3.10 JAERI FEL Applications in Nuclear Energy Industries

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The JAERI FEL has first discovered the new FEL lasing of 255fs ultra fast pulse, 6-9% high-efficiency, 1GW high peak power, a few kilowatts average power, and wide tunability of medium and far infrared wavelength regions at the same time. Using the new lasing and energy-recovery linac technology, we could extend a more powerful and more efficient free-electron laser (FEL) than 10kW and 25%, respectively, for nuclear energy industries, and others. In order to realize such a tunable, highly-efficient, high average power, high peak power and ultra-short pulse FEL, we need the efficient and powerful FEL driven by the JAERI compact, stand-alone and zero boil-off super-conducting RF linac with an energy-recovery geometry. Our discussions on the FEL will cover the application of non-thermal peeling, cutting, and drilling to prevent cold-worked stress-corrosion cracking failures in nuclear energy and other heavy industries.

Keywords : FEL applications, Nuclear Energy Industries, Ultrashort laser pulse, Femtosecond free-electron laser, Stress-corrosion cracking failure, Cold-worked , Nuclear Power Reactors, Non-thermal peeling, cutting, drilling

1. Introduction

In order to realize a tunable, highly-efficient, high average power, high peak power and ultra-short pulse free-electron laser (FEL) as a versatile laser tool [1] for all, the JAERI FEL group has developed an industrial FEL driven by a compact, stand-alone and zero-boil-off superconducting rf linac [2] with an energy-recovery geometry. Our discussions on the versatile tool will cover many requirements for the industrial FELs, especially from the nuclear industries, some possible answers from the JAERI compact, stand-alone and zero-boil-off cryostat concept, non-stop cooling, and operational experience over these 10 years, our discovery of the new, highly-efficient, high-power, and ultra-short pulse lasing mode [3], and the energy-recovery linac technology. A very efficient and powerful FEL has been long required to use for almost all industrial applications, for typical examples, nuclear energy industry, defense, shipbuilding, and so on [1] instead of the conventional lasers, and other light and heat sources. As the industrial FELs would become popular in the world near future, the JAERI FEL group has tried to develop a compact, stand-alone and zero-boil off superconducting rf linac-based FEL with and without an energy-recovery geometry [2]. The JAERI cryogenics will be explained briefly, and the future directions and plans discussed.

Original strategy to develop the industrial FELs at JAERI consists simply of three steps, the first of making a highly efficient and high power FEL driver using an rf superconducting technology, the second of demonstrating a powerful FEL lasing using the driver [2], and the third of increasing an total system efficiency using a beam-energy recovering. After we found the new FEL lasing mode of high efficiency in the beginning of 2000 [3], we modified slightly the original, and added a new path to the old in the third step to develop and to realize the industrial FELs using the new lasing mode. The new path using the new efficient lasing will be discussed in the following.

2. Industrial Free-Electron Lasers

2.1 Long Holding Requirements and Hopes

Long holding requirements and hopes for the industrial FELs from their users and designer should be discussed, and itemized for each category to check how much they can be fulfilled before the FEL businesses would become popular. We could bring out them as typical examples of costs, reliability, compactness, easiness in the production, operation and maintenance, the operational and maintenance intervals, fulfillment for radiation safety code, pressure vessel code, other official regulatory rules and so on. The capital, operational, and maintenance costs for the industrial FELs should be minimized as low as the costs for existing and future conventional laser systems. Compactness of the FEL is very important because the FELs used in the factories, schools, hospitals and other small facilities must be fitted into a tabletop sized, or a trailer sized space being available in these small buildings. Most of them have been replied positively by the JAERI cryogenics design concept and others up to now [2].

2.2 Compactness, Stand-Alone, Zero-Boil Off Cryostat and Non-Stop Cooling Operation

Once we decide to introduce the stand-alone FEL, we do not need any huge central liquefier station of He and N_2 gas compressors to cool down the FEL driver outside the accelerator room or building. As each module of the superconducting rf linac has its own shield cooler and liquid He re-condenser, it independently stands alone without any cryogenic liquid coolant outside the module. In short, the stand-alone super-conducting rf linac based FEL will be run freely and independently in contrast with a parasitic FEL with the central liquefier station.

The zero-boil off cryostat for a superconducting rf linac has been first designed and developed for the JAERI FEL since the beginning of the program in 1989[4]. The JAERI zero-boil off cryostat has duplex heat shields, and the 20K/80K shield-cooler and 4K He-recondenser refrigerators integrated into the cryostat vacuum vessel. Unlike super-conducting magnet cryostats, the super-conducting rf linac cryostat has intrinsically large heat invasion through many heat bridges, for examples, two beam pipes, main and higher order mode couplers, support rods, refrigerator or liquid N_2 and liquid He transport pipes, sensor wiring, coaxial cables and so on. Heat economics in the cryostat has been optimized to minimize the heat invasion adopting a finite-element method of temperature distribution calculation in the cryostat. Calculated and measured stand-by losses to be from 2.5W to 4.5W at the JAERI cryostats are consistent with each other, and the zero-boil off one usually cuts around 80% or more of the loss in the conventional one. A compact 4 K He^4 GM-JT (Gifford-McMahon refrigerator with Joule-Thomson expansion valve) gas closed-loop refrigerator was introduced to realize a stand-alone and zero-boil off superconducting linac using 500MHz UHF band cavities. Cooling efficiencies of the liquefier is about 30% or more higher than the GM-JT recondenser. If the liquefier efficiency includes transferring losses, both liquefier and recondenser have nearly the same efficiencies but the slightly lower. The capital cost of the liquefier and coolant transferring system is nearly the same with or slightly cheaper than the GM-JT refrigerator as long as the system is as small as the existing JAERI system.

We have introduced an 8W 4K refrigerator being originally developed for the Japan Railways' Maglev train, and modified it to an 11W one to cool down our 500MHz UHF cavity cryostats about 16 years ago. We could successfully keep running the whole system over these 12 years. There have been successfully no trouble and no malfunctioning in the 4 shield coolers for about 12 years up to now, and no experience to dry up liquid He inside any He vessel of the 4 modules since the beginning in 1992.

The compact, stand-alone, zero-boil-off cryostat, and non-stop cooling operation with no warm-up or very long maintenance interval except for a few hours of maintenance each year will completely solve a large number of operational and maintenance problems. Like a superconducting magnet based MRI (magnetic Resonance Imaging), we plan to perform a cold maintenance in exchanging a displacer unit of the shield coolers and to keep the whole cryostat cool without de-conditioning the superconducting rf cavities. Because the domestic pressure vessel code does not allow to perform such a cold maintenance for the liquefier, and actual mechanical design or structure of the liquefier practically makes the cold maintenance and cold disassembling impossible, the non-stop cooling operation is only available for the stand-alone, zero-boil off cryostats like the JAERI FELs, and MRIs. We have run the cold maintenance 8 times over a few months as an aging test of the cold maintenance. Once we accidentally made wet air contamination into the cold refrigerator, we found and cofirmed that the contamination could be remove by replacing the displacer of the refrigerator. Because we have not found any accumulated contamination or dirt, and resultant instabilities and malfunctioning in the cooler, we thought we could keep the module and linac cold for a few tens of years or as long as we want practically. We have to perform a so-called "On-Call Maintenance" like a Xerox copier or an air-conditioner once per year for each recondenser and once per 3 or 4 years for each of the shield cooler. Since the May 2001 up to now, we have successfully kept non-stop cooling or running cool over about 4 years using cold maintenance technology.

2.3 Novel Ultrashort-Pulsed and Highly-Efficient Lasing Mode

A novel lasing mode has been discovered to realize ultra-short pulsed and highly efficient lasing in FELs at the JAERI FEL laboratory in the beginning of 2000 [3, 5]. As at that time the world-highest 2.34kW average power and about 1GW peak power were obtained at JAERI FEL, they will be replaced by their new records soon. As well known that an FEL conversion efficiency from the beam power equals with $1/2N_w$ where N_w stands for the number of wiggler periods, it is naturally understood that the FEL efficiency will become large if N_w will become small by another novel mechanism. There have been expected to be effectively small number of the period, and efficient after the FEL saturation because of some pulse-shortening and spiking mechanisms. As reported that pulse width of the new mode was measured to be a few cycle lasing of 3.4 cycle and 255 fs at 22.4 micron [3], the high efficiency of 6-9% is consistent with $1/2N_{cycle}$ where N_{cycle} stands for the number of cycle over the ultrashort pulse FEL width. If we can find some mechanism and succeed to realize the smaller cycle numbered lasing than the 3.4 cycle, the higher FEL efficiency from the beam power can be feasible to convert almost the whole beam power to the FEL power. For examples, a single cycle lasing of about 75 femtosecond would be expected to have 50% efficiency if the FEL efficiency could equal with $1/2N_{cycle}$.

2.4. Energy Recovery FELs at JAERI

The energy recovery circular loop at the JAERI FEL has been under operation and 10kW upgrading recently.

Energy recovery concept had been discussed and tried at Stanford University, Los Alamos National Laboratory and Jefferson laboratory since 1980's[6]. First demonstration of the same-cell energy recovery of the superconducting rf linac has been successfully done in 1999 at Jefferson laboratory to cut 75% of the needed rf power. Only a few % or slightly larger rf power of the non-energy recovering FEL is needed to run the energy recovering FEL, and the same wall thickness of an ordinary building is enough to shield very weak and low energy X rays level being generated. Therefore, we can easily cut most of the budgets of rf power amplifiers and heavy shielding walls of the buildings to construct the energy recovering FELs facility. The 360-degree circular energy recovery geometry is also planned to be used for academic facilities like an X-ray FEL and a light source to produce soft and hard X-rays ranging from 10 to 0.01nm.

Another energy recovery geometry and conceptual explanation have a 180-degree isochronous bending magnet to decelerate the electron beam anti-parallel with the acceleration direction. According to the original Canadian patent [7] in 1970's, the geometry and magnet were used to call a reflextron. In the 180 degree bending geometry, average or centorid velocities of the electon pulses in both the acceleration and deceleration are roughly the same along the accelerator cavity on the contrary to the circular recovering one which has a large velocity difference around the entrance and exit of the accelerator cavity. We could expect no serious head-on collisions from the 180 degree bending geometry because no collision had been found practically in the medical reflextron accelerator. The reflextron geometry has a relatively small number of beam optical components in line, and small building space required by the machine layout. The reflextron one can accept and recover the lower energy electron beam than a few MeV because nearly no velocity difference can be occurred between the deceleration and acceleration.

2.5 Industrial FELs near Future

Four nuclear industrial FEL models having the reflextron geometry are planned to apply some industrial applications..

Three of them are infrared FELs, and the forth ultraviolet or visible FEL. As planned already, the far-infrared FEL (FIR FEL) ranging from 200 to 50micron wavelengths uses the 500MHz UHF band cavity of 5-10MeV electron energy with the reflextron energy recovery geometry. The smallest model of the industrial FIR FEL will be made to perform an FEL higher power demonstration than 100kW or 1MW, to produce an intense Compton-backscattering gamma-ray flux of about 10MeVin synchrotron light sources, to image foreign materials inside foods, grain, fruits and powder as nondestructive testing and inspection, custom inspection, nuclear decommissioning and so on.

A mid-infrared FEL ranging from 50 to 8micron wavelengths will use the 500MHz UHF band cavity of 12-24MeV electron energy with the reflextron geometry. Possible and typical applications are expected to be large-scaled photochemical processing, medical, pharmacy, rare-material separation, radio isotope seperation in nuclear decommissioning and so on. A near infrared FEL ranging from 12 to 2micron uses the same 500MHz cavity of 24-48MeV electron beam energy with the reflextron. A 10 or 20kW industrial FEL which can lase at around a fiber-transmittable wavelength of 1.3-1.5 micron and at around water transmittable wavelength centered around 0.5micron will be very useful to transmit their power to a pin-pointed position in a distant area from the FEL. The FEL will be widely used in the many factories like a shipyard, automobile factory, civil engineering, nuclear power plant and so on. 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 in the nuclear decommissioning industry. As a very thin cutting width has been thought to realize a so-called 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. And we also have demonstrated to prevent cold worked stress-corrosion cracking of the vital components like pressure vessel shrould and recirculating pump piping in the nuclear power plant. The cold worked stress-corrosion cracking sample like BWR shrould has been found very frequently in the nuclear power plants. The FEL will be applied to lithography, photochemical processing, polymer surface modification, nuclear decommissioning, and so on.

3. Summary

The FELs driven by the superconducting rf linac have intrinsically very high average power capability because the linac driver is highly efficient and powerful. Relatively low efficiency converted from the electron beam to FEL power can be overcome, and increased to recover the remained beam power after the lasing by the ERL. As discovered the new lasing mode, we could make the FEL pulse ultra-short and very efficient without the ERL. Both paths of the energy recovery and the new lasing can be usable to make the FEL efficient drastically, and to realize the industrial FELs for the nuclear decomissioning soon. The reflextron geometry can be applied to make the industrial FELs compact, powerful, and efficient because an absolute value of the velocity difference is very small between the acceleration and deceleration along the accelerator cavity, and we can recover very efficiently the beam power at a few MeV or less electron energy.

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