COMPACT HARD X-RAY SOURCE VIA INVERSE COMPTON SCATTERING BASED ON THE X-BAND LINAC

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Abstract

We are designing a compact inverse Compton scattering hard X-ray (33 keV) source based on X-band linac. X-band 1.5- and 3.5-cell photocathode RF guns and X-band linac were analyzed with PARMELA simulation, and X-ray flux was estimated for several types of lasers. The theoretical scaling law of the RF guns among charge, emittance, and RF wavelength is confirmed by PARMELA. The maximum RF field at the cathode surface should be higher than 300 MV/m. The X-ray was 1.6 x 10^9 photons/shot for a 10 TW 1 ps laser. Since 10^{11} photons within 10ms is required for dynamic angiography, we considered multiple collisions using multibunch beam and multipath optics to increase the flux.

1 INTRODUCTION

The national project of “Development of Advanced Medical Compact Accelerators” have begun this year continuing for five years. In this project we are going to develop two compact accelerators. One is a heavy-ion synchrotron for cancer therapy, and the other is a X-band linac based inverse Compton scattering hard X-ray (33 keV) source for dynamic angiography. We present the design study of the latter here.

We can find a hard X-ray source in large facilities of electron storage rings. For promotion of more applications of hard X-rays, more compact system is needed. By making use of intense lasers, much lower energy accelerators are enough to produce them. By choosing X-band RF structures, further compactness can be achieved.

The schematic view of a compact hard X-ray source is shown in Fig. 1. The electron beam is generated at the X-band photocathode RF gun driven by the third harmonics of all-solid-state stabilized Ti:Sapphire laser, and accelerated up to 50 MeV in two X-band accelerating tubes. The beam is focused to collide with an intense laser to produce hard X-ray (33 keV) flux after an achromatic bending system to avoid noise radiations.

For an application of this system we aim to make a dynamic angiography system which requires the X-ray of 10^{11} photons within 10ms.

2 X-BAND LINAC

At first we started with a 1.5-cell X-band photocathode RF gun according to the RF gun scaling law on the charge and the RF wavelength [1] taking advantage of an S-band system. The scaling law is derived from the beam envelope equation,

$$\sigma_x'' + \sigma_x' \left(\frac{(\beta\gamma)'}{\beta\gamma} \right) + K_x \sigma_x = \frac{2I}{I_0 (\beta\gamma)^3 \sigma_x} f\left(\frac{\sigma_x}{\sigma_z} \right) \tag{1}$$

where σ_x and σ_z are the horizontal and longitudinal beam sizes, respectively, $\beta = v/c$, $\gamma = (1-\beta^2)^{-1/2}$, K the applied focusing force, I the peak current, I_0 the Alfven current, and the prime represents derivative by z. To confirm the scaling law we calculate the beam transportation and beam parameters in the RF gun by PARMELA code.

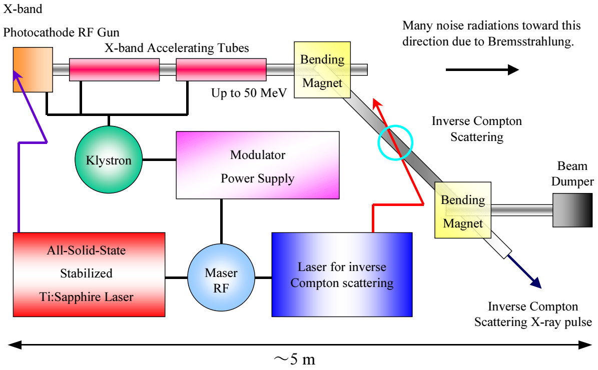


Fig. 1 Compact hard X-ray source

According to the charge scaling law, the data points are to be on the following equation

$$\varepsilon_x = \sqrt{\left(aq^{2/3}\right)^2 + \left(bq^{4/3}\right)^2} \tag{2}$$

where ε is the emittance, a and b constants, q the charge. This equation contains the space charge effect and the RF defocusing effect. Results of the calculation are well fitted to Equation (2) (see Fig. 2).

The RF wavelength scaling means that the emittance and the beam size are proportional to the RF wavelength. Normalized by the RF wavelength these quantities of the S- and X-band RF guns agreed with each other so that we confirmed the scaling law.

In this design the field strength at the cathode surface is 400 MV/m which is so high that we might not apply due to the discharge. Then we also calculate the lower field cases (140 MV/m, 200 MV/m 300 MV/m). In the low accelerating field the electrons cannot reach the energy where the space charge effect is not serious. Then the bunch expands as it propagates. This causes large energy spread, low transparency.

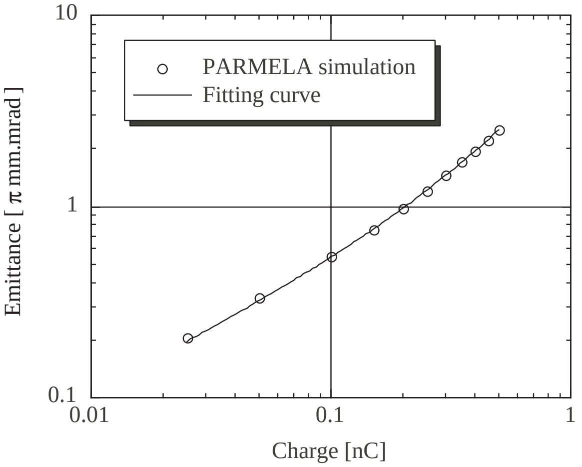


Fig.2 Charge scaling law

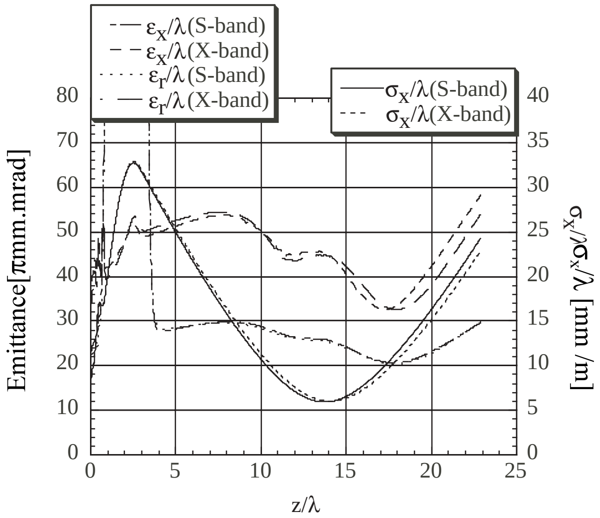


Fig.3 RF wavelength scaling

To avoid above probrems more cells are added to the 1.5-cell RF gun. Since multicell RF guns have little actual performances and longer cavity makes the vacuum worse, we add only 2 cells. Then, the transparency becomes higher. However, the energy spread (Fig. 4) is not improved because of the bunch extension at the first 1.5 cells. The emittance is almost the same as in the 1.5-cell case, but higher charge can be obtained (see Fig.5).

The electron beam generated at the 3.5-cell photocathode RF gun is accelerated up to 50 MeV in two accelerating tubes. We calculated the 140 MV/m and 400 MV/m cases. In the 400 MV/m case an emittance compensation solenid is effectively used, while it is not in the 140 MV/m case. Because the solenoid cannot focus the beam with large energy spread and the pulse extends to 20 ps after 50 cm drift space.

As an achromatic bending system after the acceleration, three bending magnets are used. The beam lattice and the roots of the β functions (x:horizontal, y:vertical) are shown in Figure 6. The parameters at the interaction point is listed in the Table 1. The pulse length is extended in the achromatic magnets.

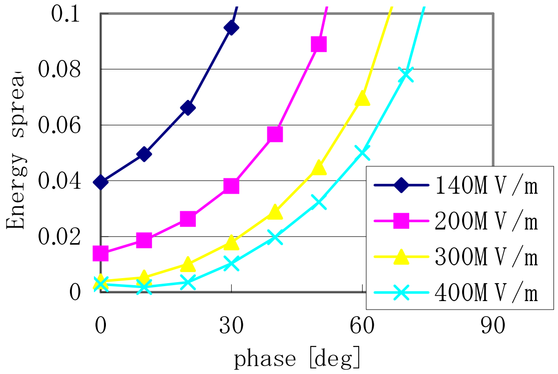


Fig. 4 Energy spread vs. incident phase

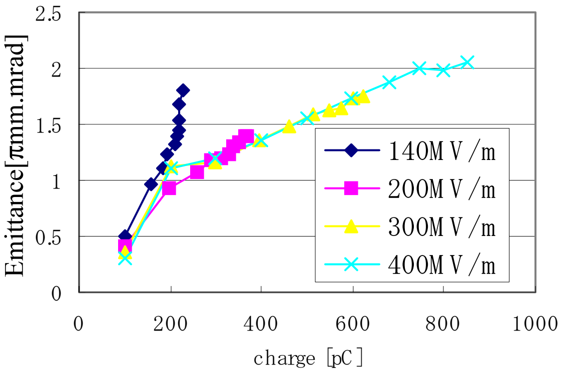
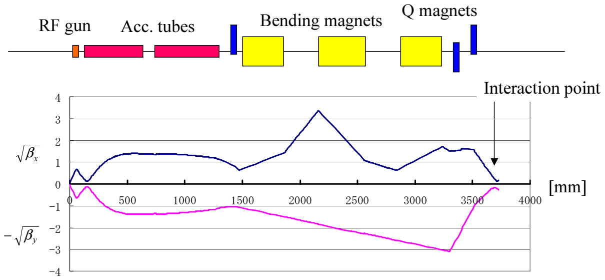
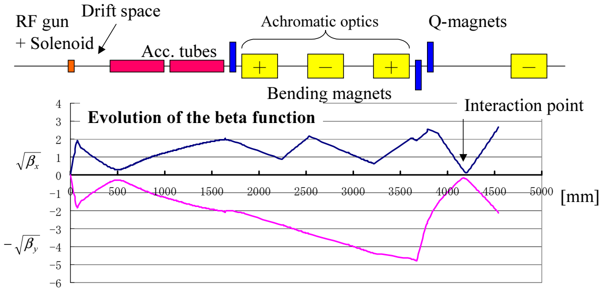


Fig. 5 Emittance vs. charge



(a) 140MV/m



(b) 400MV/m

Fig. 6 Beta functions

3 INVERSE COMPTON SCATTERING X-RAY

The way of analysis on the inverse Compton scattering begins from solving the Lorenz equation. From the electron motion in the laser field we can calculate the radiation spectrum and the distribution by Lienard-Wiechert potential equation,

$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2\omega^2}{4\pi^2 c}\left| \int_{-T/2}^{T/2} dt[\mathbf{n}\times\mathbf{n}\times\boldsymbol{\beta}] \times \exp[i\omega(t-\mathbf{n}\cdot\mathbf{r}/c)]\right|^2 \tag{3}$$

where I is the intensity, ω the frequency, Ω the solid angle of the radiation, **n** the observation, and **r** the position of electron.

To estimate the X-ray energy and flux we use the following equations[2].

$$E_p[\text{keV}] = \frac{0.019E_b^2[\text{MeV}]}{(1+a_0^2/2)\lambda_0[\mu\text{m}]} \tag{4}$$

$$F[photons/s] = 8.4\times10^{16} f\frac{L}{Z_R} I_b[A]\times P_0[GW]\frac{\Delta\omega}{\omega} \tag{5}$$

where E_b the electron energy, a_0 laser strength parameter, λ_0 the wavelength of the laser, f the ratio of laser and electron beam spot size, L the interaction length, Z_R Rayleigh length, I_b the beam current, P_0 laser peak power. By using the values in Table 1 in these equations, we got the solutions for the three lasers as shown in Table 2. Here we consider 100 MW 7 ns laser as an possible intense pulse laser supercavity, 12 TW 50 fs the laser which is in our facility, and 10 TW 1 ps Nd:Glass laser. Since only a part of the long pulsed laser of 100 MW 7 ns can interact with the beam, the X-ray flux is lower than the other cases. Using the 10 TW 1 ps laser, we can obtain 1.6 x 10^9 photons/shot X-rays, which is still less than 10^{11} photons within 10ms by 2 orders.

Table 1 Parameters of the electron beam at the interaction point

	140MV/m	400MV/m
Energy	46.8 MeV	56.3 MeV
Energy spread (rms)	0.73 %	0.89 %
Charge	218 pC	903 pC
Bunch length (FWHM)	13.7 ps	18.5 ps
Radius (rms) (x, y)	93, 93 μm	77, 77 μm
Emittance (x, y) [π mm.mrad]	8.4, 7.2	6.3, 6.2

Table 2 X-ray parameters

	140MV/m	400MV/m
Energy	41.6 keV	60.2 keV
Laser	Flux [photons/shot]	
100MW7ns(700mJ)	1.1 x 10^6	6.4 x 10^6
12TW50fs(600mJ)	1.6 x 10^7	9.6 x 10^7
10TW1ps(10J)	2.7 x 10^8	1.6 x 10^9

To increase the flux, increase of the energy of the laser or the charge of the electron beam is the solution. Considering a compact system, we should not increase the laser energy. The Nd:Glass laser to achieve 10 TW 1 ps is rather large as 10 x 10 m^2. Since we cannot increase the charge in one bunch because of the space charge effect, we increase the number of bunches with micro-seconds intervals in one pulse to establish multiple collisions. To make the multibunch beam in the photocathode RF gun, we need to develop a multipulse laser and high-quantum-efficiency cathodes to save the laser energy. We also need to consider colliding one intense laser pulse with the multibunch beam. Multipath optics for 6-times collisions, for example, will be constructed to produce 10^{10} photons/pulse. After the optimization of this system, we expect to reach 10^{11} photons/pulse.

4 SUMMARY

We calculated X-band 1.5- and 3.5-cell photocathode RF gun and X-band linac for inverse Compton scattering X-ray system. The field applied to the gun should be 300-400 MV/m. We also evaluated the X-ray flux. Using 10 TW 1 ps laser, we got 1.6 x 10^9 photons/shot. When we make the multibunch beam and multipath optics for 6-times collisions, we can obtain 10^{10} photons/pulse.

REFERENCES

[1] J. Rosenzbeig et al., in *Advansed Accelerator Concepts*, AIP Conf. Proc. **335** 724 (1995)

[2] E. Esarey et al, Phys. Rev. E **48** 3003 (1993)