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A STUDY OF LASER SYSTEM REQUIREMENTS FOR APPLICATION IN BEAM DIAGNOSTICS AND POLARIMETRY AT THE ILC

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Abstract

Advanced laser systems will be essential for a range of diagnostics devices and polarimetry at the ILC. High average power, high beam quality, excellent stability and reliability will be crucial in order to deliver the information required to attain the necessary ILC luminosity as well as for efficient polarimetry. The key parameters are listed together with the R & D required to achieve the necessary laser system performance.

INTRODUCTION

As a part of advanced diagnostics in ILC, it is planned to measure electron/positron beam profiles/sizes within a bunch train and thereby determine the time-resolved Emittance/Luminosity. This also enables a comparison of train to train characteristics. This diagnostics is planned to cover almost the entire accelerator complex from Linac to Beam delivery system (BDS). This is a part of an excellent interactive strategy to attain, preserve and optimize the high beam quality accelerator performance. For the range of ILC particle beam densities and for the required sub-micron resolution coupled with a preferred non-invasive feature, the diagnostics tool is limited to the one based on Lasers, the Laser-wire (LW) [1,2]. A Laser-wire is based on Compton scattering of a finely focussed laser beam by the particle beams. The particle beam profile/size is estimated by the variation in the accumulated energy of Compton scattered gamma photons as the laser beam is scanned over the particle beam.

This paper presents a study of the Laser system requirements for ILC laser-wire for time resolved particle beam profile/size measurements within an ILC bunch train. The future laser system, to be developed for LW purpose, can also function as a highly efficient laser based polarimeter.

ILC LASER WIRE–LASER PARAMETERS

It is clear from Table 1 that ILC laser-wire has to be a mode-locked laser system operating at MHz rep. rate (ILC, 307.7 ns/153.8 ns) with a very small, 1ps pulse width (ILC, 0.3 mm bunch length). The laser repetition rate needs to be locked to the external accelerator master clock with a very good timing accuracy. The laser rep. rate also need to be tuneable around the central frequency to exactly match with ILC bunches in time. The laser beam quality has to be excellent for the laser beam to be focussed down to its diffraction limited size by a specially designed aberration free focussing optics. High laser pointing is necessary for reliable particle beam size measurements. The laser wavelength (λ) choice is a compromise among, small focussed beam size, d ($d \propto \lambda$) for better spatial resolution, large Rayleigh range, R ($R \propto 1/\lambda$) for flat laser wire condition and small Compton X-section, σ ($\sigma \propto \lambda$), requiring more laser power for same the number of Comptons at reduced λ. The laser peak power is decided by the numbers of Comptons produced for measurement with a very small errors. The larger the peak power, the better the accuracy of the final results.

Table 1: ILC Laser wire- Laser parameters

Laser parameters	Guidelines/Values
1. Repetition rate	ILC repetition rates 3.25 MHz or 6.5 MHz ± 25 kHz Sync. to reference RF < 1ps rms
2. Pulse duration	ILC bunch length, 1 ps
3. Overall temporal structure	ILC time structure, 900µs@ 5Hz
4. Beam quality	TEMoo mode, $M^2 \cong 1$, Gaussian beams, High pointing stability
5. Wavelength	Focus laser beam size and Compton X-section, 250-500nm
6. Peak power	No.of Comptons, 10MW/250nm

THE LASER SYSTEM

The LW laser system to be employed in the accelerator complex has to be based on mature technology in terms of reliability, flexibility and compactness. This points to the choice of solid state laser system working at around 1 µm. Also the laser system has to be an oscillator and amplifier architecture (MOPA), as a single laser can not generate 50 MW IR peak optical power at MHz rep. rate required to obtain about 10 MW power at UV by non-linear frequency conversion. Table 2 list the seminal parameters

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Table 2: Laser medium parameters

Laser medium	λ (nm)	Stimulated emission x-section (10^{-19} cm^2)	Upper laser life time (μs)	Gain-bandwidth (nm)	dn/dt $10^{-6}/^{O}C$	Thermal conductivity W/mK	Pump λ (nm)
Nd:YAG	1064	2.8	230	0.45	7.3	13	808/LD
Nd:YLF	1047 1053	1.8 1.2	490 540	1.4	-4.3 -2.0	7	800/LD
Nd:VAN	1064	20	90	0.8	4.7	5.1	808/LD
Nd:Glass	1053	0.42	330	20	8.6	1.2	808/LD
Yb:YAG	1030	1.0	1000	5	9	14	940/LD
Yb:S-FAP	1047	0.8	1300	4.7	-9	5	900/LD
Yb: Glass Fiber laser	980 - 1070	0.5	2000	90	-0.2		975/LD
Ti:Sapphire	700 - 1100	4.0	3.2	230	73	26	500/Laser

of all the potential solid state lasing mediums. There, the parameters point to the achievable laser gain, amplifier energy storage, mode-locked pulse duration, wave-front distortion, beam quality, pointing stability, etc. The laser oscillator, pre-amplifier and the main amplifier needs to be judiciously chosen based on these parameters.

The Laser Oscillator and Pre-Amplifier System

The oscillator will be a continuous wave diode pumped mode locked (ML) laser of ps pulse width with excellent frequency synchronization with external RF signal. In addition, it also needs to have high beam quality, good pointing and high energy stability. Of all the choices, a Fiber laser oscillator offers mode locked operation with 1ps pulse width, temporal stability of 10s of fs [3], polarized, diffraction limited beams of smooth Gaussian profiles, very low pointing jitter down to a few micro-rads and very high energy stability. Closed loop control on ML frequency can be achieved by control of Fiber laser cavity length, either by placing one of the resonator mirrors on a Piezo driven linear stage or by changing the temperature of the Fiber. However external synchronization and the repetition rate tuning and control of the Fiber laser is still not industry standard and has to be paid more attention.

Apart from a Fiber laser, the other ML solid state laser oscillators based on Nd and Yb e.g. YAG, VAN, YLF, S-FAP, can, at low diode pumping power, also give reasonably good beam quality (perhaps not as good as that from a Fiber laser). However the mode locked pulse duration is in the range of 5 to 10 ps due to their much smaller gain-bandwidth (Table 2). A ML Ti:Sapphire laser can easily give a 1 ps pulse width but requires another laser as pump, hence a more complicated and costly route.

Irrespective of the choice of laser oscillator, fiber or conventional, several common issues need to be tackled. First, the laser oscillator would work on much higher rep. rate (40 to 50 MHz) in view of a limit on affordable large cavity length before the laser beam becomes unstable. Hence a pulse picker is needed to down rep. rate to 3 or 6 MHz. The same/another pulse picker is to also select laser pulse packets, 900μs @ 5Hz to match ILC bunches. Second, the oscillator beam needs to be linearly polarized for several reasons, e.g. as an input to polarization based pulse pickers (Pockels cells), for propagation with minimum losses through Brewster angle optics to amplifiers and for the efficient frequency conversion by non –linear optical crystals. Some anisotropic laser crystal i.e. Nd:YLF, Nd:VAN produce polarized output on their own. For others, additional intra-cavity polarizers are needed. Third, a pre-amplifier is needed to raise the very low, nJ pulse energy from master oscillator to 100s of nJ, enough to saturate the first power amplifier. Fourth, in case, the laser oscillator and amplifiers are based on different lasing mediums, the bandwidth of the laser oscillator should exactly match with that of the pre/power amplifiers for the optimum energy extraction. This would require additional efforts. In addition, the choice of master oscillator wavelength, λ, is linked to choice of power amplifiers capable of delivering 50 MW peak power with good beam quality as discussed in next section.

The Laser Power Amplifier System

Power amplifiers are needed to boost the IR laser pulse energy to the required value. This is 50 μJ for 1 ps ML input pulses and 500 μJ for 10 ps pulses. Obtaining a large average pulse train power up to 1.5kW and, at the same time having an output with good spatial coherence and pointing, demands for a careful choice of amplifier medium, its pump source and its overall design. Amplifies with large energy storage ($\propto$ upper laser life time, t), achieve the same laser output energy with fewer no. of stages. This is important for better output beam quality and also for lower cost. In this respect, Nd:YLF ($t \cong 500$ μs) scores over Nd:YAG ($t \cong 230$ μs) and Nd:VAN ($t \cong 90$ μs). Nd:YLF also offers lower wave-front distortions, producing better beam quality and pointing, due to much lower dn/dt values (thereby lower thermal effects) w.r.t. other Nd mediums. The Nd:YLF amplifiers system has been most successfully employed in accelerators as photo-injectors [4]. The wavelength, pulse energy, pulse width and the rep. rate requirement of the Laser-wire and Polarimeter closely follows those of photo-injectors, however in addition there is a demand for very smooth Gaussian beams, extremely high beam quality and pointing stability. It needs to be worked out.

In principle, the Yb based mediums should offer even much better energy storage due to their much larger (ms) upper laser life times. However their amplifier performance to the level that required for ILC LW, still needs to be demonstrated. The closest is, 1 μJ pulse energy for ps pulses at MHz rep. rate and 1 mJ at 50 kHz from Yb doped fiber laser amplifiers and 100 J/pulse@3ns@10 Hz, from bulk Yb: S-FAP, as a part of fusion laser project of LLNL, also tipped as a future $\gamma\gamma$ laser. However, it is worth keeping an eye on future performances of Yb: amplifiers suitable for ILC LW.

The laser power amplifiers will be pumped by high power pulsed laser diodes of appropriate wavelength (Table 2). Diode pumping ensures much reduced thermal effects thereby much reduced beam distortions, much better laser beam quality/pointing stability and long operational life. For uniform pumping, diode bars need to be arranged uniformly all along the amplifier rod length. It is expected that about 10 kW peak diode pump power will be used for each amplifier. For long pulse mode-locked ILC LW (900 μs@5Hz), the amplifier pump diode laser pulse width also needs to be about twice as large (2.0 ms@ 5Hz) for good amplification with high energy stability. This requirement on laser diode long pulse width is a little unconventional compared to that readily available in the market from 0.5 to 0.8 ms, but with the required duty cycle of only 1%, it should be feasible. Low diode duty cycle pumping also ensures that the amplifier medium does not fracture due to thermal effects as the overall laser/thermal average power is only a few watts.

It is expected that ILC LW system would have two power amplifiers, in double pass regime, under overall modular design architecture.

The Laser Frequency Conversion

The final amplifier output at IR needs to be converted down to about 250 nm in, two steps, by non-linear (NL) optical crystals. For the first step (1 μm to 500 nm), probably the best choice would be, temperature tuned, non–critically phase matched LBO. Long interaction length, large acceptance angle and high damage threshold LBOs, produce, high efficiency (>70%), excellent beam quality, second harmonic beams. The other good, room temperature choice can be β-BBO with high damage threshold but with large walk-off. KDP is the cheapest option but is hygroscopic and must be kept in dry condition in sealed housing. For the second step (500 nm to 250 nm), β-BBO is only option with efficiency of 30%.

The ILC Laser Wire System Schematic

Fig. 1 shows the tentative ILC LW system based on marriage of Fiber laser as oscillator/pre-amplifier and conventional solid state medium pulsed diode pumped high power amplifiers. Fiber laser oscillator with selectable wavelengths from 1000 nm to 1100 nm, can be the choice for all the solid state laser amplifiers (Table 2).

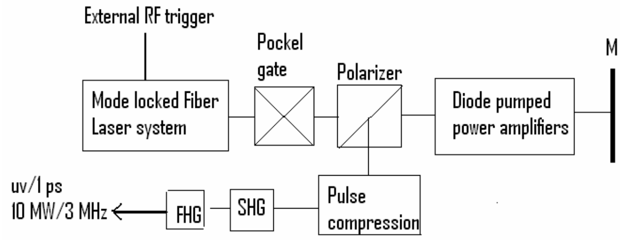

Figure 1: ILC LW system.

SUMMARY

The issues, requirements and possible implementation of the Laser system for advanced ILC particle beam diagnostics and polarimetry, are discussed. More R&D is planned to explore the options. Fiber laser oscillator provides an interesting candidate technology.

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