COMPACT X-BAND (11.424 GHZ) LINAC FOR CANCER THERAPY

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Abstract

Monochromatic hard X-ray inspection device based on Compton scattering effect between electron and laser beam is very useful for medical purposes such as for dynamic Intravenous Coronary Arteriography. To realize compact system of the monochromatic hard X-ray source a compact X-band (11.424 GHz) electron linear accelerator (linac) is introduced. The linac have been studied and under designing in Nuclear Engineering Research Laboratory (NERL), the University of Tokyo. X-band thermionic cathode RF gun is used. X-band accelerating structure type of standing wave, pi/2-mode is designed. A 45 MeV electron beam with 20 pC/bunch is generated. In order to simplify in radiation shielding and avoid neutron radiation, we realize deceleration of the electron beam before dumping.

INTRODUCTION

Monochromatic hard X-rays of 10 to 50 keV could be the best choice for medical inspection such as Intravenous Coronary Arteriography. One may have monochromatic hard X-rays by Synchrotron radiation via a monochrometer. However, most of Synchrotron radiation sources are too large to apply and use widely for public Intravenous Coronary Arteriography. Therefore, in NERL, a 50 MeV X-band (11.424 GHz) traveling wave linac have been designed and under construction to realize the remarkable compact monochromatic hard X-ray of 33 keV based on the electron-laser collision, seen from Fig.1. However, design this linac we aim to test acceleration operation and all of its components such as Klystron, laser system and so on. It would not to be install in hospitals.

For the second development phase we are designing a 45 MeV X-band standing wave linac that is more compact and easily to realize for decelerate the electron beam before dumping. Since the size of this linac is reduced so that it is easily to install in hospitals for widely public diagnostic/treatment. The X-band linac with two energy modes, maximum electron beam energy of 45 MeV will be driven to laser beam to produce a very monochromatic and intensive X-ray beam by Compton scattering effect. The monochromatic hard X-ray would be used for Intravenous Coronary Arteriography. Other mode is of 20 MeV electron beam hits a target to produce a high energy Bremsstrahlung X-ray beam and would be used for cancer therapy. Figure 2 shows schematically the X-band (11.424 GHz) standing wave linac that we are designing.

In order to reduce the refection power from the linac structure to Klystron, one of possible scheme that linac structure is separated into multi parts. In this design, 80 cm linac structure would contain 4 short standing wave structures (of 20 cm, 15 cells for each). Multi-bunch electron beam generated by a thermionic cathode RF gun is collimated and compressed by a alpha magnet and accelerated by 4 accelerating structures of the linac. The beam is bent by the achromatic bends and focus at the collision point, here hard X-ray is generated via Compton scattering on laser-electron collision. After collision with the laser, the electron beam is bent and injected to the structure again with suitable injection phase it will be decelerated down to less than 1MeV at the beam dump.

Design and numerical analysis of cavity structure for the X-band linac is presented in this paper.

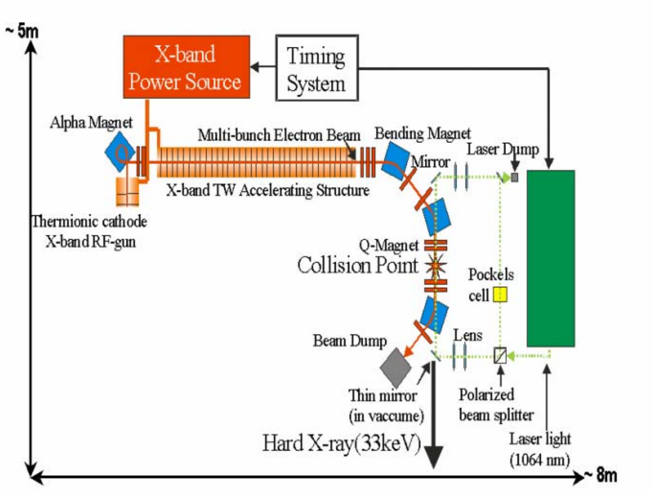

Figure 1: Schematic of Compact hard X-ray source based on the 50 MeV X-band TW linac and laser system in NERL (under construction).

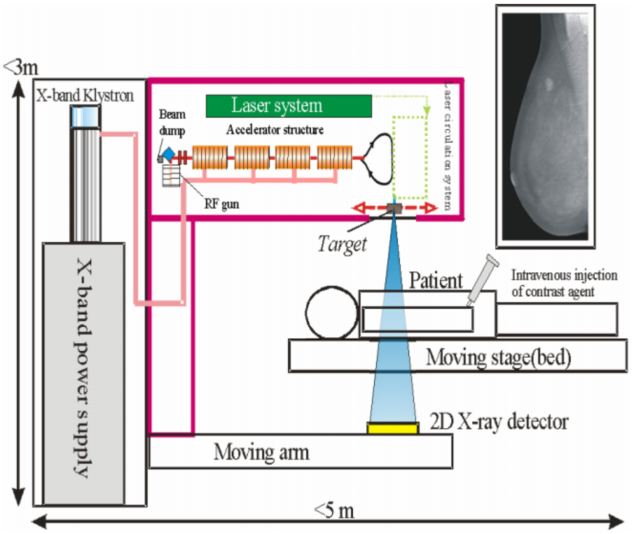

Figure 2: Schematic of Compact hard X-ray source based on the 45 MeV X-band SW linac and laser system in NERL (under design).

DESIGN OF CAVITY

Numerical Analysis

The X-band linac is applied for the compact hard X-ray source. The cavity is designed for RF X-band frequency of 11.424 GHz (wave length of 2.624 cm). Average field gradient of 67 MV/m is applied to the structure realize the remarkable of compact accelerator. As fixed frequency of 11.424 GHz, there are still many important parameters of an accelerator cavity to consider in designing a highly efficient linear accelerator. They are shunt impedance, quality factor Q, transit time factor, power loss, stored energy, and peak surface electric field. These values can be obtained by solving Maxwell's equations with given boundary conditions, it could be performed by computer programs. SUPERFISH simulation program is one of the codes that provide accurate fields, and other electromagnetic properties of an axis-symmetric cavity.

We have designed the compact X-band (11.424 GHz) accelerator structure using SUPERFISH simulation computer code. Structure type of X-band (11.424 GHz) standing wave, pi/2- mode, on-axis coupling is designed. The result is confirmed by running PARMELA simulation computer codes.

Numerical Results

In design the accelerator cavity, one of the most important parameters for cavity geometry optimization is the effective shunt impedance, ZT^2/L. Since the resonant frequency depends on all cavity parameters, so that during optimization of the cavity geometry, these dimensional quantities should be varied together to keep the fixed resonant frequency of 11.424 GHz.

High effective shunt impedance of 85 Mohm/m was achieved when we designed the cell with a nose. Figure 3 shows the two full on-axis coupling regular cells of the accelerator structure. Table 1 shows the geometry dimensions of the cavity that optimised in designing. The computational result is shown in Table 2. The result indicates stored energy for one cell is of 0.048 Joules. Since the Klystron RF power source of 50 MW is apply for the structure implies maximum energy of 0.05 Joules for one cell that value is very consistent with realistic case. Peak field to average ratio is of 3.2 indicates the maximum field on the surface is about 200 MV/m. It is possible to apply for the X-band linac.

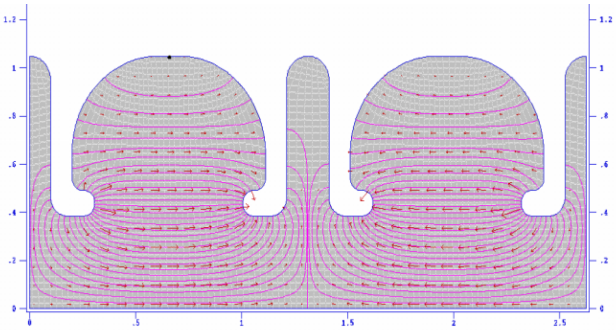

Figure 3: Two cells of the X-band linac

Table 1: Parameters of the cavity X-band, pi/2- mode, SW, on-axis structure type

Cell length, L_c	13.121 mm
Cell radius, R_c	10.490 mm
Beam hole radius, R_b	3.850 mm
Nose height, L_n	3.065 mm
Coupling cell diameter	2.000 mm

Table 2: Cavity parameters computed by SUPERFISH

Average gradient	67 MV/m
Frequency	11.424 GHz
Transit time factor	0.80
Quality factor	7768
Effective shunt impedance	85 Mohm/m
Stored energy	0.048 Joules
Power dissipation	447 kW
E_{max}/E_0	3.2

After successful optimizing the cavity in design by SUPERFISH it is running by PARMELA. PARMELA has been used to simulate the beam trajectory along the whole structure taking in consideration the space charge effect. At the first stage we simulate for the beam transport for the system including the thermionic cathode RF gun and for the whole X-band accelerating structure. The simulation has been considered to space charge effect. The number of electron bunch per pulse is 10^4; beam charge is 20pC/bunch. The RF pulse width is supposed to be 1 μ second.

Table 3 shows the output beam parameters of the RF gun that injected to the main accelerating structure.

Table 3: Estimated output beam parameters of the RF gun

Energy	3.5 MeV
Charge	20 pC/bunch
Beam size (x, y plane)	0.7 mm x 0.7 mm
Electron bunch length	0.5 ps
Beam emittance	2.5 pi-mm-mrad

In the simulation, four accelerating structures would be assembled on-line with 2.5 cm drift space between each short structure. The total length of whole structure is to be 86.2 cm. At the space between the alpha magnet and the structure we set a pair of quadrupole in order to focus the electron beam. The first quadrupole is used for focusing the beam in y and defocusing in x-direction. The second quadrupole is used for focusing in x and defocusing in y-direction. The net effect is focusing the electron beam.

Figure 4 presents the beam profile in x-y plane and figure 5 presents the energy spectrum at the end of the accelerating structure. This profile indicates the beam size at the end of the linac is of 960 micrometer in horizontal and 870 micrometer in vertical. This shows that the beam is spread so that we have to compress the beam before it is injected to the accelerating structure.

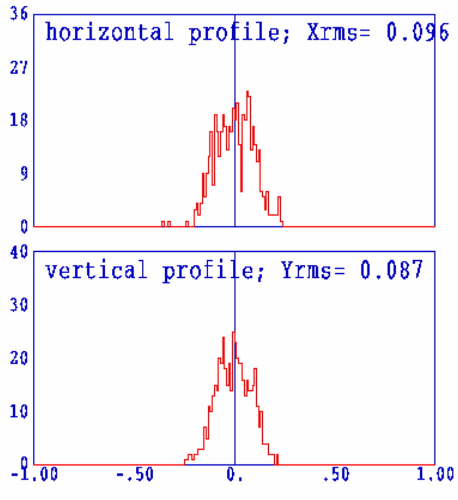

Figure 4: Beam profile in x-y plane at the end of the X-band linac

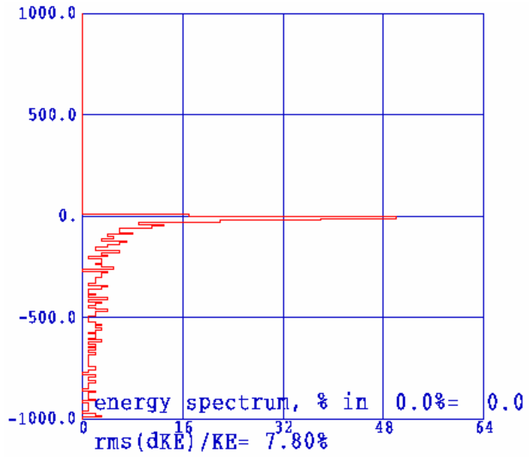

Figure 5: Beam energy spectrum at the end of the X-band linac

Table 4 summaries the specifications of simulated the X-band accelerator structure. The simulation results indicates that energy rise about 10 MeV after each accelerating structure. Final energy is reached 45.9 MeV that match the desire. 45 MeV is enough to realize Compton scattering between the electron beam and laser beam to produce 33 keV hard X-ray.

The beam after collision with laser beam is bent to the structure again in order to realize deceleration. On the beam dump, three energy levels (3.5 MeV, 1.5 MeV and 0.9 MeV) of the deceleration beam are considered to simulate and compare the radiation dose of each. Since radiation dose is proportional to cubic of kinetic energy, radiation dose for the case of 0.9 MeV is 3% compare to the case of 3.5 MeV while for the case of 1.5 MeV is about 10%. At this time we have estimated the radiation dose for 3.5 MeV at the distance of 1 meter from the beam dump is of 288 Sv/week. It could be much smaller if the beam would be decelerated to 0.9 MeV. So that radiation shielding for treatment room could be more simplify.

Table 4: Specification of the simulation for the whole structure of the X-band linac by PARMELA

	End of ACC1	End of ACC2	End of ACC3	End of ACC4
Total length [cm]	19.68	41.86	64.04	86.22
No. of cell	15	30	45	60
Energy [MeV]	13.69	24.35	35.14	45.93

CONCLUSIONS

We are designing the X-band medical linac to developing the compact X-ray source by electron-laser collision based on the X-band linac for Intravenous Coronary Arteriograpgy. To realize the compact system and deceleration of the beam we have chose X-band standing wave structure type to design. The design of the linac considers four accelerating structures to reduce the refection power to the Klystron. We are going to complete the design to realize the beam size to be 100 micrometer, 2.5 pi-mm-mrad. At the next step, we proceed to design with the deceleration system.

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