JAERI Superconducting rf linac based Free Electron Laser Program

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Abstract:

Recently, the JAERI superconducting rf linac based FEL has successfully been lased to produce a 0.3kW FEL light and 100kW electron beam output in quasi continuous wave operation. 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 multi-MW class electron beam output in average, quasi continuous wave operation of multi-MW electron beam will be planned in the JAERI superconducting rf linac FEL driver facility. Conceptual design options needed for such a very high power operation will be discussed to improve and to upgrade the existing facility.

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 low errors of the amplitude and phase in acceleration, we 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 6years 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 averaged FEL power in a quasi-CW operation with a 30% of the expected extraction efficiency. To realize a 1kW FEL output, we plan to improve the FELdevice, resonator opticals and injection system[7]. Third, beam energy recovery will be demonstrated by adding an 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.

2. Superconducting rf Linac Driver

We spent a few years to study feasibility on FEL' s in the ending 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 driver, we have developed a numbers 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 Nb accelerating cavity module, liquid-coolant-free cryogenic refrigerator system, a personal-computer based accelerator control system, hybrid wedge-pole permanent planer undulator and optical resonator system. After the ending of the second, some demonstrations of a few applications should be planned and now under preparation. In addition to them, an industrial superconducting rf linac based FEL machine and an academic FEL user facility have been discussed since the beginning. Since1989, 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.

The electron gun consists of a SF_6 gas-insulated pressure vessel, a fast grid pulsar and a high voltage power supply. In the beginning, a micropulse width had been 4ns or 6ns, recently the width became shortened to be 1ns or less, and the peak current increased to be several times larger than the original. The micropulse is compressed to be about 30 ps or less by the subharmonic buncher of 83.3MHz. There are two kinds of time structure of the micropulses and macropulses. The gun fires once every 100ns, and micropulse repeats at 10.4125MHz. In the first macropulse mode, every 100ms, the gun typically fires for 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 of the second mode is 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 as long as 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 use the true CW mode using the energy recovery, especially in the small 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 tip 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 4K and 20K/80K 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 20K/80K He gas Gifford-McMahon (GM) refrigerator as a heat shield cooler and a He gas 4K 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 iron 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 4K and 300K, and thickness of the heat shields, we performed the finite element method calculation 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 80K 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 end 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 system 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 50kW 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 0.2degrees, respectively, except for a front tens μs shoulder of the beam loaded drop. Since the installation of 1992, two of the 50kW 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 26-th February 1998. 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 planer 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. 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 in the quasi CW average. Recently, the power was increased to be 0.3kW or more. 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. The tuning range of the cavity is recently about 150μm. The FEL beam spot and wavelength spread were measured using a commercial pyro-electric camera and 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]. After a stepwise increase of the amplified spontaneous emission over a few days, detuning and fine tuning of the resonator and the driver were performed to maximize and to stabilize the light. Recently, the third and fifth higher harmonics were measured, the seventh, ninth and eleventh and the higher ones are not confirmed yet, and underway.

4. Future Programs and Related Technological Developments

The current goal of 1kW or larger will be achieved to modify the 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, 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 observed 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 1mW. 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 0.1pm by channelling radiation and coherent Bremsstrahlung. Conventional lasers, which are currently and commercially available, are very attractive for a variety of applications in the region from MIR to ultraviolet (UV). As well known, FEL' s are very competitive in the two regions from FIR to MIR, and from the UV to the shortest because of the tunability and a lack of another available light source.

5. Summary

We have done nearly two of the three steps of the current program goal up to now as we mentioned above. And, we discussed the next program towards 100kW class FEL machine above. We may summarize our recent activities and fruitful results 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 virtually infinite life span[2].

(3) Successful operation and demonstration of the world-largest recondensing 11.5W 4K 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 antenna in the rf electron linac, and optimization of the power losses in the rf transmission 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 neighbouring electrons beam pulses[5].

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

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

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

(11) Successful operation of the 500MHz UHF band superconducting rf electron linac with accelerating gradient from around 5MV/m up to 8.3MV/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 1.2nC, 1.ns, and 10MHz quasi CW firing of the 250kV thermionic triode electron gun without any spurious micro pulse[8].

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