QUASI-CONTINUOUS WAVE OPERATION OF MULTI-MEGAWATTS ELECTRON BEAM IN THE JAERI SUPERCONDUCTING RF LINAC FEL DRIVER

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Abstract

Recently, the JAERI superconducting rf linac based FEL has successfully been lased to produce a 0.1kW FEL light and about 70kW electron beam output in quasi continuous wave operation. The 1kW class output as our present program goal will be achieved to modify the optical outcoupling method in the FEL optical resonator and to improve the electron beam optics and basic performances in the JAERI FEL driver. As our next program goal is a 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 within a few years. Conceptual and engineering design options needed for such a very high power operation will be discussed to modify and to upgrade the existing facility in the conference.

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1 INTRODUCTION

As well known, a laser system consists of three major parts, i.e., a laser driver like a flash lamp, a gain medium like a glass or a crystal, and an optical resonator of paired or several mirrors. Since the invention of the laser in 1960's, efficiency and average power level of the conventional lasers have been seriously limited to very low by their huge heat losses in the laser drivers and gain media, and damages in the mirrors. Because a free electron laser(FEL) has an high energy electron beam in alternating magnetic field as the gain media, we could neglect the heat losses in the FEL gain media. Unfortunately, as long as conventional normal conducting accelerators were used to produce the high energetic electron beam as the FEL driver, we still have the large heat losses in the accelerator cavity wall of the FEL driver. Therefore, in order to make a highly-efficient, and high average power FEL, we resultantly have to minimize the heat losses in the driver to very low level in comparison with total rf power consumption. This is our motivation why we try to apply the superconducting rf linac to the JAERI FEL driver.

A developmental program[1,2] of the FEL system for a far-infrared region from the wavelength of 10μm to 100μm has been undertaken at Japan Atomic Energy Research Institute(JAERI), Tokai. The purpose of the present JAERI FEL program lies in constructing a very long pulse simulating the continuous wave(cw) and, or quasi- cw superconducting rf linac FEL driver of 100kW beam power, and demonstrating a high-average power FEL of 1kW in the far-infrared wavelength region.

Because the wall losses and required rf power become minimal in the superconducting accelerator cavity, we recently could realize the 100kW-class high-power rf linac driver in the quasi- cw, and hence the high-average power laser up to 0.1kW class. Each major part of the program including future plans has been reported in other papers [1,2] in detail. Here, we present an outlook of the program including the present status and future plans. Especially, the achievement of the present design goal of 1kW FEL output, and a quasi-cw electron beam of multi-MW class for realizing a 100kW FEL output will be discussed in briefly using an energy recovery scheme.

2 INJECTOR

An injector of the JAERI FEL consists of a thermionic cathode electron gun with a pulsing grid, a sub-harmonic buncher(SHB). The accelerating voltage in the single gap electron gun is typically around 235kV, and the gun is usable from 220 to 250kV recently. The cathode is mounted horizontally in a stainless-steel pressurized vessel with SF_6 gas to 2kg/cm^2 in order to prevent break down across a 45 cm-long insulating ceramic tube of the gun. The accelerating gap electrodes are fabricated in a re-entrant geometry to increase the accelerating gradient. As the old was located far from the pump, the new was made to locate just above the pump and to shorten the beam axis distance in September 1998. Resultantly, we could realize a arc or discharge related voltage degradation-free high voltage holding system. Conceptual design of the geometry and the optimization were made again by computer-modeling of electron beams using E-GUN[3], and beam parameter measurements, respectively.

The injector was first installed, and commissioned late August 1991, and had been operated routinely till the beginning of 1997. In 1997 and 1998, an intensive study of the pulser and electron gun performances and improvements had resulted in minimizing a pulse width and incresing the peak current and pulse charge. The improvements typically obtained are as follows: an electron beam ranging from 0.8 to 1.2A with 1ns bunch length was extracted from the gun at the accelerating voltage of 235kV. The beam was successfully compressed to 60 ps or less at around the time focus point by the bunching system[1]. Normalized emittances after the SHB were measured around 20 to 30 π mmmrad. Transmissions of the injector and the whole system were

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measured to be around 100% by using the JAERI-made current core monitors, fast Faraday cups and others

Time jitters of the pulses were measured to be as small as several tens ps around the gun. No firing of the unwanted pulse during the quasi CW mode, and very small peak current deviation of being well lower than 1% in each pulse have been achieved.

3 SUPERCONDUCTING RF LINAC

The JAERI superconducting rf linac consists of two pre-accelerator modules of the single-cell cavity type and two main modules of the 5-cell cavity one. The resonant frequency of the cavities is 499.8MHz which is exactly the same with the buncher, and the sixth harmonic of the SHB one.

We decided to choose a superconducting 500MHz cavity design with similar geometry's being found in KEK, DESY, and other high energy physics labs, and the fabrication technology refined by Siemens Energieerzeugung KWU for the JAERI FEL superconducting rf linac accelerator late September,1990. Design values of the accelerating field strength and quality factor for the cavities are 5MV/m, and 2 x 10^{+9}, respectively. In the beginning of 1993, we have successfully demonstrated a very good cryogenic performance of stand-by loss<4.5W at 4.2K, and accelerating fields' ones of 8.3MV/m and quality factor 2 x 10^{+9} in four JAERI superconducting accelerator modules, and installed them in the FEL accelerator vault.

As a main coupler was designed to have a variable coupling coefficient over 3 and half decades from the critical, we could inject not only low current but also high current electron beams into the accelerator cavity without losing rf power by mismatching in the coupler. In order to do some rf system diagnostics, we could easily and quickly perform low and high rf power tests anytime adjusting the coupler. Typical peak rf power for the coupler was measured up to the 50kW without any trouble in JAERI. The coefficient was designed to be adjusted by pushing and pulling a center conductor into the cavity over about 10cm.

Three sets of the higher mode couplers were made to suppress unwanted and harmful TE and TM modes having a higher resonance frequency. Two monitor couplers were used in monitoring and phase detecting in the feedback loop of a fast tuner. Slow and fast tuners were made to tune a resonance frequency of the cavity. The slow tuner consists of a stepping motor driver and an manually-controlled interface from the control system. The fast tuner consists of three sets of a piezo-electric actuator and a high voltage power supply, a feedback loop, an interface from the phase detector, and the control system in one module. During the beam acceleration, the system keeps the phase constant within 0.2 degree p-p, and keeps the amplitude constant within 0.05% p-p except for the first 10μs.

4 CRYOSTAT AND REFRIGERATORS

We have newly developed zero-boil-off (ZBO) multi-refrigerators system integrated into the superconducting accelerator module cryostat to realize a independent, and highly-efficient system without any liquid coolant. Instead of liquid He coolant, we need some amount of liquid He to stabilize the pressure and temperature inside the liquid He vessel and Nb cavity. Each accelerator module has own heat shield cooler and recondensor being equipped with two sets of refrigerator and compressor, independently. This modular structure of the cryostat makes it possible to remove any single module for repairing, and to add more modules without stopping and warming other module.

A 4K closed-cycle He gas refrigerator mounted just above a liquid-He supply tower of the module was adopted to cool down and to recondense cold vapor of liquid He around a heat exchanger in the liquid He container. Required electricity of a conventional liquefier is around 1kW for 1W cooling at 4.5K, and the required of the JAERI recondensor 1.8kW at 4.2K. In order to run the recondensor economically, we introduced a new heat buffering material of ErHoNi magnetic compound instead of Pb, and successfully reduced the required down to 0.9kW. A 40K/80K two-stage closed-cycle He gas refrigerator, which was mounted in a vacuum vessel of the module was adopted to cool down the 40K and 80K heat shields and other major components of the cryostat. These two kinds of the refrigerators are available commercially in Japan. The 4K refrigerator fixed in a heavy steel frame can be winched up and down to remove the heat exchanger out of the liquid He container, and to insert the exchanger into the container using two small in-house cranes. Cooling capacity of the 4K refrigerator is about 11.5W at 4.2K and 60Hz. We could run the whole system continuously with no trouble and no additional supply of liquid He for one year in 1996. Recently, we have prepared to increase effective cooling power by increasing the number of recondensor twice or three times and increasing cooling capacity of the single recondensor up to 25W

The 40K and 80K heat shields are used to prevent heat invasion from outside into the liquid He container. In order to minimize heat loads to the container, the heat shields work as a thermal anchor, and make the heat flow return route having a temperature higher than 4.2K for all heat bridges from the outside. The 40K/80K refrigerator used here provides two cooling stages with a typical pair of temperature of 40K and 80K and heat load capacities of 40W and 120W , respectively. As heat loads of the two stages in typical condition were very small,2W and 50W respectively, operational temperatures of them were very low, 10K and 50K, respectively. We have had absolutely no trouble in the heat shield coolers for about 6 years continuous running.

These two refrigerators and whole ZBO system including the prepared multi-recondensor ones have been authorized to run with no operational crew as a open dewar with the cooler by the Japanese central and local governmental offices under a full control of the Japanese pressure vessel codes.

5 RF POWER SUPPLIES

One of the largest merit of a superconducting accelerating cavity is very low power loss, which makes it possible to use all-solid-state rf power amplifiers for all of the cavities[1]. Because the required voltage of the all-solid-state amplifiers is lower than that of a klystron and a tetrode, a more stable, wider band width and faster-responsing rf power is expected to be realized. We chose two sets of all-solid-state 50kW rf power amplifiers for the main accelerators, two sets of 6kW for the preaccelerators, and 4kW for the SHB.

Performance of the rf power supplies has been successfully demonstrated to be better than 0.05% of amplitude and within 0.2 degree of phase stability at an rf power level of 35kW or more in lasing experiments. We have had no malfunctioning of the rf power supply since the installation, and we expect semi-infinite lifespan, no needs for aging, repairing and maintenance near future.

6 ELECTRON BEAM TRANSPORT SYSTEM

The energy of electron beams accelerated by the linac usually ranges from about 10 to 25 MeV. A conceptual design of the transport system was done by using the beam optics code TRACE-3D [4]. High current beams have to be fed to the undulator under isochronous or achromatic conditions for efficient lasing of FEL. Because of the large amount of charge density, space charge effects would become serious in a long transport line and a beam waist, especially from around the capture to just before the main accelerator module . Since the code could take into account partially space charge effects, the transport system has been investigated using the code.

A beam dump was capable of handling about 100 μA of true average current or more, and 2 kW of beam power. Cooling of the dump which was made from an Aluminum cylindrical block was provided by air flowing. About 40 cm-thick lead blocks surrounds the dump to reduce the radiation levels during routine operation to natural background levels outside the shielding walls made of 150 cm-thick concrete and soil.

7 PRESENT STATUS AND FUTURE PLANS

First saturated and stable FEL oscillation were observed to be around 25μm and 0.1kW at 16MeV electron energy in 26th February, 1998. An achievement of the present design goal of 1kW FEL output is partially discussed in each developmental items like the electron gun and others above. In addition to them, we planned and prepared to improve the optical outcoupling in axially-symmetric manners.

As our next program goal is a 100kW class FEL light and multi-MW class electron beam output in average, quasi continuous wave operation of multi-MW electron beam is planned in the JAERI superconducting rf linac FEL driver facility. As an example, several tens mA and 50MeV linac driver in the energy recovery, and 100kW 1.5μm FEL device for heavy industries are under consideration in cooperation with Japanese private firms. Conceptual and engineering design options needed for such a very high power operation are now under preparation to modify and to upgrade the existing facility.

After the current developmental program will be successfully ended, we plan to build a large-scaled high average power FEL facility driven by a superconducting rf linac with a 200MeV recirculating configuration, or to build a UV and shorter wavelength FEL facility without a recirculating configuration. After or before the second step, an industrial superconducting rf linac based CW FEL machine(Industrial SCFEL) will be built to demonstrate 1.5μm 20kW high average FEL output power capabilities of the superconducting rf linac FEL driver. These three plans under consideration in JAERI are not approved yet by Japanese government.

8 SUMMARY

In conclusion, we have presented the status and purpose of the JAERI quasi-cw, high-average power FEL program concerning the superconducting rf linac driver, and other FEL opticals. We reported our successful demonstration on the performances of the JAERI superconducting rf linac driver and FEL device. We are now active in realizing a demonstration of the 1kW FEL output and next step of mutli-MW FEL driver using the energy recovery technology.

9 REFERENCES

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