THE JAERI SUPERCONDUCTING RF LINAC DRIVER FOR AN INDUSTRIAL 1.3 MICRON 40 KW HIGHLY-EFFICIENT FREE-ELECTRON LASER

E J. Minehara, T. Yamauchi, M. Sugimoto, M. Sawamura, R. Hajima, R. Nagai, N. Kikuzawa, T. Hayakawa, N. Nishimori, and T. Shizuma, JAERI, Tokai, Naka, Ibaraki 319-1195, Japan

Abstract

As the JAERI superconducting rf linac based free-electron laser (FEL) has successfully been lased to produce a 2.34kW FEL light and 100kW or larger electron beam output in quasi continuous wave operation in February 2000, it resultantly exceeded twice of the 1kW program goal [1-4]. These results have been achieved by improving the electron gun, rf phase and amplitude controls, optical out coupling methods in the FEL optical resonator, and electron beam time-focusing in the JAERI FEL driver. As our next high power FEL program goal is the 40 kW FEL light and 4 MW electron beam output in average, quasi continuous wave wave operation of the light and electron beam will be planned in the JAERI superconducting rf linac based FEL facility. Conceptual and engineering design considerations needed for such a very high power operation will be discussed to improve and to upgrade the existing facility, especially about the superconducting rf linac FEL driver. Reflected geometry, which was originally invented as a medical linac's energy doubler is introduced to improve a wall-plug efficiency for a full energy recovery in the driver.

1 INTRODUCTION

In a conventional laser device, there are commonly three major components of the driver like a flash lamp, the gain medium like a crystal, and the optical resonator mirrors. In the conventional laser system, heat losses and damages in the components give the serious limitations to the applications and intrinsic performances since the invention in 1960. In a free-electron laser (FEL) system unlike the conventional, the losses in the gain medium will be quickly removed from the inside because the medium consists of an undulator generating an alternating magnetic field and a highly energetic electron beam. Resultantly, no deterioration is observed in the optical quality of the gain media during the high power operation. However, a normal conducting rf linac as the FEL driver produces a large amount of heat, and is very inefficient like the lamp. In order to improve drastically the efficiency and power output, and to realize very small errors of the amplitude and phase in acceleration, we have to introduce a superconducting rf linac because of a negligibly small heat loss inside the cavities.

We summarize our results in three steps of the JAERI superconducting rf linac based FEL program [1-4]. Final goal of the program is a demonstration of the high power and highly-efficient continuous wave (CW) FEL lasing using the JAERI superconducting rf linac driver with a full energy recovery scheme. After a successful ending of the program, the wall-plug efficiency will be expected to be very high. First, we spent about 7 years to build a prototype of the driver [1]. We could operate the driver with a nearly 100% conversion efficiency from the rf power to the electron beam one optimizing the adjustable coupler. Second, we spent another 4 years to demonstrate 2.3kW FEL power averaged in a quasi-CW operation with the world-highest extraction efficiency of 4.6%. To realize twice or more of a 1kW FEL output, we have improved the electron gun [4], rf phase and amplitude controls, resonator opticals and injection system. Third, beam energy recovery will be demonstrated by adding another electron beam recirculation half loop in the existing FEL facility within a few years [2,3].

In the following, the superiority of the superconducting rf linac based FEL, the brief history and current improvements, the world-strongest FEL oscillation achievement of 2.3kW in quasi CW operation February, 2000 are discussed, and future programs and/or related technological developments added. Especially, conceptual design and considerations are discussed about a 40kW CW 1.3 micron Industrial FEL.

2 SUPERCONDUCTING RF LINAC DRIVER

As explained already, the first step is decided to build a prototype of the quasi-CW superconducting rf linac FEL driver, the second the high power FEL lasing, and the third the energy recovering. In the prototype FEL driver, we have developed a number of accelerator components and technologies listed in the following. They covers the 250kV thermionic triode electron gun generating a 1ns width and 1.2nC micropulse, all-solid-state rf power supplies, superconducting bulk Nb accelerating cavity module, liquid-coolant-free cryogenic refrigerator system, a personal-computer based accelerator control system, a hybrid wedge-pole permanent planar undulator and optical resonator system. After the ending of the second, some demonstrations of a few applications should be planned, and we have already gotten some preliminarily results in environmental problem ones. In addition to them, an industrial superconducting rf linac based FEL machine and an academic FEL user facility have been discussed since the beginning. We spent about 7 years to build the JAERI superconducting rf linac FEL driver since 1989. Each component of the facility is explained and discussed briefly in the following. All of them are planned to develop in the industrial machine.

The electron gun consists of a SF6 gas-insulated pressure vessel, a fast grid pulsar and a high voltage power supply. In the beginning, shortened to be 0.8ns or less, and the peak current a micropulse width had been 4ns or 6ns, recently the width became typically increased to be several times larger than the original. The micropulse is compressed to be 4.8 ps or less by the subharmonic buncher of 83.3MHz and others. There are two kinds of time structure of the micropulses and macropulses. The gun fires once every 96.04ns, and micropulse repeats at 10.4125MHz. In the first macropulse mode, every 100ms, the gun typically fires for about 1ms long or less. In the second mode, at the end of the macropulse train, the gun typically fires for 100ms or longer and once. The final macropulse duration of the second mode is made to be adjustable and continued to fire up to 5000ms. The second mode power supply was successfully tested by a dummy load and the third rf power supply up to 100ms. We decided to use these two modes instead of a true CW mode because of a thin shielding wall, avoiding some damages from the beam hitting in the low energy side and a shortage of the electricity in the FEL building. After the third step, we may minimize the electricity consumption using the energy recovery scheme, and use the true CW mode. The first is so long to simulate the FEL physical process and an rf power amplifier's thermal process inside the transistor's ceramic housing. Thermal processes in the superconducting cavity modules, and optical resonator and optical transport systems are so slow not to simulate by the two modes within a few seconds.

The JAERI design option for the superconducting cavity and cryogenic system are explained briefly in the following. As we have no maintenance and operation crew and no specially trained specialist, we have to run the system by ourselves without any maintenance for one or two years. In order to realize a maintenance free and an easy operation in the JAERI FEL, we world-firstly introduced a so-called Zero-Boil-Off (ZBO) cryostat concept in the field of the superconducting rf linac technology[1]. Unique features of the cryostat are as follows. (1) Stand-alone, possibly movable structure, not a parasitic one, (2) Independent modular refrigerator structure, each cryostat for a pair of 4K and 10K/50K refrigerators, (3) liquid coolant free, no need for liquid Nitrogen and liquid Helium except for the liquid buffer to stabilize the temperature and pressure inside the module. Liquid He buffering is not mandatory, near future liquid-free system to be realized, and (4) Each module of the cryostat has a 10K/50K two-staged He gas Gifford-McMahon type (GM) refrigerator as a heat shield cooler and a He gas 4K JT (Joule-Thomson)-GM composite refrigerator as a liquid He recondensor inside the cavity liquid He container. In addition to them, the JAERI module has a vibrational isolation steel frame between the module and the refrigerators, and Piezo fast tuner and mechanical slow one, three higher mode couplers and an adjustable main coupler, and double heat shields. As expected in the above explanation, we can easily replace any one module in the system for repairing and improvements within a few hours, and add another module very easily to the system for future expansion without any serious problem. Therefore, we can run it continuously over a few years without stopping by exchanging the refrigerator system. In order to minimize the heat invasion and to optimize a thermal anchoring in all heat bridges between 4K and 300K, and thickness of the heat shields, we performed the finite element method simulation to calculate temperature distribution of the heat shields, and heat invasions through the beam pipes, liquid He supply tower, higher mode couplers and main coupler. A typical example of the 50K heat shield temperature is ranging from 49K to 55K. Heat invasions of the four modules are measured to be in the range from 2.5W to 4.5W, and typically around 4W in the factory measurement. Quality factors and accelerating gradients of the cavities are in the range from 2.0x 10+9 to 2.5 x 10 +9, and from 5.8MV/m to 8.3MV/m. Once a year in the middle of October, a regular maintenance of the cryogenic system is usually performed to replace some sealing parts, rotary valves, oil filter and absorber materials for a week. In the 1996 Japanese fiscal year, we could run them continuously all cryogenic systems for one year without any stop and repairing except for the regular maintenance, scheduled and unscheduled power and water failures. The main coupler was designed, and needed to be adjustable, and used to minimize an insertion loss through it, and to maximize the efficiency.

3 WORLD-STRONGEST FEL OSCILLATION

The strongest and stable oscillation was first achieved in the JAERI FEL in the 26-th February 1998. Typical electron beam energy and resolution are 15.8MeV, and 0.4% respectively, the beam current and 10Hz-macropulse width 2-4 mA and 0.9ms or less, respectively. The optical resonator with a 52 period hybrid planar undulator (K=0.7) is 1.7m long and uses Au coated Cu mirrors of 120 mm diameter. Remotely controlled actuators adjust the optical axes and distance of the mirrors in order to coincide with the electron beam and micropulse repetition rate, respectively, before the oscillation. During the first successful operation, the highest FEL power was measured to be about 0.1 kW in the quasi-CW operation. The FWHM of the FEL spectrum is less than 0.09 micrometer, which corresponds to wavelength spread = 0.4% or less, and very near to the Fourier transform limited. Recently, the power was increased to be 2.3kW or more. A detuning range of the cavity is measured to be about 200micrometer. The FEL wavelengths spread were measured using a monochrometer with a pyro-electric line sensor during the measurements. An optical resonator length was measured and matched to a half of the micropulse separate distance with an accuracy of 0.1 micrometer or less using the JAERI quick resonator matching method. The third harmonic lasing were performed recently using a pair of enhanced reflectivity Gold-coated mirrors, the fifth, seventh, ninth and eleventh and the higher ones are underway.

4 FUTURE PROGRAMS AND RELATED DEVELOPMENTS

The goal of 1kW was already achieved to improve the lasing mode, introduction of wavelength-selective elements, optical out coupling method and so on in the FEL optical resonator and the electron beam performance upgrading in the driver. The modification and upgrading are still under way to extend further increase of the extraction efficiency. The electron beam energy recovery using the superconducting cavities and a recirculation loop will minimize resultant radiation hazards and shielding wall thicknesses, and maximize the FEL output and total conversion efficiency from electricity to the light output. A prototype of the energy recovery system in the JAERI FEL will be added in the FEL accelerator room by the middle of this year, the first recirculated beam will be expected till the end of this year.

5 INDUSTRIAL FEL DESIGN CONSIDERATIONS

In order to apply the superconducting rf linac based high power FEL to many fields of the world, we have to demonstrate its superiority with all other light sources in many itemized features and performances, i.e., high power capability, high wallplug-efficiency, low weight, small volume, tunability, low toxicity, no harmful by-products, little radiation hazard, low running cost, low capital cost, easy operation, maintenance free an so on. In a shipbuilding yard, high speed welding and cutting machines being free from post and pre processings have been needed to develop a 1.3micron 40kW Iodine chemical laser welder. The Iodine laser is coupled with a small diameter of 0.8-1.2mm and several tens meter long transmission fiber in order to realize the high speed welding of thick steel plates. Instead of the Iodine chemical laser, we plan to do a conceptual design work of a 1.3 micrometer 20kW superconducting rf linac based high power FEL, and to do some developmental works of the components in the FEL facility at Tokai, JAERI. As dispersion-free is observed to be 1.3 micrometer, and the minimum loss 1.6 micrometer in a telecommunication textbooks, we plan to shorten the wavelength and to tune too be 1.3 micrometer for the industrial FEL machine in the design.

Requirements to such a high power industrial FEL machine are already itemized above. An FEL device of the industrial are rather conventional except for the huge heat load of the laser light. We need some cooling devices and their interlocks to remove the huge heat concentration in the mirrors, windows and outcouplers. Electron beam power also become huge, but interruption of the beam means a sudden beam stop, and no damage in the driver like a storage ring because the rf power is planned to recycle inside the superconducting rf linac's cavities.

Basic design options for the JAERI industrial FEL are as follows.

1) A 180 degrees reflected or half-turn geometry of the recirculated energy recovery scheme shall be used instead of the 360 degrees full-turn one to improve the recovery efficiency of the superconducting cavities up to 100% in low energy.

2) A coupling coefficient of the main rf coupler shall be very small for each superconducting cavity to minimize losses in the rf system. Resultantly, very low powered simple main coupler and low rf power supply are enough to excite the cavity.

3) Low cost sputter-coated Nb cavities without higher mode couplers shall be used in order to minimize the capital cost of the machine.

4) A laser illuminated photocathode cw electron gun at a very high working voltage up to 0.5-2MV, or the existing thermionic high current and high charge cw electron gun at 0.25-0.5MV shall be used.

5) An energy recovering DC decelerator coupled with the electron gun shall be used to maximize the wall-plug efficiency, and to minimize the radiation hazards.

6) Other options of the machine shall be the same or the similar with the existing facility.

We have to pay about 30% of the total captital cost for the superconducting rf linac modules, the 20% for the rf system, the 20% for the refrigerators, the 20% for the electron gun, injection and transport system, and the 10% for the FEL related. We can cut about 70% or more of the superconducting cavity modules and 90%-99% of the rf system by developing above items. Electricity of the system is mainly consumed in the refrigerators, electron gun and decelerator. The industrial FEL machine has about several tens mA of electron beam current, 40kW of FEL power, and several MW of beam power.

We have already done two of the three steps of the program goal up to now as we mentioned above. A high-extraction efficiency regime which we confirmed recently is a good news, and a kind of a bonus for small-scaled applications and an offering another way to realize a high power FELs. And, we also mentioned about the next program towards 100kW class FEL machine above.

Especially, we discussed and itemized above some developmentals for the JAERI industrial FEL machine for a shipbuilding industry and de-poisoning environmentally-harmful chemicals like Dioxins, Furans and so on.

REFERENCES

[1] E.J.Minehara et al., pp159-161, in the proceedings of Particle Accelerator Conference, 1995, Dallas.

[2] T.Shizuma, et al., "Injector Design for the JAERI-FEL Energy Recovery Transport ", in this proceedings.

[3] R.Hajima, T.Shizuma, and E.J.Minehara, "Study on Emittance dilution in the JAERI-FEL Energy –Recovery Transport", in this proceedings.

[4] N.Nishimori, et al., "A Thermionic Electron Gun System for the JAERI Superconducting FEL", in this proceedings.