COMPTON SCATTERING IN THE ALS BOOSTER*

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Abstract

Femtosecond x-ray pulses may be generated by 90° Compton side scattering of a short visible laser beam by a well-focused relativistic electron beam.[1] A proof-of-principle experiment is underway using the ALS linac[2]. From this experiment an x-ray pulse of 10^5 photons with a duration of 230 fs in a bandwidth of 10% at 10 Hz is expected. In this paper we explore using the ALS booster instead to increase the average x-ray flux. To generate the small beam size we plan to radiation damp electrons by accelerating them to 600 MeV and decelerate quickly to 50 MeV before intra-beam scattering can increase the beam size. We can achieve a vertical emittance of $< 5 \times 10^{-9}$ m-rad. With a small modification of the booster lattice it is possible to focus the beam to a vertical beta function of $\beta_y^* = 10$ cm. By reflecting the incident laser pulse many times we expect to be able to obtain an increase of the average x-ray flux.

I. INTRODUCTION

At Lawrence Berkeley Laboratory's Advanced Light Source (ALS) there is an experiment in progress to generate short x-ray pulses by colliding short laser pulses with highly focused electron bunches.[2] The electron bunches which are produced in the ALS injection linac are emitted once a second at 50 MeV and with a charge per bunch of >1nC per bunch. Each bunch is then focused to a small transverse size of 50 μm at which time it collides with a laser pulse of ~100 fs duration. In the laboratory frame the laser pulse is traveling in the vertical direction and collides with the electron bunch at a 90° angle. Due to the collision, some of the light is Compton scattered in the direction of the electron beam producing a pulse of x-rays. As a result of the laser pulses short duration and the electron bunches small vertical size the Compton scattered x-ray pulse will have a duration of about 200 fs.[1].

The Compton scattering cross section is very small (6.66×10^{-25}cm^2) so most of the electrons and photons pass through each other unaffected by the collision. These remaining photons and electrons are then deposited in a beam dump and a new bunch of electrons and photons are produced for the next collision. In principle it would be nice to recycle these "unused" electrons and photons and have them recalled many times increasing the average x-ray flux.

There have been several proposals for electron photon recirculating colliders using photon storage rings [3–9]. We investigate the concept in detail for the ALS booster synchrotron.

II. ALS BOOSTER SYNCHROTRON

The booster is normally used to accelerate electrons from an energy of 50MeV to 1.5GeV at which point these bunches are extracted from the booster and injected into a storage ring. The booster has a circumference of 75m and the electron bunches have a revolution time of 4 MHz. Its repetition rate is more than 6 orders of magnitude larger than that of the linac.

A. *Decreasing the Vertical Beta Function*

To produce femtosecond x-ray pulses the electron bunch must be focused down to $< 50\ \mu$m. In order to achieve such a small spot size it is necessary to decrease the vertical β-function at the center of a straight section. In the linac scheme β_y is brought down to 4 mm. To reduce β_y in the booster the magnet lattice needs to be modified.

The magnetic lattice of the booster is basically a FODO structure with four fold periodicity where the beam is vertically defocused in the center of the straight section with $\beta_y = 10$ m(see Figure 1). In order to focus the bunch vertically an extra half period is added to the lattice. This requires splitting the quadrupole which is in the center of the straight section and adding two more quadrupoles (see Figure 2). The rings vertical beta function is then reduced from 10 m to 10 cm.

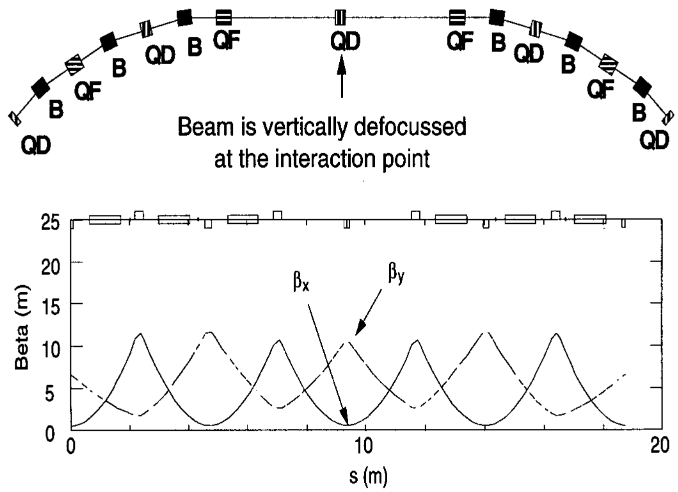

Figure 1. A typical booster cell. The beam is vertically defocused at the center of the straight section.

Reducing the β-function much further requires unrealistically large quadrupole strengths.

Even though β_y is substantially reduced in the modified lattice it is still 25 times larger than in the linac. Therefore in order to get to the same vertical spot size it is necessary for the vertical emittance to be 25 times smaller than that of the linac.

B. *Decreasing the Vertical Emittance*

The beam emittance in the ALS booster is determined dynamically by the mechanisms comprising synchrotron radiation damping, synchrotron radiation excitation, intra-beam scattering, and adiabatic damping. It is possible to reduce the vertical

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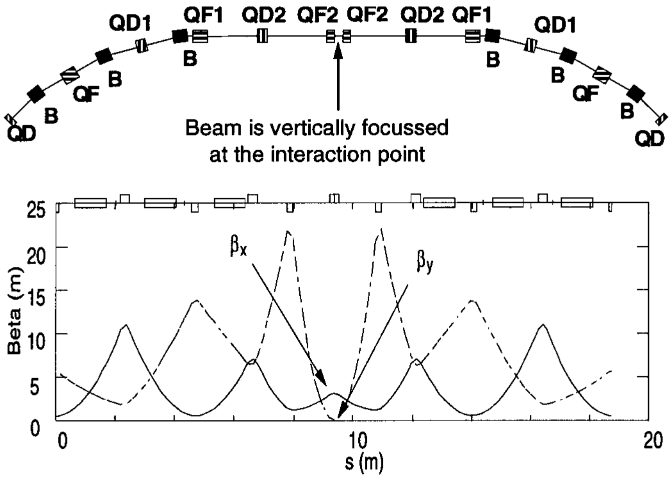

Figure 2. A modified booster cell. The beam is vertically focused at the center of the straight section.

emittance by ramping the bunch to a larger energy where there is a significant synchrotron radiation damping and remain at this energy for several damping times until the vertical beam size is reduced to a small size then ramp its energy down to a lower energy for Compton scattering experiment.

The ultimate beam size will be determined by intra-beam scattering and the coupling of the horizontal motion to the vertical motion by machine imperfections. The shorter Touschek lifetime may determine the usefulness of the beam. Simulations were done using ZAP (modified to include time dependence) to test the feasibility of this scheme. The results of these simulations suggest that there is a broad optimal energy for radiation cooling at about 600 MeV. We assumed a 2 Hz operation with 110 ms for ramping to 600 MeV, 240 ms for damping at 600 MeV, 50 ms to ramp down to 50 MeV, and 100 ms for experiments as shown in Figure 3. The ramping schedule can be easily generated using the present power supply.

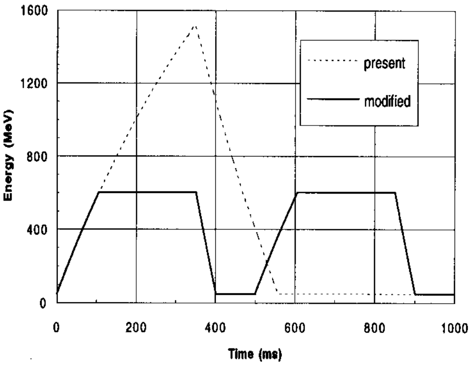

Figure 3. Ramping schedule for the ALS booster. The dotted line is the booster schedule for normal operation.

When the electron bunch is initially injected into the booster its emittance is 0.3 mm-mrad in both the horizontal and vertical plane. If we assume that there is a 1 % horizontal- vertical emittance coupling, the vertical bunch emittance should decrease to smaller than 0.005 mm-mrad, as shown in Figure 4. If we can achieve a 0.1 % coupling the corresponding emittance will be less than 0.0002 mm-mrad.

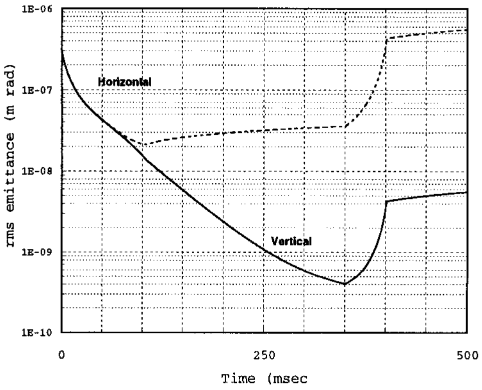

Figure 4. Emittance as a function of time in the booster.

The horizontal bunch size will be much larger than that of the linac. This is a result of the beam being horizontally defocused at the collision point (β_x = 1 m). This increased horizontal size reduces the single pulse x-ray flux in the booster scheme.

C. Colliding at 21° verses 90°

There are two advantages of colliding at a larger energies than 50 MeV. First, the Toushek scattering lifetime is longer at larger energies. As a result one can use a larger fraction of the cycle for colliding beams. Second, the final horizontal and vertical emittances are smaller. Because of the larger energy it is necessary to reduce the scattering angle in order to produce x-rays with the same energy. Reducing the angle will reduce the luminosity of the collision. Therefore there is a balance between energy and angle. In addition to 90° scattering at 50 MeV we have also considered the possibility of colliding at 200 MeV with an angle of 21° and the results are discussed in section IV.

III. LASER

In the case of the linac experiment the laser to be used is a Ti:Al$_2$O$_3$ laser with a 10 Hz repetition rate and energy per pulse of 0.175 J. The linac currently operates at 1 Hz so the experiment is not able to take full advantage of the laser. In the future the linac may be able to operate at 10 Hz.

The are several papers which discuss the possibility of storing 100 MW in 100 ps length bunches[8] [5]. Presently the is no optical cavity which can store more than 1 W of energy in a 100 fs pulse. In fact, due to dispersion in the mirrors, even at 1 W the pulse length tends to grow. This stored power is similar to what can be delivered in a single pulse. So even with the boosters high revolution frequency there is no gain in average power by using an optical cavity at this time.

Due to the limitations of short pulse optical cavities a better way to maximize the average x- ray pulse is to simply reflect the incoming laser pulse many times between two mirrors. The path length that the laser pulse travels between the mirrors should be commensurate with the circumference of the booster so that the electron and photon ring could be synchronized to collide every turn. The number of reflections we are able to use will depend upon dispersion and losses in the mirrors. We have assumed that it may be possible to have 25 usable collisions for each laser pulse.

IV. SYSTEM PARAMETERS

Based upon the above considerations we arrive at table 1. In Table 1 there are four parameter lists given for the booster, 2 at 90° and 2 at 21°. For both the 90° list and the 1° list a "conservative" list and an "aggressive" list is presented. There are several differences between the conservative and aggressive lists. In the conservative lists we assumed 1% emittance coupling whereas in the aggressive lists we assumed 0.1% emittance coupling. This leads to smaller vertical sizes. In addition the horizontal and longitudinal bunch sizes are smaller in the aggressive case resulting from stronger focusing. In the conservative cases the we assume a 1.75 W laser with a 10 Hz repetition rate and a pulse energy of 0.175 J. In the aggressive case we assume a 17.5 W laser.

PARAMETER	LINAC	BOOSTER 90° (Conservative)	BOOSTER 90° (Aggressive)	BOOSTER 21° (Conservative)	BOOSTER 21° (Aggressive)
ELECTRON BUNCH					
Energy (MeV)	50	50	50	200	200
Charge Per Bunch (nC)	1.5	1	1	1	1
Bunch Length (ps)	10	40	10	40	10
Vertical Size (μm)	50	50	20	25	10
Horizontal Size (μm)	50	1000	600	666	400
LASER PULSE					
Wavelength (μm)	0.8	0.8	0.8	0.8	0.8
Energy/Pulse (J)	0.175	0.175	1.75	0.175	1.75
Pulse Length (fs)	117	117	66	85	33
Pulse Width (μm)	35	35	20	25	10
X-RAY PULSE					
Wavelength (Å)	0.4	0.4	0.4	0.4	0.4
RMS Pulse Length (fs)	230	230	120	144	60
Collection Angle (2θ) (mrad)	6	6	6	0.4	0.4
# of X-Rays per Collision (10% bandwidth)	8×10^4	6.8×10^2	3.9×10^4	3.1×10^2	2.1×10^4
# of Collisions per Second	1	50	50	100	100
# of X-Rays per Second (10% bandwidth)	8×10^4	3.4×10^4	2×10^6	3.1×10^4	2.1×10^6

Figure 5. Table 1. Comparison of 0.4 Å radiation produced in the linac and the booster.

We determine the number of collisions per second in the following way. We assume that the electron bunch goes through two ramping cycles as shown in Figure 3. The time between laser pulses is 100 ms. Because the intra-beam scattering time is 40 ms at 50 MeV it is possible to use 1 pulse per ramping cycle (2 per second). In the 200 MeV case the intra-beam scattering lifetime is 100 ms therefore it is possible to use 2 pulses per ramping cycle (4 per second). We also assume that we can reflect the pulse 25 times providing that multiplicative factor. Therefore for 50 MeV case we have 50 collisions per second and in the 200 MeV case we have 100 collisions per second.

A. Conclusion

In this scheme we can not gain full advantage of the increased revolution frequency of the electron bunch in the booster because photons storage ring cavities of the required capability have not yet been developed. However with the expected improvements in laser technology and the development of storage ring cavities this approach seems very attractive. We hope that in the future that with advances in short bunch laser technology it may be possible to realize the full potential of an optical cavity scheme which could result in very high average short x-ray pulses.

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