8. Present and Next Steps of the JAERI Superconducting rf Linac based FEL Program

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The JAERI superconducting rf linac based FEL has successfully been lased to produce a 0.3kW FEL light and 100kW or larger electron beam output in quasi continuous wave operation in 1999. The 1kW class output as our present program goal will be achieved to improve the optical out coupling method in the FEL optical resonator , the electron gun, and the electron beam optics in the JAERI FEL driver. As our next 5 year program goal is the 100kW class FEL light and a few tens MW class electron beam output in average, quasi continuous wave operation of the light and electron beam will be planned in the JAERI superconducting rf linac based FEL facility. Conceptual design options needed for such a very high power operation and shorter wavelength light sources will be discussed to improve and to upgrade the existing facility.

Keywords: high power, free electron laser, superconducting rf linac, quasi-cw, beam energy recovery

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]. Final goal of the program is a demonstration of the high power and high 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, very high wall plug efficiency will be expected. First, we spent about 6 years to build a prototype of the driver[1-6]. We could operate the driver with a nearly 100% efficiency from the rf power to the electron beam power optimizing the adjustable coupler. Second, we spent another 3 years to demonstrate 0.3kW FEL power averaged in a quasi-CW operation with a 30% of the expected extraction efficiency. To realize a 1kW FEL output, we plan to improve the FEL device, resonator opticals and injection system[7]. Third, beam energy recovery will be demonstrated by adding another electron beam recirculation half loop in the existing FEL facility within a few years[8].

In the following, the superiority of the superconducting rf linac based FEL, the brief history and current improvements, the world-strongest FIR FEL oscillation achievement of 0.3kW in quasi CW operation August , 1999 are discussed, and future programs and/or related technological developments added. Especially, conceptual design and considerations are discussed about a 20 kW CW 1.5 micron Industrial FEL.

2. Superconducting rf Linac Driver

We spent a few years to study feasibility on the FEL's in the end of 1980's. As explained already, the first step is decided to build a prototype of the quasi-CW superconducting rf linac of FEL driver, the second the 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 250 kV thermionic triode electron gun generating a 1 ns width and 1.2 nC 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. Since 1989, just after the feasibility, we spent about 6 years to build the JAERI superconducting rf linac FEL driver. Each component of the facility is explained and discussed in the following. All of them are planned to be used 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, a micropulse width had been 4 ns or 6 ns, recently the width became shortened to be 1 ns or less, and the peak current typically increased to be several times larger than the original. The micropulse is compressed to be 30 ps or less by the subharmonic buncher of 83.3 MHz. There are two kinds of time structure of the micropulses and macropulses. The gun fires once every 100 ns, and micropulse repeats at 10.4125 MHz. In the first macropulse mode, every 100 ms, the gun typically fires for 1 ms long or less. In the second mode, at the end of the macropulse train, the gun typically fires for 100 ms or longer and once. The final macropulse of the second mode is adjustable and continued to fire up to 5000 ms. The second mode power supply was successfully tested by a dummy load and the third rf power supply as long as 100 ms. 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 use the true CW mode using the energy recovery, especially in the compact industrial machine. The first is so long as 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 specialist, we have to run the system by ourselves without any maintenance for one year. In order to realize an easy maintenance and an easy operation in the JAERI FEL, we first introduced a so-called Zero-Boil-Off (ZBO) cryostat concept in the field of the superconducting rf linac technologies[4]. Unique features of the cryostat are as follows. (1)Independent modular refrigerator structure, each cryostat for a pair of 4 K and 20 K/80 K refrigerators, (2) 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, and (3) each module of the cryostat has a 20 K/80 K two-staged He gas Gifford-McMahon (GM) refrigerator as a heat shield cooler and a He gas 4 K JT-GM composite refrigerator as a liquid He recondensor inside the cavity liquid He vessel. 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, and add another module very easily to the system for future expansion without any serious problem. In order to minimize the heat invasion and to optimize a thermal anchoring in all heat bridges between 4 K and 300 K, and thickness of the heat shields, we performed the finite element method simulation to calculate temperature distribution of the heat shields, and heat invasions of the beam pipes, liquid He supply tower, higher mode couplers and main coupler. A typical example of the 80 K heat shield temperature is ranging from 49 K to 55 K. Heat invasions of the four modules are measured to be in the range from 2.5 W to 4.5 W, and typically around 4 W 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 5.8 MV/m to 8.3 MV/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 all cryogenic systems for one year without any stop and repairing except for the regular maintenance and scheduled and unscheduled power 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.

A 50 kW all solid state amplifier has a 32 fold coaxial stripline combiner, and several microwave monolithic integrated circuit (MMIC) and peripheral circuits in one print circuit board inside each of the 32 amplifiers of 1.8kW. In comparison with a vacuum tube amplifier, a solid state one has very wide band and resultantly fast response features. During the beam acceleration, errors of the field amplitude and phase were observed to be 0.05% and 0.2 degrees, respectively, except for a front tens μψ shoulder of the beam loaded drop. Since the installation of 1992, two of the 50 kW amplifiers have run very steadily without any malfunctioning.

3. World-Strongest FEL Oscillation Achievement in Quasi-CW Operation

The strongest and stable oscillation was achieved in the JAERI FEL in the 26th February 1998. Typical electron beam energy and resolution are 15.8 MeV, and 0.4% respectively, the beam current and 10 Hz-macropulse width 2-4 mA and 0.9 ms or less, respectively. The optical resonator with a 52 period hybrid planar undulator (K=0.7) is 1.7 m 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. The power is scattered from 10^{+8} to 10^{+9} times higher than that of the spontaneous emission. During the first successful operation, the highest FEL power was measured to be about 0.1 kW of 28μm in the quasi CW average. The FWHM of the FEL spectrum is less than 0.09 μm, which corresponds to $\Delta\lambda/\lambda$=0.4% or less, and very near to the Fourier transform limited. Recently, the power was increased to be 0.3kW or moreof 21μm. The detuning range of the cavity is recently about 150μm. The FEL wavelength 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 0.1μm or less using the JAERI quick resonator matching method[5]. The third and fifth higher harmonics were measured, the seventh, ninth and eleventh and the higher ones are not confirmed yet.

4. Future Programs and Related Technological Developments

The current goal of 1kW or larger will be achieved to modify the lasing mode, optical out coupling method in the FEL optical resonator and the electron beam performance upgrading in the driver. The modification and upgrading are now under way[7,8]. 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 the next year, the first recirculated beam will be expected next year.

In addition to them, we plan to use the existing and near-future-available facilities as coherent and partially coherent light sources. Several kinds of the light sources being under consideration and their regions of peak output power are planned in ranging from 100MW to 1 mW. Currently, available wavelengths are located in the region from far-infrared (FIR) to near-infrared (NIR) by fundamental and higher harmonics of the FEL, ones from a few tens nm to a few nm by an intra-cavity FEL Compton backscattering, and ones from several tens pm to 0.1 pm by channeling radiation and coherent Bremsstrahlung. Conventional lasers, which are currently and commercially available, are very attractive for a variety of applications in the region from NIR to ultraviolet (UV). As well known, FEL's are very competitive with other light sources in the two regions from FIR to mid-infrared (MIR), and from the UV to the shortest because of the tunability and a lack of another available light source.

5 Industrial FEL Design Consideration

In order to apply the superconducting rf linac based high power FEL to every field of this 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 processing have been needed to develop a 1.5 micron 20 kW Iodine chemical laser welder. The Iodine laser is coupled with a small diameter of 0.3 mm and several tens meter long transmission fiber in order to realize the high speed welding of thick steel plates. Instead of the Iodine laser, we plan to do a conceptual design work of a 1.5 micron 20 kW superconducting rf linac based high power FEL, and to do some developmental works of the components in the FEL facility at Tokai, JAERI.

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 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 coupler shall be very small or weak 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 0.5-2 MV, or the existing thermionic high current and high charge cw electron gun at 0.25-0.5 MV 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.

Usually, we have to pay about 30% of the total capital 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% 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, 20 kW of FEL power, and several MW of beam power.

6. Summary

We have done nearly two of the three steps of the current program goal up to now as we mentioned above. And, we also mentioned about the next program towards 100kW class FEL machine above. Especially, we discussed and itemized some developmental for the JAERI industrial FEL machine for a shipbuilding industry. We may itemize our recent activities and fruitful results except for the energy recovery work in the following.

(1) Successful operation of the first superconducting rf electron linac in Asia[6].

(2) Successful operation and construction of the first all-solid-state rf system for an electron rf linac with a practically infinite life span[2].

(3) Successful operation and demonstration of the world-largest recondensing 11.5 W 4 K He4 refrigerators system[1].

(4) Successful realization and operation of the world-first modular and independent Zero-Boil-Off (ZBO) cryostat for the JAERI superconducting rf electron linac FEL driver.

(5) Successful demonstration of the first coupling-adjustable main coupler in the rf electron linac, and optimization of the power losses in the rf system.

(6) Construction of the first shift- and deflection- compensated wedge pole hybrid undulator system[3].

(7) Successful realization one of the most precise and the quickest matching between twice of the optical resonator length with separate distance between two neighboring electron beam pulses[5].

(8) Successful demonstration of the world-first and largest recondensing 2 W 2 K He3 refrigerators system for a future higher frequency system.

(9) Successful demonstration of the world-strongest 0.1 kW FEL oscillation in a quasi-continuous operation in 1998, and upgrading to 0.3kW in 1999.

(10) Successful operation of the 100 kW-class electron beam output using the JAERI superconducting rf electron linac FEL driver.

(11) Successful operation of the 500 MHz UHF band superconducting rf electron linac with accelerating gradient from around 5 MV/m up to 8.3 MV/m[4].

(12) Successful 24 hour- and one year continuous operation of the JAERI FEL cryogenic system with no maintenance and operation crew and specialist in 1996 Japanese fiscal year.

(13) Successful achievement of 1.2 nC, 1.ns, and 10 MHz quasi CW firing of the 250 kV thermionic triode electron gun without any spurious micro pulse[8].

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