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3.11 Free-Electron Laser and Related Quantum Beams

Eisuke J. MINEHARA

FEL Laboratory at Tokai, Advanced Photon Research Center,
Kansai Research Establishment, Japan Atomic Energy Research Institute
2-4 Shirakata shirane, Tokai, Naka, Ibaraki 319-1195 JAPAN

Past, present and future developmental programs of the JAERI super-conducting rf linac-based FELs and light sources with and without energy recovery have been discussed and introduced briefly. The JAERI FEL group has successfully discovered, and realized the brand-new FEL lasing mode of 255fs ultra fast pulse, 6-9% high-efficiency, one GW high peak power, a few kW average power, and wide tunability of medium and far infrared wavelength regions at the same time. Using the new lasing, we could realize a powerful and efficient free-electron laser (FEL) for industrial uses near future. In order to realize such a tunable, ultra-short-pulse, high averaged-power FEL, we have needed the efficient and powerful CW FEL driver of the JAERI compact, stand-alone and zero-boil-off super-conducting rf linac with an energy-recovery geometry. The JAERI energy-recovery and/or super-conducting rf linac driver has been developed to use as an industrial electron irradiator, and millimeter-wave, far-infrared, mid-infrared, near-infrared and shorter wavelength quantum beam sources.

Keywords :Free-electron laser, Ultra-short pluse, High peak and average power, Super-conducting rf linac, Non-warm up low-temperature operation, electron irradiator, quantum beam sources

1.Introduction

In order to realize a tunable, highly efficient, high average power, high peak power and ultra-short pulse free-electron laser (FEL), the JAERI FEL group has developed an industrial FEL driven by a compact, stand-alone and zero-boil-off super-conducting rf linac [1] with an energy-recovery geometry. The JAERI FEL group has tried to develop a compact, stand-alone and zero-boil off super-conducting rf linac-based FEL with and without an energy-recovery geometry. The JAERI cryogenics will be explained briefly, and the future directions and plans itemized.

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 super-conducting technology, the second of demonstrating a powerful FEL lasing using the driver, 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 [2], 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 briefly. Now, the JAERI energy-recovery and/or superconducting rf linac driver will be usable for producing a variety of quantum beams from milimter wave to gamma-ray, electron and other charged and neutral particles.

2.JAERI FEL Cryogenics

As each module of the super-conducting rf linac has its own shield cooler and liquid He re-condenser, it independently stands alone without any cryogenic liquid coolant outside the module. The zero-boil off cryostat for a super-conducting rf linac has been first designed and developed for the JAERI FEL since the beginning of the program in 1989. 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. Heat economics in the cryostat has been optimised 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 about 4.5W at the JAERI cryostats are consistent with each other, and the zero-boil off one usually cuts around 80% of the loss in the conventional one.

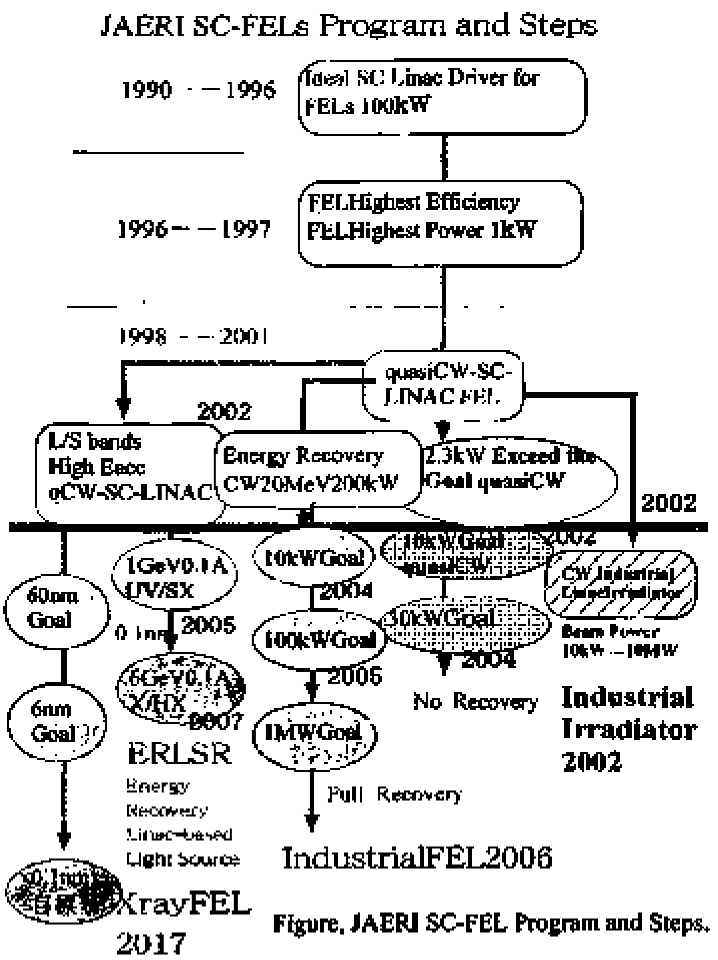

Figure. JAERI SC-FEL Program and Steps.

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% higher than the GM-JT recondenser. If the liquefier efficiency includes transferring losses, both liquefier and recondenser have nearly the same. 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 capacity is as small as the JAERI system.

We have introduced the 8W 4K refrigerator for the Japan Railways' Maglev train, and modified it to an 11W one to cool down our cavity cryostats about 15 years ago. We could successfully keep running the whole system over these 10 years. There have been successfully no trouble and no malfunctioning in the 4 shield coolers for about 10 years up to now, and no dry up of liquid He in the 4 modules. We could successfully and routinely run the system without any trouble for 355days or 500days.

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 quarter hour of maintenance every one and half years will completely solve a large number of operational problems. 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 super-conducting cavities. We have performed the cold maintenance 6 times over a few months as an aging test of the cold maintenance including air leak accidents. Because we have not found any accumulated contamination or dirt, and resultant instabilities and malfunctioning in the cooler, we expected we could keep the module and linac cold over a few tens of years.

3.Novel Ultra short-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 in the beginning of 2000 [2]. As the world-highest 2.34kW average power and about 1GW peak power were obtained at JAERI FEL. 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 [2], the high efficiency of 6-9% is consistent with $1/2N_{cycle}$ where N_{cycle} stands for the number of cycle over the ultra short 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.

The new lasing can open up new possibilities in FEL science and technology that we can drastically increase an FEL conversion efficiency and the FEL peak and average power from the electron beam power, to realize an ultra-short and a few cycle FEL pulse, and to understand the new FEL lasing mechanism.

4. Energy Recovery FELs at JAERI

The energy recovery circular loop at the JAERI FEL has been under commissioning from December 2001 after one-year construction. The 360-degree circular energy recovery geometry has been planned and 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. The 180-degree 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.

The JAERI plans to make a prototype for the industrial FELs using the 180-degree geometry because the reflextron has intrinsically several better features discussed above to realize an ideal energy recovering FELs near future.

5. Industrial Free-Electron Lasers

Market requirements for the industrial Feels from the users should be discussed briefly here, and itemized for each category to check how much they can be fulfilled before the FEL businesses would be started. They are tentatively itemized here, for examples, costs, reliability, compactness, easiness in the production, operation and maintenance, the operational and maintenance intervals, fulfilment 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 truck-cart or trailer sized space being available in these small buildings. In addition to them, we can easily find other important requirements of readiness to use any time, easiness to use, no specialist required in the operation and maintenance, safety in the operation and maintenance, very long maintenance intervals, and no regulations from any legal and official codes and rules. Most of them have been replied positively by the JAERI cryogenics design concept and others up to now [2].

6. Industrial FELs near Future

Four industrial FEL models having the 180degree (reflextron) geometry are under consideration at JAERI. Three of them are infrared FELs, and the forth ultraviolet FEL. 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 non-destructive testing and inspection, custom inspection, and so on.

A mid-infrared FEL (MIR 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 and so on. A near infrared FEL (NIR 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 -1.55micron 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 and so on. Possible large-scale applications in nuclear industry have been discussed recently from the laser cutting for the nuclear reactor decommissioning like the reactor pressure vessel and container steel walls, stable and radio isotope enrichment, fiber-transmittable light and heat sources, and so on.

An ultraviolet FEL (UV FEL) ranging from 0.3 to 0.1 micron wavelengths will be planned to use an S or L band cavity of 200-300MeV electron energy with the reflextron geometry. The FEL will be applied to lithography, photochemical processing, polymer surface modification, optical mass spectrometer, and so on.

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