three different targets[10]. The horizontal axis is a parameter of $J = E * N/S$, where E is driving electron beam energy in GeV, N is the maximum number of incident electrons in 100 ns time interval, S is the transverse cross section of driving electron beam in mm^2. The reason of choosing 100 ns duration is that the stress made by the incident beam has up to 300 ns time scale and the generated shock wave is maximized up to 100 ns duration[9],[10].

Assuming the positron yield per electron is 2.0, the average power of primary electron beam is calculated to be $\mathrm{P_{pri}} = 6.2(\mathrm{GeV}) \times 1.6(\mathrm{nC}) \times 2625 \times 5(\mathrm{Hz}) = 130\mathrm{kW}$. Measure of the shock wave damage is $\mathrm{J} = 6.4(\mathrm{GeV}) \times 16 \times 1.0\mathrm{E} + 10/1.0(\mathrm{mm}^2)$, where 16 is number of bunches in 100 ns, $1.0E+10$ is number of electrons in a bunch, which corresponds to 1.6 nC. The incident spot size can be larger, but we assume $1.0\mathrm{mm}^2$ conservatively. J is calculated as $0.99\mathrm{GeV}/\mathrm{mm}^2 10^{12}$. This operation point is even inside of the available area shown in Fig. 1 and the short pulse mode works well from the target vitality point of view.

Matching Device

The short pulse mode gives another profit on Matching Device. The roll of Matching device in the positron source is transforming the phase phase space distribution of generated positrons for further acceleration. There are three ways to make this phase space matching: QWT(Quarter Wave Transformer), AMD (Adiabatic Matching Device), and LL(Lithium Lens). QWT is implemented by a strong solenoid magnet followed by a weaker solenoid. AMD consists of solenoid field same as QWT, but the field strength is gradually decreased and smoothly connected to weaker and flat solenoid field. LL has azimuthal magnetic field for the positron focusing. QWT and LL are energy selective and relatively a small acceptance[1].

Higher magnetic field is always better for better capture efficiency. By considering actual devices to make a strong magnetic field, most of them are pulsed devices and shorter pulse length is easier. Fig. 3 in Ref. [10] shows operable pulse duration for these devices. FC (Flux Concentrator) is a AMD, which can generate field as high as 10 T, but is operable up to 30 μs. With the short pulse mode operation, FC can be used as Matching Device, which improves the positron yield.

Positron Booster

In the short pulse mode, the average beam current in the macro pulse is more than 500 mA and NC tube is feasible for accelerator up to 5 GeV, DR injection energy. If 2 of 3m L-band accelerating tube with 15 MV/m gradient is driven with one klystron, 82 tubes and 41 klystron-modulator systems are required. The system repetition is 5 Hz.

If the pulse is splitting (for example) into 10 pulses with 6.7 ms interval, the pulse duration becomes 1.63 μs. In that case, a conventional S-band system can be used. If a couple of 20 MV/m 3m tube driven by one S-band klystron-modulator system, totally 54 tubes and 27 klystron-modulator systems are required. The system should be operated in 150 Hz instead of 5 Hz if the train spacing is 6.7 ms.

DR Injection

In DR, the bunch spacing is 6.2 ns to keep the DR circumference in a reasonable length. In the baseline design, because the positron is generated and accelerated with 369.2 ns spacing, independent bunch manipulation is necessary; a bunch should be injected to DR bucket without any disturbance to neighbor bunches. A fast kicker, which implements such difficult bunch by bunch manipulation, is under development in KEK[11]. From a technology point of view, injection is more difficult because the kick angle is much larger than that in the extraction due to the large emittance of injection beam, $\gamma\eta_{\mathrm{x,y}} \sim 0.03\pi\mathrm{m.rard}$. In the short bunch mode, this complicated manipulation is not necessary at all. The positron is generated in the identical spacing and injected into DR with a conventional magnet kicker.

COMPARISON TO UNDULATOR METHOD

In Undulator method, the e+ beam is generated by high energy gammas produced by undulator radiation. Energy of the gammas has to be more than 10 MeV, in where the pair crea tion process is dominant over photo-electron and Compton interactions. Energy of undulator radiation into super-forward direction, $E_{ph}[eV]$ is expressed as[18]

$$E_{ph}[eV] = 950\frac{nE^2[GeV]}{\lambda_u[cm](1+\frac{1}{2}K)}, \quad (1)$$

where n is harmonic number, $E[GeV]$ is electron beam energy in GeV, $\lambda_u[cm]$ is undulator periodic length in cm, and K is undulator strength parameter. The electron beam energy has to be more than 130 GeV with $n = 1$, $\lambda_u = 1.0$, and $K = 1.0$ to produce gammas with enough energy for the pair-creation process. A dedicated electron beam for the undulator radiation is quite unrealistic; The electron beam before the collision at 150 GeV is used. This relation makes inter-system dependence between electron and positron Linacs and several system constraints.

Generally, inter-subsystem dependence makes system availability lower. According to a study[19], ILC availability is decreased by 10 % with Undulator positron source comparing to that with Conventional positron source. A back-up positron source is assumed in RDR[3] to cure this availability loss. It is Conventional positron source, but the intensity is only 10%.

Another constraint is Self-reproduction condition, in which the electrons generates the new positrons, who is the collision partner in the next pulse. Assuming this self-reproduction, the generated positrons can be accepted by DR with any DR fill patterns, because the corresponding positron bunch is already extracted. To realize this condition, the path length for the round trip from and to the e+ DR has to be an integer of DR circumference[20].

Undulator for the positron generation is placed at position of 150 GeV electron energy. In case of collisions at an energy lower than 150 GeV, the electron beam is decelerated after the undulator section. It wastes a lot of electricity and energy spread is spoiled; Energy spread after passing the undulator section becomes 0.15% and it is enhanced by deceleration up to 0.45% in case of 50 GeV[21][22].

In Conventional positron source, these constraints and problems are resolved and disappeared.

SUMMARY

Conventional positron source based on Liquid metal target is considered. A large potential of the liquid metal target allows us to shorten the bunch spacing and total pulse length in the positron generation. This short pulse mode improves the positron capture by employing stronger pulsed solenoid magnet as Matching device and higher gradient L-band accelerating tube as the capture RF. In addition, this system resolves system constraints introduced by Undulator positron source, which is the advanced baseline of ILC.

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