

Laser Super Cavity*

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Abstract

We are developing Laser Super Cavity for compact X-ray generator based on Inverse Compton Scattering with several tens MeV electron beam. The laser supercavity increases the laser power and makes small laser beam size at the collision point with the electron beam. A Fabry-Perot cavity as the laser supercavity has been tested at the KEK-ATF (Accelerator Test Facility) and the design for the increase of the enhancement factor is under consideration. I will describe the experimental results at the ATF and the design for high flux inverse Compton Scattering X-ray Source.¹

1 INTRODUCTION

The generation of high flux X-rays has many applications in various areas. For medical use it has a potential to take a snapshot of the blood flow of a living human heart using the absorption by Iodine or Xenon at 33keV to 35keV, which is so-called dynamic angiography. Only synchrotron radiation from an undulator at a GeV electron storage ring could be allowed to receive the treatments. Recent progress in laser and accelerator technology makes an X-ray source much more compact based on Compton scattering [1]. The X-rays are generated by colliding an intense laser with a relativistic electron beam. The low energy beam, less than 100MeV, is enough to get hard X-rays in this regime, and hence much smaller system can be built.

New project was accepted for the development of the laser supercavity and demonstration of the high flux X-rays production using high duty 10MeV L-band linear accelerator which is called QTF (Quantum Technology Development Facility). We have a possibility to generate the high flux X-rays in the range of several hundreds eV to several keV for Atomic, Molecular Physics and Materials Science.

In this report we describe the design study on the high flux inverse Compton scattering X-ray source. Especially, we discuss a technology on the laser supercavity for above-mentioned application. This paper is organized as follows. In Sec. II we describe the design of our new project. Then the technology on the laser supercavity is presented in the Sec. III. As an example of the laser supercavity, section IV is devoted to the explanation of the laser wire using the Fabry-Perot cavity at the KEK-ATF. Finally, we present the

summary and discussions in the Sec. V.

2 DESIGN OF X-RAY SOURCE

In the future, we need many compact facilities of the high flux X-rays source for medical diagnostics and life sciences. Our Ministry asked National Institute of Radiological Sciences (NIRS) to promote this project for five years. The purpose of this project is to develop the laser supercavity with the enhancement factor more than 10^4 and to generate the X-rays more than 10^{13} photons/sec using QTF. Table 1 summarizes the achieved accelerator performance and design parameters of QTF. Normalized emittance of electron beam at QTF should be reduced from 50 to $3\mu\text{mrad}$. Modification on the electron source and beam instrumentation system is under design. We are testing a model of electron source, bunch monitor and beam synchronization system for the modification.

We have designed colliding section between 10MeV electron beam and laser beam. The optics of this section which consists of several quads for final focus, S-chicane to make collision angle for the installation of the laser supercavity and to reduce background from upstream linac, and beam dump at the end of linac is shown in Figure 1.

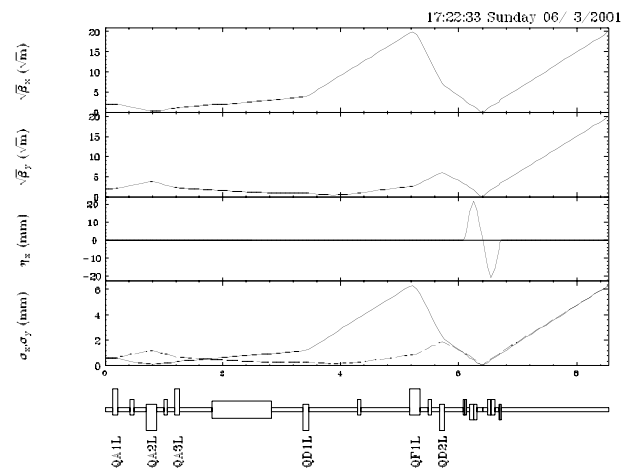


Figure 1: Optics near Interaction Point.

The center of the S-chicane is laser-electron beam interaction point (IP). Electron beam size can change from $50\mu\text{m}$ to $10\mu\text{m}$ in the standard deviation (σ) at IP. Since the beam energy is 10MeV, we collimate X-rays, which are generated by the inverse Compton scattering, into 50mrad

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Table 1: Achieved and design parameters at QTF.

Items	Achieved Values	Design
Maximum Beam Energy	7MeV	10MeV
Peak Current	100mA	100mA
Average Current	5mA	20mA
Repetition Rate	35pps	50pps
Pulse Width	1.43msec	4.0msec
Duty Factor	5%	20%
Energy Spread (Full Width)	not measured (90% beam)	< 0.5% (90% beam)
Charge/Micro-pulse	80pC	80pC
Beam Average Power	35kW	200kW

along electron beam direction. First, we will develop small Fabry-Perot supercavity to make $\pi/2$ crossing angle at IP. Then, 100kW laser and 200kW electron beam will collide to generate soft X-rays. In the next step, large Fabry-Perot supercavity with the distance of about 1m will be developed to make the collision with small crossing angle at IP. Differential cross section of the Compton scattering and luminosity which is determined by the collision geometry are well known if we assume that both the electron and the laser beams satisfy the Gaussian distribution [2]. Table 2 gives the number of X-rays collected within 50mrad in the case of $\pi/2$ crossing angle and head-on collision. The wavelength of CW laser is 532nm (λ). Also, both beam sizes are shown in Table 2. In our calculation, the focusing effect of both beams is included with the interaction length of 180mm. So, total number of X-rays in the case of $10\mu\text{m}$ beam size is less than in the case of $50\mu\text{m}$ beam size regarding the head-on collision, because the hourglass effect of both beams is effective comparing the beam sizes at the present design. It is noted that real crossing angle should be more than 3 degrees, because the damage due to X-rays should be minimized by the collimator.

3 LASER SUPERCAVITY

3.1 Power Enhancement Factor

The nonconfocal Fabry-Perot cavity consists of two high reflection (up to 99.99%) concave mirrors. The reflectivity of the mirror (R) can be enhanced to more than 99.999% (5N) by existing optical coating technology [3]. The laser power enhancement inside the cavity can be estimated as follows.

The laser beam trapped inside the cavity makes an infinite geometrical series of reflected and transmitted electromagnetic field. If we assume same reflectivity (R), transmissivity (T) and absorption (A) of two mirrors, summation of the series gives following results. The relation $T + R + A = 1$ is satisfied because of power conservation.

$$T_c = \frac{T^2}{(1-R)^2 + 4R\sin^2(\theta)}, \quad (1)$$

$$R_c = \frac{RA^2 + 4R(1-A)\sin^2(\theta)}{(1-R)^2 + 4R\sin^2(\theta)}, \quad (2)$$

$$S_c = \frac{T(1+R)}{(1-R)^2 + 4R\sin^2(\theta)}, \quad (3)$$

, where T_c and R_c are transmissivity and reflectivity of the cavity, and S_c total power enhancement factor inside the cavity. θ depends on cavity distance and laser wavelength, which is $n\pi$ on resonance (n =integer). The FWHM width ($2 \times \Delta\theta\lambda/2\pi$) of above functions is given by following equation.

$$\Delta\theta = \frac{\lambda}{4\pi} \frac{1-R}{\sqrt{R}} = \frac{\lambda}{4F}, \quad (4)$$

, where the F, called Finesse, is defined by

$$F = \frac{\pi\sqrt{R}}{1-R}. \quad (5)$$

For example, Institute for Laser Technology in Japan developed flat mirror with $R = 99.99984\%$ and $A = 1.1 \times 10^{-6}$ as best one. We obtain T_c , R_c and S_c using available values as shown in Figure 2. You can expect the enhancement factor of $\sim 2 \times 10^4$ in the future.

3.2 Laser Beam Waist Size

When the wave front of the gaussian beam exactly matches curvatures of the cavity mirrors, the beam propagates back along the same passage to the original point which is injected. We assume same curvature of radius (ρ) and the distance of the supercavity is D. z_0 is defined by following equation as Rayleigh length using laser waist size (σ_0) at the center of cavity.

$$z_0 = \frac{4\pi\sigma_0^2}{\lambda}. \quad (6)$$

Also, the following equations must be satisfied to match the wave front with the curvature of mirrors.

$$\rho = \frac{D}{2} + \frac{2z_0^2}{D}, \quad (7)$$

From equations above, σ_0^2 is derived.

$$\sigma_0^2 = \frac{\lambda}{4\pi} \frac{\sqrt{D(2\rho - D)}}{2}, \quad (8)$$

Table 2: Total number of the X-rays generated within 50mrad.

Items	$\pi/2$ crossing angle	Head-on
Maximum X-ray Energy	1.78keV	3.56keV
Energy Spread of X-rays within 50mrad	19.3%	19.3%
Number of X-rays with $50\mu m$ beam size,[photons/sec]	9.8×10^6	1.5×10^{10}
Number of X-rays with $10\mu m$ beam size,[photons/sec]	4.9×10^7	1.3×10^{10}

T_c and R_c ($R=0.9999$, $A=0.000002$)

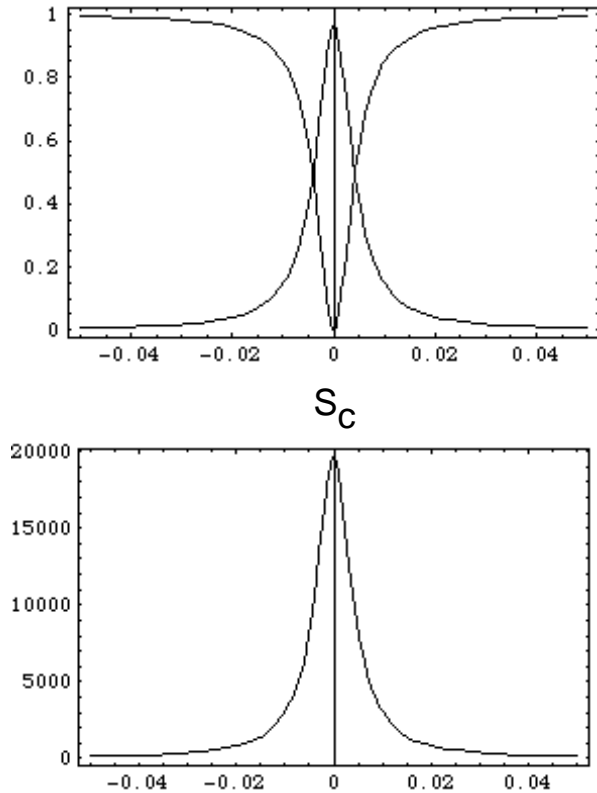


Figure 2: T_c , R_c and S_c Power Enhancement Factor. The unit of horizontal axis is nm.

When the curvature radius of mirrors is $0.5m$ (ρ), laser wavelength $532nm$ (λ) and laser beam size at IP $50\mu m$ (σ_0), we can calculate the laser size on mirrors of $420.35\mu m$ and the distance of mirrors (D) of $985851.018\mu m$. Usually, we control the distance within the accuracy of sub-nanometer by piezoelectric (remotely controlled) actuators [4]. However, more accurate control of the distance or the laser frequency (of single mode TEM_{00}) is necessary for keeping enhanced power in the cavity. Since sub-Angstrom control of the distance is so difficult (see Figure 2), we are testing fine feedback control of the laser frequency within 1kHz which corresponds to 0.2 Angstrom in the case of green laser (532nm) [5]. Also, this means the coherent length of the laser must be longer than 3×10^5m .

Regarding the small Fabry-Perot cavity for $\pi/2$ crossing angle at IP, KEK-ATF and Kyoto University group (ATF laser wire group) have developed with the waist size of $\sim 7\mu m$ [4]. So, we briefly review recent preliminary results in next section [6].

4 LASER WIRE DEVELOPMENT AT THE KEK-ATF

The ATF damping ring was constructed for the generation of extremely flat "multi-bunch beam" that can be squeezed down to a few nanometers at the collision point of LC(Linear Collider) [8]. Of crucial importance is a vertical emittance measurement in the damping ring. We have been developing a new type of beam profile monitor, which is based on the Compton scattering process of electrons with laser beam. In order to achieve both good spacial resolution and fast response for the monitor, the target laser beam must be very thin and intense. These requirements are realized by injecting a cw laser beam into the Fabry-Perot optical cavity. We call this system a laser wire beam profile monitor [6]. The curvature radius of mirrors is $0.02m$ with surface roughness less than $\sim \lambda/100$ and the Finesse reaches ~ 2500 . In this case, the reflectivity and the absorption of the mirror are 99.96% and 80ppm, which were measured by manufacturing company. There are some missing parameters according to injected, reflected and transmitted power measurements. We still need detail study of the mirror to increase the enhancement factor of the supercavity [7]. Thus, the small supercavity already exists for the compact X-ray source and the power in the cavity can be increased by high quality and high power laser. Then, we decide same type of the small Fabry-Perot optical cavity should be newly manufactured with careful consideration, especially the consideration of feedback system on the position of mirror and the frequency of the laser. Of course, we continue the detail study of the mirror itself.

5 SUMMARY AND DISCUSSIONS

From the Table 2, we can not reach our target yield of the X-rays more than 10^{13} photons/sec using QTF. However, there are several possibilities to increase the yield of the soft X-rays using QTF. One possibility is use of the mirror of the reflectivity more than 99.999% (5N). Other possibility is to develop high quality cw laser with the power of 100W. Development of the supercavity technology was motivated by the interest in gravitational wave observation

[9]. We can get the detail information from the project for the gravitational wave observation and modify our feedback system to increase the enhancement factor of the laser supercavity. Also, Nd:YAG laser operating at $1064nm$ has a possibility to increase the yield by other factor 4 but the energy of X-rays is reduced by 2. Thus, we will reach our target yield of X-rays after five years *R&D* of this project.

We discuss the technical issues on the optical coating damage due to the radiation from the accelerator and thermal effect from the laser power density. The damage threshold of the thermal effect depends on the absorption coefficient without scattering loss on the mirror surface and dielectric material for the multi-layers. We expect the threshold value of $10MW/mm^2$ if the absorption is less than 2ppm. Therefore, we must research the thermal damage threshold using the high power laser. Regarding the radiation damage, we had better generate high quality beam without the beam halo and make enough radiation shield for the mirrors. The configuration for experimental set-up near IP is important for the reduction of the radiation damage.

Since a small storage ring with multi-supercavity and a high power cw laser was already proposed [10], we are planning to use 10 sets of the developed supercavity in a $50MeV$ small ring in order to generate the hard X-rays more than $10^{15}photons/sec \cdot \%$ for the dynamic angiography after we will confirm the technology of the laser supercavity.

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