DEVELOPMENT OF THE JAERI FEL DRIVEN BY A SUPERCONDUCTING ACCELERATOR

E.J.Minehara, M.Sugimoto, M.Sawamura, R.Nagai and N.Kikuzawa,
Free Electron Laser Laboratory, Department of Physics,
Japan Atomic Energy Research Institute
2-4 Shirakata-shirane, Tokai-mura, Naka-gun, Ibaraki-ken, 319-11 Japan

A prototype for a quasi-cw, and high-average power free electron laser (FEL) driven by a 15 MeV superconducting rf linac has been developed, and constructed at Tokai, JAERI. Expected cryogenic(stand-by loss<3.5W at 4.5K) and accelerating fields' performances (Eacc ~ 7MV/m and Q ~ $2\times10^{+9}$) of four JAERI superconducting accelerator modules have been demonstrated, and installed them in the FEL accelerator vault. A beam test and commissioning of the JAERI superconducting rf linac as an FEL Driver have been successfully performed to get an electron beam ranging from 10 to 20 MeV with nearly full transmisson. FEL opticals and beam transport elements around the undulator, which have been already assembled, are now under commissioning. Spontaneous emission in the wavelength of 20 μm to 80 μm or longer has been observed by using the Ge (Cu) and Ge (Ga) detectors and fast current amplifier system.

I. 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 mirrors. Since the invention of the laser in 1950's or 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 energy 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 accelerator to the JAERI FEL driver.

A developmental program [1,2] of the FEL system for a far-infrared region from the wavelength of 20 μm to 80 μm or longer 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 or quasi-continuous wave (cw) superconducting rf linac electron accelerator, and demonstrating a high-average power FEL in the far-infrared wavelength region.

Because the wall losses and required rf power become minimal in the superconducting accelerator cavity, we may realize a quasi-cw and high-current rf linac driver, and hence a high-average power laser. Each major part of the program including future plans has been reported in other papers [3-8] in detail. Here, we present an outlook of the program including the present status and schedule.

II. INJECTOR

The injector of the JAERI FEL consists of a thermionic cathode electron gun with a pulsing grid, a sub-harmonic buncher (SHB), and a buncher. The accelerating voltage in the single gap electron gun is typically around 210KV, and the gun is usable from 200 to 240 KV. 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. Optimization of the geometry was made by computer-modeling of electron beams using E-GUN [9].

The injector was installed, and commissioned late August 1991, and is now operated routinely. An extensive study of pulse characteristics as a function of injector parameters has resulted in sets of optimized operating conditions which minimize pulse width at a time focus point while maintaining the beam quality as good as possible. The characteristics typically obtained are as follows: an electron beam ranging from 85 to 140mA with 4ns bunch length was extracted from the gun at the accelerating voltage of 210-240KV. The beam was successfully compressed to less than 70 ps at around the time focus point by the bunching system [1] in the injection beam line. Measured normalized emittance after the SHB was scattered around 10 to 20 π mmmrad. Transmission of the injector was measured to be around 100% by using the JAERI-made current core monitor.

III. 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 type. The resonant frequency of the cavities is 499.8MHz which is exactly the same with the buncher, and the sixth harmonic of SHB in the injector.

We decided to choose a so-called DESY concept of the cavity geometry 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 Q-value for the cavities are 5MV/m, and 2×10^9, respectively. In the beginning of 1993, we have successfully demonstrated very good cryogenic (stand-by loss < 3.5W at 4.5K) and accelerating fields' performances (Eacc~7MV/m and Q~$2 \times 10^{+9}$) of 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, we could inject not only low current but also high current electron beams into the accelerator module without changing a rf matching condition in the coupler. In order to do some diagonostics, we could easily perform low and high rf power test anytime shortly utilizing the coupler. Typical peak RF power for the coupler was measured up to the 50kW without trouble in JAERI. The coefficient was designed to be adjusted by pushing and pulling a center conductor into the cavity.

Three sets of the higher mode couplers were designed, and fabricated to suppress unwanted and harmful TE and TM modes having a higher resonance frequency. Two monitor couplers were designed, and fabricated to use in monitoring and phase detecting in the feedback loop of a fast tuner. Slow and fast tuners were designed, and fabricated to tune a resonance frequency of the cavity in the module. The slow tuner consists of a stepping motor driver and an interface from the control system. The fast tuner consists of a piezo-electric actuator, a high voltage power supply, a feedback loop, an interface from the phase detector, and the control system. During the accelerator operation, the system keeps the phase constant wthin 1 degree, and keeps the amplitude constant within less than 1% .

IV. CRYOSTAT AND REFRIGERATORS

We have newly developed a multi-refrigerators system[5] integrated into the superconducting accelerator module cryostat to realize a independent, and highly-efficient system without any liquid coolant. Each accelerator module has own heat shield cooler and recondensor being equipped with refrigerators and compressors, independently. This modular structure of the module makes it possible to remove any single module for repairing, and to add more modules without 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. In order to run the recondensor ecomonically, 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 and other countries. The 4K refrigerator supported 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. Cooling capacity of the 4K refrigerator is about 12W at 4.5K and 60Hz.

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 4K 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.

V. RF POWER SUPPLES

One of the largest merit of a super- conducting accelerating cavity is very low power loss, which makes it possible to use all-solid-state RF power amplifiers for all of the cavities[4]. Because the required voltage of the all-solid-state amplifiers is lower than that of a klystron and a tetrode, a more stable RF power is expected to be realized. We choose to use two sets of all-solid-state 50kW RF power amplifiers for the main accelerator modules, two sets of 6KW for the preaccelerators, and 4KW for the SHB, and 2KW for the buncher.

All sets of the power supply have been already installed, and have been ready to use at the experimental area since the middle of August 1992. Performance of the rf power supplies has been preliminarily measured to be better than 1% of amplitude and within 1 degree of phase stability at an rf power level of 50kW or more. We have had no malfunctioning of the rf power supply since the installation, and we expect no repairing and no maintenance in the rf amplifiers near future.

VI. ELECTRON BEAM TRANSPORT SYSTEM

The energy of electron beams accelerated by the linac usually ranges from about 10 to 20 MeV. A conceptual design of the transport system was done by using the beam optics code TRACE-3D [10]. High current beams have to be fed to the undulator under isochronous and 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. Since the code could take into account partially space charge effects, the transport system has been investigated by using the code.

A beam dump in preparation will be capable of handling about 40 mA of true average current or more, and 1 kW of beam power. Cooling of the dump is provided by air flowing in channels or pipes machined into an aluminum rod. About 30 cm-thick lead 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.

VII. HYBRID UNDULATOR

A wedged-pole hybrid undulator will be used for the first lasing experiment of the JAERI FEL. The undulator was originally designed and built as a prototype undulator for the SPring-8 project [11]. This device is expected to generate brilliant photon beams of energy ranges around 10 keV by installation into the low emittance high energy storage rings such as the Spring-8 [12]. In order to fit the undulator into the JAERI FEL system, the undulator was characterized by three-dimensional field calculation and two-dimensional field mapping.

In order to characterize the undulator, a distribution of the multipoles was derived from the field distributions in the median plane of the undulator. A strip of the three-dimensional field distribution was obtained by using a conventional finite element method (FEM) calculation code ANSYS [13]. An experimental distribution was obtained by field mapping with commercially-available three-dimensionally measuring equipment.

Calculational and experimental distributions of the multipole components along the undulator axis were derived up to dodecapole components from the field distributions by a least-square fitting method. The calculated distributions of the multipoles quantitatively shows very good reproduction of the experimental distributions.

IX. ACCELERATOR VAULT

A new extension was completed to an old 5.5 MV electrostatic accelerator building as an FEL accelerator vault in March 1992. Two sets of the main accelerator module, the beam transport system, hybrid undulator, and FEL opticals were installed inside the vault in the beginning of 1993.

X. PRESENT STATUS AND FUTURE PLANS

In the beginning of 1993, we have successfully demonstrated expected cryogenic (stand-by loss < 3.5W at 4.5K) and very good accelerating fields' performances(Eacc > 7MV/m and $Q > 2\times10^{+9}$) of four JAERI superconducting accelerator modules, and installed them in the FEL accelerator vault. In 1993, Optical resonators and beam transport systemwere already assembled, and installed in the accelerator vault.

Before ending of the 1994 Japanese fiscal year (before March 31st, 1995), a beam test of the JAERI superconducting rf linac FEL was successfully performed to get an electron beam of ten and several amperes of peak current after the main accelerator at around 15 MeV. Measured energy resolution of a pre-accelerated beam is about 3% of FWHM , and that of a fully-accelerated beam about 0.8% or less. Maximum transmission of the beam from the gun to the undulator is now obtained to be at around 100%. Since September 1994, we have tried several number of spontaneous and stimulated far-infrared (FIR) emission measurements. By utilizng Ge (Cu) and other detectors equipped with the JAERI made fast current amplifier [14], very stable and large, and intermittantly very large FIR signals were observed around 25 μm during the measurements.

After the current developmental program will be successfully ended, we plan to build a large-scaled high average power FEL facilitydriven 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 FEL machine (Industrial SCFEL) will be built to demonstrate higher average power capabilities of the superconducting rf linac FEL driver. These three plans under consideration in JAERI are not approved yet by Japanese government.

XI. 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 injector, rf power supplies, four JAERI superconducting accelerator modules, hybrid undulator, and Liquid He refrigerators, which have been installed for these four years. We are now active in transporting electron beams in the JAERI FEL, and in performing some lasing experiments in the optical resonator.

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