STABLE PLANAR TYPE FOUR-MIRROR CAVITY DEVELOPMENT FOR X-RAY PRODUCTION AS BASIC DEVELOPMENT OF QUANTUM BEAM TECHNOLOGY PROGRAM*

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Abstract

According to the plan of "Quantum Beam Technology Program", a new beam line using superconducting RF cavity accelerating system is now under construction. To obtain quasi-monochromatic X-ray via inverse Compton scattering, highly intensified laser beam is also needed. In this report, we describe out R&D situations about pulsed laser system that consists of laser oscillator, amplifier, and external optical cavity.

INTRODUCTION

Nowadays, in KEK-STF, a new beam line using superconducting RF cavity accelerating system is under construction. This project is pushed ahead according to the plan of "Quantum Beam Technology Program". The beam line is for inverse Compton scattering with an electron beam accelerated by superconducting RF cavity and stacked and intensified mode-locked laser in external optical cavity to create quasi-monochromatic X-ray. Our target of the yield of the X-ray is 1×10^{11}photons/sec in 10% bandwidth when operation mode is selected as 5Hz repetition rate, 30MeV beam energy, and 10mA bean charge. Now, we're hastening to proceed each construction of accelerator beam line, laser system for collision, and detector system. In this paper, we precisely report about development status of mode-locked laser system for collision. About the laser system, we can separate it into three major components as "oscillator", "amplifier", and "external optical cavity". In following sections, we'll describe each progress of above three object's R&D situation more precisely.

OSCILLATOR PART

To achieve inverse Compton scattering, mode-locked laser oscillator is necessary. Previous experiments done in KEK-ATF, the oscillator which contains balk laser crystal as an intrinsic cavity mirror is used. Recently, using rare-earth-doped fiber and its amplified spontaneous emission (ASE), a fiber oscillator can be constructed for many purposes. Adding proper mode-locking scheme, pulsed output can be also obtained. In accordance with those trends, we have decided to construct our own fiber laser oscillator for this project by ourselves. It acts as a seed laser of all following processes, required quality for laser light, stability, and cost performance etc. is quite high. But comparing usual laser experiments, accelerator experiments always request laser to act as a peace of whole system. So, laser system development itself is very challenging and important issue to obtain good adjustment with specific accelerator system.

Because of the STF bunch spacing of 6.15ns, our laser oscillator has to have 162.5MHz fundamental repetition rate. About pulse duration and output intensity, our design value is ~30ps and ~100mW for each. To achieve mode locking, we introduce fiber coupled Mach-Zehnder interferometer into the optical fiber circuit, and using external RF signal, intensity modulation could be occurred. This intensity modulation makes periodic envelope which has nodes at where all oscillating laser light except having a complete phase condition will vanish. That means introduced modulation by the interferometer has a phase locking function, and, as a conclusion, a kind of active mode-lock is realized. Following figure 1 shows our oscillator components.

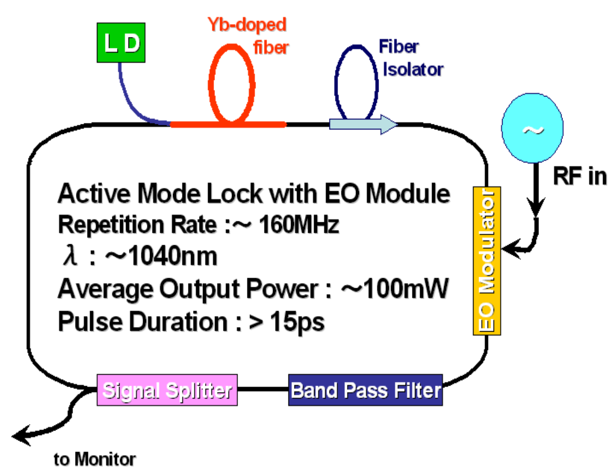

Figure 1: Layout of Oscillator

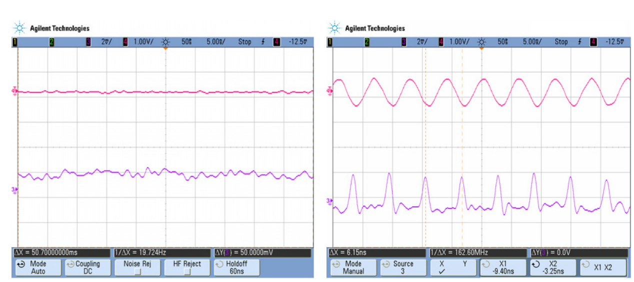

Figure 2: Snap Shots of Output from the Oscillator

Figure 2 shows output laser properties of our oscillator.

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Pink line shows external RF signal, and purple line corresponds to the laser intensity monitored by fiber coupled photo diode. Left hand side picture, there's no RF input (interferometer is fixed at a certain path difference). If the path difference is constructive, ASE light emitted from excited doped fiber starts to circulate inside of the optical circuit. The purple line certainly shows DC like oscillating status. If RF signal turned on, shift to the right hand side of figure 2, intensity modulation is started, and mode-locked pulse shape is observed. Now we already succeeded to achieve more than 100mW average output power, and repetition rate is about 160MHz.

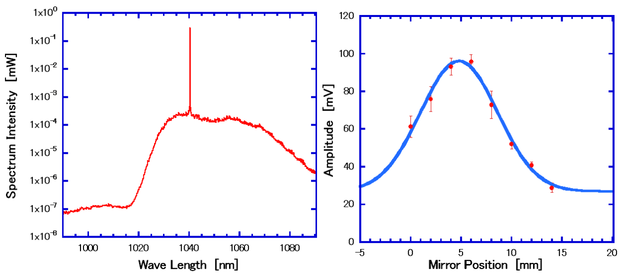

Figure 3: Spectrum and Pulse Duration of the Oscillator

We also observed oscillating laser's spectrum. Left hand side of figure 3 shows measured result. On the typical spontaneous emission spectrum of Yb-doped fiber, shape spike around 1040nm region exists. Considering high efficiency of fiber amplifier system, provided laser wavelength is quite important, and we surely succeeded to have oscillating laser with designed wavelength using narrowband optical pass filter. About pulse duration, we use autocorrelator, and measure. Right hand side of figure 3 shows convoluted intensity of two pulses. From Gaussian fitting, we found lower limit of FWHM of our oscillator's pulse width about 15ps with 10% errors.

Up to this stage, our laser oscillator satisfied most part of design requests, already. For further improvement, we planned to insert Fabry-Perot etalon. This optical filter ensure that super-mode noise which becomes main reason of intensity fluctuation of fiber oscillator can be reduced to negligible level, and much more important fact that, such kind of intrinsic etalon will arrange the phase of circulating pulses. For our case, at the final part of the laser system, all emitted pulses are stacked inside of the external optical cavity. So all those laser pulse must have fixed phase relation with each other. Otherwise, constructive pulse stacking couldn't be achieved. As the etalon, we'd introduce, for example, 4-mirror optical cavity, and govern it with PID feedback scheme to create perfectly synchronized pulse train to accelerator clock system.

AMPLIFIER PART

Receiving about 100mW laser pulse, amplifier section multiplies laser power to up 1000 times larger than that of initial state. Our target output of this amplifier system is about 50W to 100W. To accomplish, we also use peculiar property of fiber. Comparing usual balk laser crystal (a few mm in dimension), several meter-long doped-fiber easily helps us to achieve high efficiency amplification. For our system, we'd use photonic crystal fiber which provide us large core diameter that is very important and useful in laser matching point of view. To take into account of those properties of photonic crystal fiber, we quite to use any combining optical devices like a WDM (Wavelength-Division Multiplexing). If treating laser power exceeds a-few-ten watt, those combining devices could not last against heating damage. Instead of that, we decide to use dichroic type mirror and construct direct injection system of pumping light from Laser Didode into doped-fiber

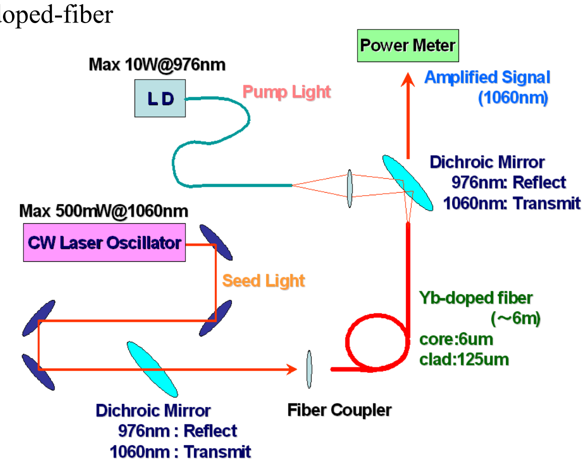

Figure 4: Fiber Amplification Test Setup

Figure 4 shows our test bench setup for direct injection. For this time, we use general type fine Yb-doped fiber (core diameter:6um). Used dichroic mirror acts as a high reflective mirror for pump light (976nm) but transmit signal laser light (1060nm). Injection matching is succeeded, and obtained the results which shows amplified signal laser intensity reached more than 1-W level. (See below figure 5.)

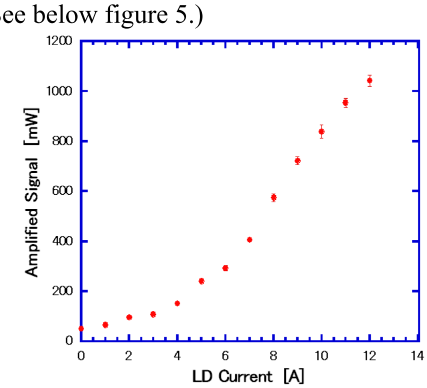

Figure 5: Fiber Amplification Test Result

As a conclusion of this test experiment, we proved that direct injection scheme using dichroic mirror works even though 6um thin core diameter doped fiber case. For real set-up, photonic crystal fiber has 40um core and 200um clad diameter, so matching efficiency could be improved more. As a rough estimation, let's assume 100W pumping LD with more than 90% injection matching, and photonic crystal fiber slope efficiency as 70%. Then we'd obtain more than 63W as an amplified laser output. Comparing our design value, above intensity is good enough to go over the target X-ray yield.

EXTERNAL OPTICAL CAVITY PART

Final section of laser system development is external optical cavity. Historically, in KEK-ATF, 2-mirror concentric cavities are developed for electron beam diagnostics [1], compact X-ray source development for medical applications [2], and also polarized positron source development for ILC [3]. But from the stability point of view, confocal cavity using 2 flat mirrors and 2 concave mirrors is much more suitable to install into accelerator. Especially, our quantum beam project uses superconducting RF cavity, and it need to be kept cold during operation time. To warrant not to disturb the superconducting RF cavity operation, we make a decision that we construct stable 4-mirror confocal cavity instead of two-mirror cavity which has a lot of satisfactory results. But this decision brings an additional advantage. Two-mirror cavity case, we have to keep crossing angle between laser and electron beam as a finite. Usually, this boundary condition comes from finite mirror size. But 4-mirror cavity guarantees good tolerance against miss alignment of optical devices, we can make large enough cavity to surround a beam line. That means, we can achieve head-on collision that helps us to enlarge the X-ray yield. According above discussion, we design out new beam line and insert about 1-m long dispersion free chicane part for head-on collision. On figure 6, top view of IP area and basic design of planar type 4-mirror cavity are showed.

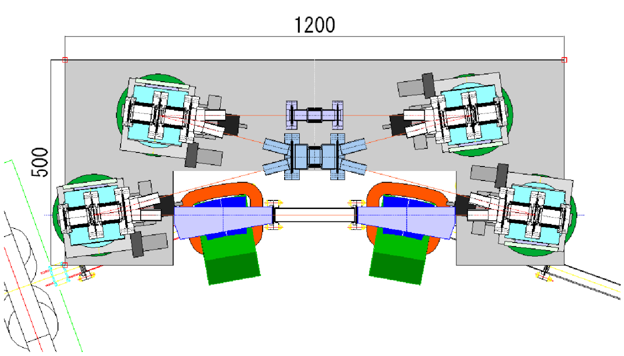

Figure 6: Top View of External Optical Cavity

Comparing with past 2-mirror cavity, there's no solid body part for our new 4-mirror cavity. Every mirror will be mounted onto movable mirror holder driven by actuators to adjust angle or position to keep optical matching. Prototype of those movable mirror holders are constructed and take a lot of laser staking tests to confirm those stability and quality. Using 99.6% reflectivity mirrors mounted on those prototype mirror holder, we constructed a cavity to check a ability by taking feedback.

Another important property we have to check is laser beam profile inside of the optical cavity. At the IP, at where evolution of laser beam profile shows the smallest size, laser waist size is required to be 20um in sigma. Out optical cavity design passes this request. Following figure 7 shows laser beam evolution inside the optical cavity. Left hand side is whole map of the evolution, and right hand side plot corresponds to enlarged part of waist point. As usual, sagittal and tangential plane are separately considered. But both evolution profile shows good coincidence with each other. This means that we can always obtain almost perfectly round shape laser profile anywhere else inside the cavity. We can conclude that out optical cavity possesses good property for easy injection with parallel beam and round shape beam waist, not loosing tolerable property. Standing above those supporting fact, we set out target that the optical cavity must equip more than 3000 enhancement factor.

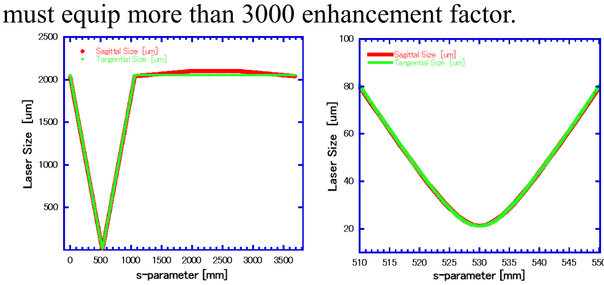

Figure 7: Laser Profile Evolution inside of the Cavity

A key technology to achieve above magnificent property of the optical cavity comes from mirror handling technique. Figure 8 shows our prototype of mirror bender, and snap shot of interference fringe pattern. Even starting from normal flat mirror, we can modify its curvature. Generally speaking, the shallower required curvature is, the more difficult to achieve with fine precision. So bender couldn't guarantee, too. But we can modify little by little instead of polish/flatten off, and finally could reach to the best value, we want. Applying those skills, making a beryllium concave mirror is also in progress.

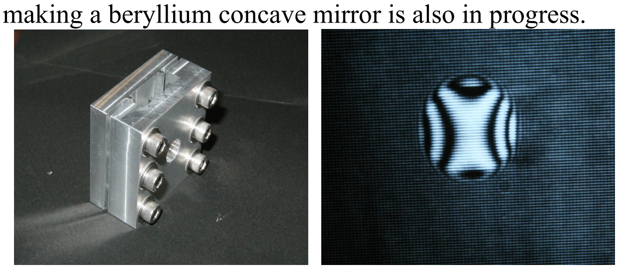

Figure 8: Prototype of Mirror Bender and Fringe Pattern

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