

# THE JAERI ENERGY-RECOVERY LINAC FOR FREE-ELECTRON LASERS

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## *Abstract*

In order to realize a tunable, highly-efficient, high average power, high peak power and ultra-short pulse free-electron laser (FEL) for all, the JAERI FEL group has developed an industrial FEL driven by a compact, stand-alone and zero-boil-off superconducting rf linac with an energy-recovery geometry (ERL) for these years. Our discussions on the supertool will cover market-requirements for the industrial FELs, some 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, and the ERL-FEL commissioning and preliminary lasing. In addition to them, I plan to discuss about a full dc injector for ERL-FELs and ERL light sources.

## 1 INTRODUCTION

A very efficient and powerful FEL has been long required to use for almost all industrial applications, for examples, pharmacy, medical, defense, shipbuilding, solid-state physics, chemical industries, environmental sciences, civil engineering, space-debris orbit control, power beaming, and so on [1] instead of the conventional lasers, and other light and heat sources. As expected that 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]. Market requirements for the industrial FELs, the JAERI compact, stand-alone and zero-boil off cryostat concept and operational experiences over these 10 years, and the future plans will be discussed in the following.

Original strategy to develop the industrial FEL 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 have found the new FEL lasing mode of high efficiency two years ago [3], we added a new path in the third step to develop and to realize the industrial FELs using the new lasing mode. The ERL-FEL is now under commissioning, and has succeeded to lase recently.

## 2 INDUSTRIAL FELS

### *2.1 Market Requirements*

Market requirements for the industrial FELs from the users should be discussed before the FEL businesses

would be started. For examples, there are several items of the costs, reliability, compactness, easiness in the production, operation and maintenance, the operational and maintenance intervals, 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 possible, and had to be the same for existing and future conventional laser systems. Compactness of the FEL is very important because the FELs used in the factories, schools, clinics, hospitals and other small-sized facilities must be fitted into a tabletop sized, or a 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 operation and maintenance, very long operational interval without any maintenance, and no regulations from any legal and official codes and rules. Most of them have been successfully demonstrated to perform in the JAERI cryogenics operation and maintenance over 10 years 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 superconducting linac-based FEL, we do not need any huge central liquefier station using He and N<sub>2</sub> gas compressors to cool down the FEL driver outside the room or building like many high energy particle physics laboratories and food processing plants. As each module of the superconducting rf linac has its own shield cooler and liquid He re-condenser, it stands alone without any cryogenic liquid coolant outside the module independently. In short, the stand-alone super-conducting rf linac-based FEL will be run freely and independently in contrast with a parasitic one 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. Unlike superconducting-magnet cryostats, the superconducting rf linac cryostat has intrinsically large heat invasion through many thick heat bridges, for examples, two beam pipes, main and higher order mode coupler cables, support rods, refrigerators or liquid N<sub>2</sub> and liquid He transport pipes 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

including the invasion through cables and wires 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 cryostats.

A compact 4 K He<sup>4</sup> GM-JT (Gifford-McMahon refrigerator with Joule-Thomson expansion valve) gas closed-loop recondensing refrigerator was introduced to realize a stand-alone and zero-boil off superconducting linac of 500MHz UHF band cavities. Cooling efficiencies of the huge liquefier is about 30% higher than the GM-JT recondensor. If the liquefier efficiency includes transferring losses, both liquefier and recondenser have nearly the same or better efficiencies. The capital cost of the liquefier and coolant transferring system is nearly the same with or slightly cheaper than the GM-JT recondensor as long as the system is small. We have introduced an 8W 4K refrigerator, and modified it to an 11W one to cool down our 500MHz UHF cavity cryostats about 14 years ago. Except for initial troubles of the recondensers, 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 experience to dry up liquid He inside any He vessel of the 4 modules since 1992. As a typical example, we could succeed to run the system without any trouble for 355days for many Japanese fiscal years.

The compact, stand-alone, zero-boil off cryostat, and non-stop cooling operation with no warm-up over very long operation interval over 10 or 20 years, except for a few tens minutes of maintenance once per a year or two will completely solve a large number of operational and maintenance problems. We performed several cold maintenance in exchanging a displacer unit of the shield coolers in order to keep the whole cryostat cool without He-evaporation and any 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 design or structure of the liquefier practically makes the cold maintenance and disassembling impossible, the non-stop cooling operation is only available for the stand-alone, zero-boil off cryostats like the JAERI FELs, and MRIs.

### *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[3, 5]. The world-highest 2.34kW average power and about 1GW peak power were obtained at JAERI FEL using the new lasing. 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[6] because of some pulse-shortening

mechanisms. As measured that the pulse width was measured to be a few cycle lasing of 3.4 cycle and 255fs at 22.4 micrometer [3], the high efficiency of 6-9% is consistent with  $1/2N_{\text{cycle}}$  where  $N_{\text{cycle}}$  stands for the number of cycle over the ultrashort FEL pulse width. The brand-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 a ultrashort and a few cycle FEL pulse.

### *2.4 Energy Recovery FELs at JAERI*

Energy recovery concept had been discussed and tried at Stanford University, Jefferson laboratory and others since 1965[7]. First demonstration of the same-cell energy recovery of the superconducting rf linac (ERL) 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 ERL-FEL, and wall thickness of an ordinary building may be enough to shield very weak and low energy X rays level. Therefore, we can easily cut most of the budgets of rf power amplifiers and heavy shielding walls of the buildings to construct the ERL-FEL facilities. A 360-degree circular ERLs are planned here to apply 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 ERL geometry with a 180-degree isochronous reflextron bending magnet[8] has been considered to decelerate the electron beam anti-parallel with the acceleration direction.

In the reflextron ERL, average or centroid velocities of the electron pulses in both the acceleration and deceleration are nearly the same along the accelerator cavity on the contrary to the circular ERL which has the largest velocity difference around the entrance and exit of the accelerator. The reflextron ERL has needed a small number of beam optical components, and small building space required to install anywhere. The reflextron ERL can accept and recover the lower energy electron beam than a few MeV because nearly no velocity difference can be between the deceleration and acceleration. The JAERI plans to make a prototype for the industrial FELs using the reflextron to realize an ideal ERL-FELs.

### *2.5 Industrial FELs near Future*

Four industrial models the reflextron ERL-FEL have been under consideration. Three of them are IR FELs, and the fourth UV FEL. The FIR FEL ranging from 200 to 50 micron wavelengths uses the 500MHz UHF band cavity of 5-10MeV electron energy. The smallest model of the industrial FIR FEL will be the best to perform an FEL higher power demonstration than 10kW or 100kW, to produce an intense Compton-backscattering gamma-ray flux of about 10MeV in synchrotron light sources, to image foreign materials inside foods, grain, fruits and powder as nondestructive inspection, custom inspection, and so on. A MIR FEL ranging from 50 to 8micron

wavelengths will use the 500MHz UHF band cavity of 12-24MeV electron energy. Possible and typical applications are expected to be large-scaled photochemical processing, medical, pharmacy, rare-material separation and so on. A NIR FEL ranging from 12 to 2micron uses the same cavity of 24-48MeV electron beam energy. A 10kW or higher industrial FEL which can lase at around a fiber-transmittable wavelength of 1.3micron will be very useful to transmit their power to a pin-pointed position in a distant area from the FEL. These ERL-FEL will be popular, and widely used in the many factories like a shipyard, nuclear fuel reprocessing and partitioning, nuclear power plant decommissioning, an automobile factory, civil engineering plant and so on. An UV FEL ranging from 0.3 to 0.1 micron wavelengths will be planned to use a S or L band cavity of 200-300MeV electron energy with the reflextron geometry. The FEL will be applied to ERL light source development, lithography, photochemical processing, polymer surface modification, optical mass spectrometer, and so on.

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