JAERI 10KW HIGH POWER ERL-FEL AND ITS APPLICATIONS IN NUCLEAR ENERGY INDUSTRIES *

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Abstract

The Japan Atomic Energy Research Institute (JAERI) FEL laboratory has successfully developed the most advanced and new accelerator technology of "superconducting energy recovery linac (ERL)" and some nuclear energy industry applications in near future using the high power ERLs. The current operation and high power JAERI ERL-FEL 10kW upgrading program, ERL light source design studies, the proof of principle experiment to prevent a so-called stainless-steel cold-worked stress-corrosion cracking failure and de-commissioning of nuclear power plants were reported and discussed briefly as some typical applications of the ERL-FELs.

INTRODUCTION

In early days of the Japan Atomic Energy Research Institute (JAERI) high power energy recovery linac (ERL) free-electron laser (FEL) program around 1987 Japanese fiscal year (JFY), we discussed, and finally decided our three steps strategy of the FEL developmental program as described below. The first step ranging from 1989JFY to 1995JFY is to build the most powerful super-conducting linac FEL driver without energy recovery linac geometry (ERL) [1, 2]. The second one ranging from 1996JFY to 2000JFY is to build the most powerful FEL lasing as the world record without ERL [3]. Because we could not find another funding to build the ERL, we decided to postpone the ERL construction after our lasing the JAERI non-ERL FEL in the second one. The third one ranging from 2001JFY to 2005JFY is to build the most efficient FEL lasing using the ERL technology, and all assignments of the third are under development up to now. During the third, we have started some large-scaled ERL-FEL applications in nuclear energy industries and other heavy industrial works. The next one is to develop and build a huge fourth generation ERL light source facility, this is a conceptual design work and key components developmental ones. In the following sections, we introduce you and discuss them our some details of existing facilities and developmental works and explained our achievements and future plans.

JAERI ERL FEL STRATEGY

We had firstly built the non-ERL superconducting radio frequency (RF) linac FEL driver to demonstrate some higher electron beam power from 80kW to 100kW in quasi-continuous wave (CW) mode successfully. In order to keep cool and to use four 500MHz UHF superconducting RF cavities, we have selected four zero-boil off cryostats with a He gas 10K / 50K two stage Gifford-McMahon (GM) refrigerator of heat-shield cooling and a 4K Joule-Thomson (JT)-GM three stage refrigerator of liquid He re-condensing inside the liquid He containers. The non-ERL FEL[3] installed in the 50 years old nuclear physics experimental building and the 16 years old main accelerator vault one[1] had the 250 kV thermionic electron gun, 8 refrigerator compressors, large and small RF amplifiers and others, and 2 main accelerator modules, an electron energy analyzer, 14m long optical resonator hybrid undulator and beam line, respectively. The non-ERL FEL driver had been modified to add an ERL capability in the third step in 2001JFY.

Secondly, we tried to perform the most powerful FEL lasing using the non-ERL driver from 1996JFY to 2001JFY. We could successfully demonstrate the world strongest FEL lasing two times, the first record of 0.1kW in the end of 1997JFY and the second one of 2.34 kW in the end of 1999JFY [4]. During the final stage of the second record, we successfully found the new lasing mode to realize the a few hundreds femto-second of 3.4 cycles, high conversion efficiency of 6-9% from the beam power to FEL light one, one GW peak power and over 2kW high average power [5,6] . These performance parameters were typically obtained in the electron energy of 16.5MeV, bunch charge of 510pC, bunch length of 2.5-5ps, bunch repetition of 10.4125MHz, wavelength of 22.4 micron and quasi CW mode.

Thirdly, we have tried to realize the most efficient FEL lasing up to a 10 kW class or larger one constructing the super-conducting energy recovery linac-based free-electron laser (ERL-FEL) [7]. The JAERI ERL-FEL was naturally extended to the current configuration from the old one. The new JAERI ERL-FEL has the capability of about 8 times larger electron beam power than the old one, and was fitted into the existing JAERI FEL building interior. In the 10kW lasing system, there are the newly upgraded 250kV electron gun in the starting position, then one sixth sub-harmonic buncher (SHB), solenoid lens beam transport line, capture section of the first superconducting single-cell cavity, pre-accelerator of the single one, staircase-structured merging system of low and high energy electron beams, two main superconducting RF 5 cell cavities, east and west arcs of the achromatic and isochronous 180 degree bending magnet systems, an optical resonator, a hybrid undulator and a beam dump after one and half turns of the beam recirculation. All of the design parameters of the 10kW ERL were not realized because of the shortage of

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construction budgets. From 2001JFY to 2002JFY, we modified the non-ERL FEL to re-construct the new ERL-FEL with the same current and electron energy, and the same beam power.

10KW UPGRADING PROGRAM

In the periods from 2003JFY to 2005JFY, the upgrade of ERL injector from the original parameters of 0.5nC x 10.4125MHz = about 5mA to 40mA has been tried to realizing higher repetition from 10.4125 to 83.3MHz, and larger charge from 0.5nC to 1nC. We currently plan to run our grid-pulsar in 20.825MHz repetition x 1nC charge=20mA, or in 41.65MHz x 1nC = 40mA. As the grid-pulsar has had larger time jitter in 41.65MHz recently, we could properly run the pulsar in 20.825MHz or slower one with 0.5nC or 1nC right now. The radio frequency amplifiers for the injector were replaced from 2 quasi CW 6kW solid state amplifiers to true CW 50kW inductive output tube (IOT, or klystrode) based amplifiers. The two 50kW RF main amplifiers for exciting two 500MHz superconducting 5cell cavity accelerators were upgraded from quasi CW 50kW to true CW 50kW ones without increasing RF power because both of them were designed to excite mainly by re-circulated and decelerated electron beams in ERL configuration. As explained above, typical electron beam power of 17MeV and 40mA case are 680kW and the FEL light power about 10kW. Maximum beam power will be obtained to be around 800kW in the maximum electron beam energy of 20MeV.

JAERI ZERO-BOIL-OFF CRYOSTAT

The JAERI stand-alone and zero-boil-off (ZBO) cryostat which we have been reported and described in references [3,6] was designed to work as a liquid He container with two kinds of cooling refrigerators, in short, a very big Dewar with two small refrigerators. The cryostat has the two refrigerators of 10K / 50K GM and 4K JT-GM ones in the back of the cryostat and duplex heat shields inside the cryostat vacuum vessel explained in the references [3, 6]. The JAERI ZBO cryostat is one option of several possible techniques and technologies to realize a compact and user-friendly cryogenic system being dedicated for superconducting RF linacs of UHF resonating wavelengths. Resultantly, we could minimize stand-by losses of the cryostat to cut off about 80% or 90% of the conductive heat invasion from outside room temperature world in comparison with a liquefier-based conventional cryostat used currently in the world as the standard...

EASY CRYOGENIC OPERATION

Non-stop cryogenic operation from the program start to the end or no warm-up operation except for the final shut-down of the whole facility is only possible in the JAERI stand-alone and ZBO superconducting RF linac based systems because cold maintenance to replace a non-stop and over a few years-long operated refrigerator with the new one is easily done for a 15 minutes, and pre- and post maintenance procedures of the cold maintenance for a few hours just before and after the maintenance. Except for the cold maintenance, and unscheduled power failures like a lightning induced power failure, as we have had no liquid Helium loss or evaporation over these 4 and half years, we can continue the non-stop operation over 30 years or more in principle. No regulation of Japanese domestic pressure vessel code has been required to run the routine refrigerator operation and to perform the cold maintenance. Major advantageous points of the cold maintenance or non-stop operation are summarized in the following. The first point is no requirement of a time-consuming and difficult RF conditioning after the first conditioning just before the first beam. The second one is to expect no serious deterioration of cryogenic and low temperature components, no necessary conditioning related with some devices and vacuum components because the system was “frozen” to keep the fragile performances unchanged and kept cold around 4K and other very low temperatures over several tens years. The third is that we can always keep the whole system ready to fire. Our operational experiences over 14 years show very good statistics of the continuous zero-boil off operation over 1year and the recent 4 and half years. One year-long operation one typically shows the cryogenic operation of 355 days, maintenance stop of 3 days, unscheduled one of 3 days, and scheduled one of 2 days in 1997. A real non-stop cooling operation over the recent 2 and half years typically showed the cryogenic operation of 22360 hours, maintenance stop of 5.6 hours, unscheduled one of 5.2 hours, and scheduled one of 1.2 hours from 2001JFY to 2003JFY. Open problem of the non-stop operation is how to minimize running cost of electricity consumption during the idling operation, national holidays, and relatively long vacation.

COMBINING ZERO-BOIL-OFF CRYOSTAT AND EXTERNAL LIQUEFIER

As we have successfully demonstrated our easy maintenance capability and non-stop operability of the JAERI ZBO cryostat over a few tens of years, then we hope to build very large cooling power 2k and 4K refrigerator systems for future JAERI ERLs like a next generation light source using our cryogenic experiences and technologies [6]. Conventional large liquid He liquefiers have intrinsically better wall-plug efficiency to cool the cavities down to very low temperature than the JAERI ZBO cryostat and integrated refrigerators system. We need another independent group of about 10 or 20 night shift operation crews to run the large liquefier for 3 terms per year of 3 months-long continuous operation and one month-long maintenance under a severe regulation of Japanese domestic pressure vessel code. We plan to avoid these time-consuming and expensive domestic rules and to shorten the required administrative procedures processing times introducing a so-called Japanese structure reform and free-trade zone policy in cooperating with Ibaraki Prefecture Office and METI (Japanese Ministry of Economy Trade and industry). We hope to combine these two different cryogenic systems into one hybrid system and to keep cool safely and reliably using the JAERI ZBO systems' small refrigerator during idling without any RF excitation, and using the large liquefier during high power radio frequency amplifiers operation. The hybrid system can minimize the electricity consumption and probability of vacuum leak failures in the hybrid cryogenics, and therefore we can economically run our cryogenic system continuously cool without stopping and warming up to the program end over 25 years or more..

CURRENT 10KW UPGRADING RELATED ACTIVITIES

Current activities itemized here are to upgrade from the over 2kW to 10kW class lasing in the following. First; the DC gun current capacity is to increase from 5mA to 50mA under commissioning. Second, capture section and pre-accelerator RF amplifiers are upgraded from 6kW to 50kW. Third, main RF amplifiers will be upgraded from the solid state quasi-CW one to IOT true CW one. Fourth, low level amplitude and phase control circuits are upgraded to reproduce their accuracy and tolerance better than 0.1 % and 0.1 degree over a very long period, respectively. Fifth, a PC-based control system is upgraded to ensure reliable and high level control capability using iTRON OS. Sixth, beam monitors will be upgraded to replace the old destructive monitors with non-destructive ones. Seventh, a timing cable network is upgraded to replace the old higher temperature coefficient and non-temperature stabilized one with low temperature coefficient and temperature stabilized one. Eighth, FEL optical transport system was redesigned and is installed to the FEL accelerator vault and the experimental hall. All of these activities will be finalized to realize the designed performances within a year.

JAERI ERL FUTURE PLANS

As we already explained the 3 chronological steps and next ones of the JAERI superconducting non ERL- and true ERL-FEL developmental activities, we hope to build larger ERLs as our next steps. Our current and future activities will be divided into 2 directions of high power ERL-FEL applications and ERL-light sources near future. These two programs have been already proposed to MEXT (Japanese Ministry of Education, Culture, Sports, Science and Technology) and the ERL light source one has been accepted to review as one candidate of the most important and basic technological targets next 10 or 20 years in the 3rd science and technology promotion committee of MEXT. In the preparatory discussions between JAERI and MEXT officers, we proposed some conceptual design and site candidate to construct the future ERL light source in Japan.

NUCLEAR ENERGY INDUSTRY APPLICATIONS

As discussed in the future plans and programs, we have recently developed a few high power ERL-FEL applications in nuclear energy industries, for examples, prevention of cold-worked stress-corrosion cracking failures, very narrow width drilling and cutting and very thin depth peeling using non-thermal ultra-fast lasers like JAERI ERL-FELs and decommissioning of the nuclear power plants.

A 10 kW class high power industrial ERL-FEL which can be tuned to maximize transmission rate at around a fiber-transmittable wavelength of 1.3 micron and at around water transmittable wavelength centered around 0.5 micron will be very useful to transmit their power to a pin-pointed position located in a far distant place from the FEL. In the near future, the FELs will be widely used in the many factories like a shipyard, automobile factory, civil engineering, nuclear power plant and so on as discussed in references [3, 6]. A few FEL application examples will cover the application of non-thermal peeling, cutting, and drilling to decommission the nuclear power plants, and to prevent stress-corrosion cracking failures in the nuclear energy industry. As a very thin cutting width has been thought to realize a so-called radio-isotope (RI) "contamination-free" decommissioning, we plan to use a water-jet guiding of FEL light for non-thermal peeling, cutting, and drilling in decommissioning the nuclear power plants. The word "contamination free" is thought to be a kind of exaggerated usage whenever we can measure how much the total amount of the steel material is evaporated. However, we can substantially cut most of the cost being needed to build a large de-contamination plant. And we also have successfully demonstrated to prevent cold-worked stress-corrosion cracking failures of the vital components like pressure vessel shroud and re-circulating pump piping in the nuclear power plant. The cold-worked (CW) stress-corrosion cracking (SCC) failures have frequently happened in boiling light water reactor (BWR) shroud in Japan, Europe, USA and other countries. A proof of principle CWSCC prevention test experiments was performed to show to prevent fully the cold worked stress-corrosion cracking failures in several test samples of the reactor-grade low-carbon stainless-steel.

SUMMARY

We briefly reported here the past and present activities, and future programs of the JAERI ERL-FEL group in the followings. First, the developmental and operational issues of the past and present JAERI non-ERL and ERL FELs were explained, especially on the cryogenics. Secondly, the JAERI 10kW class upgrading program has been designed to increase the beam power from about 80kW to 800kW, and a current status of the program was explained briefly. Thirdly, preliminary and preparatory results of the JAERI ERL-FELs' applications in nuclear energy industries were briefly reported that the first proof of principle experiments successfully could prevent cold-worked stress-corrosion cracking failures in small sized reactor grade low-carbon stainless steel pieces and nuclear reactor decommissioning was planned using non-thermal laser drilling, cutting and peeling using ultra-fast JAERI FEL pulses, respectively. Fourthly, as reported in some other JAERI ERL-FEL contributions to the ERL and accelerator workshops, preparatory paper works, proposals, and conceptual design activities of the JAERI ERL light source development were reported and discussed very briefly.

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REFERENCES

[1] M.Ohkubo et. al. , Nucl. Instrum. Methods A296 (1990)270.
[2] M.Sawamura et. al. , Nucl. Instrum. Methods A318 (1992)127.
[3] E.J.Minehara et al., Nucl. Instrum. Methods A445, 183 (2000).
[4] N.Nishimori et al., Phys.Rev. Lett. 86, 5707 (2001).
[5] T. Yamauchi, et al., Jpn. J. Appl. Phys. 41 (2002) 6360-6363.
[6] E.J.Minehara, Nucl. Instrum. and Meth. A483 (2002) 8-13.
[7] R. Hajima, et al., Nucl. Instrum. Meth. A507 (2003) 115-119.