DEMONSTRATION OF THE HIGHLY-EFFICIENT AND HIGH-POWER FELS DRIVEN BY A SUPERCONDUCTING RF LINAC

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Abstract

We need a powerful and efficient free-electron laser(FEL) for industrial uses, for examples, pharmacy, medical, defense, shipbuilding, semiconductor industry, chemical industries, environmental sciences, space-debris, power beaming and so on. In order to realize such a tunable, highly-efficient, high average power, high peak power and ultra-short pulse FEL, the JAERI FEL group and I have successfully demonstrated the efficient and powerful FEL driven by a compact, stand-alone and zero-boil-off super-conducting rf linac with an energy-recovery geometry. Our discussions on the FEL will cover market-requirements and roadmap for the industrial FELs, some answers from the JAERI compact, stand-alone and zero-boil-off cryostat concept and operational experience over these 8 years, our discovery of the new, highly-efficient, high-power, and ultra-short pulse lasing mode, and the energy-recovery geometry.

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, space-debris orbit control, power beaming, and so on [1] instead of the conventional lasers, and other light and heat sources. In the table listed in the last page, there are summaries of possible academic and industrial fields, itemized applications and examples. As expected that the industrial FELs would become popular in the world near future, the JAERI FEL group and I have 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, and some replies from the JAERI compact, stand-alone and zero-boil-off cryostat concept and operational experiences over these 9 years will be discussed fully in the text. The JAERI cryogenics will be explained briefly, and the future directions and plans discussed shown in fig.1.

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 found the new FEL lasing mode of high efficiency last year [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.

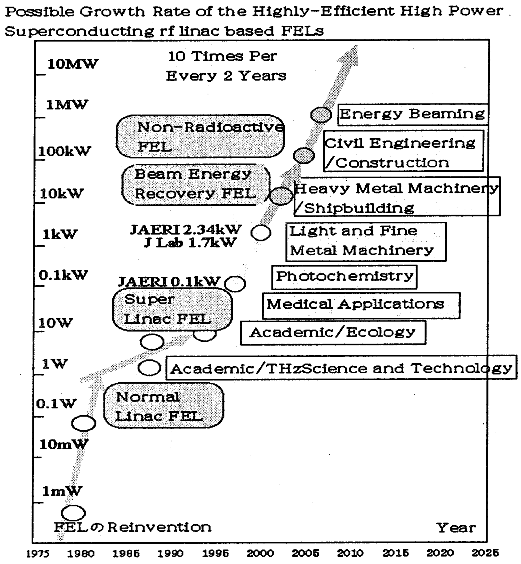

Fig.1, Roadmap for the industrial FELs

2 INDUSTRIAL FELS

2.1 Market Requirements

Market requirements for the industrial FELs from the users should be discussed, 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, 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. 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 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].

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 N2 gas compressors to cool down the FEL driver outside the room or building. 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 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]. As shown in fig.1, 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.

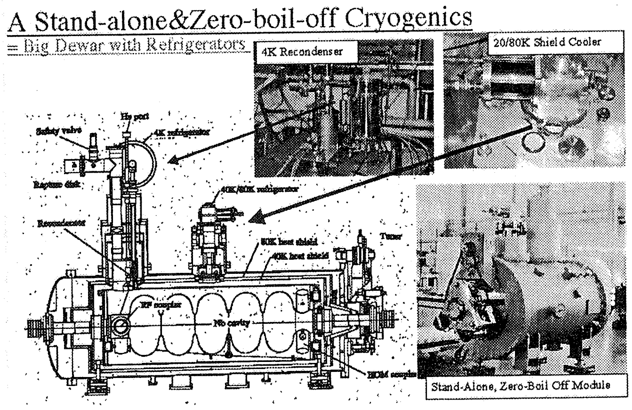

Figure 2: The JAERI stand-alone, and zero-boil off cryostat has duplex heat shields, and the shield-cooler and He-recondenser refrigerators integrated into the cryostat vacuum vessel.

Unlike superconducting-magnet cryostats, the superconducting 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 N2 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 to be about 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 shown in fig.2 was introduced to realize a stand-alone and zero-boil off superconducting linac using 500MHz UHF band cavities. A 1.65 K He^3 GM gas closed-loop refrigerator has been designed, and tested to realize a stand-alone and zero-boil off superconducting linac using L and S bands 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 efficiencies. 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 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 recondesers, we could successfully keep running the whole system over these 9 years. There have been successfully no trouble and no malfunctioning in the 4 shield coolers for about 9 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. As a typical example, we could succeed to run the system without any trouble for 355days in 1996 Japanese fiscal year and without warming up for about 500days from November 1999 to March 2001.

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 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 laboratory in the beginning of the last year [3, 5]. As 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 250fs at 22.4 μm [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 $1/2N_{cycle}$. 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 ultra-short and a few cycle FEL pulse, and to obtain a new knowledge in quantum optics understanding the new FEL lasing mechanism.

2.4 Energy Recovery FELs at JAERI

The figure 3 shows the energy recovery circular loop at the JAERI FEL under construction from April 2001.

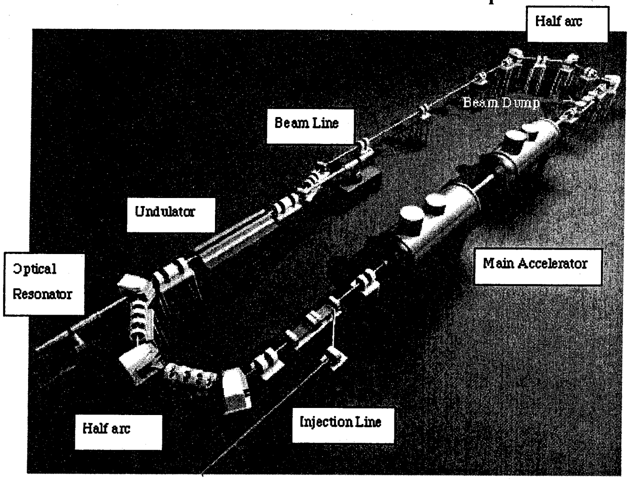

Figure 3: The energy recovery circular loop at the JAERI FEL facility under construction.

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 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 shown in the fig.4 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. The reflextron geometry has a relatively small number of beam optical components in line, and small building space required by the 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. The JAERI plans to make a prototype for the industrial FELs using the reflextron geometry because the reflextron has intrinsically several better features discussed above to realize an ideal energy recovering FELs.

2.5 Industrial FELs near Future

Four industrial FEL models having the reflextron geometry are illustrated in figs. 5, and 6. Three of them are infrared FELs, and the forth ultraviolet FEL.

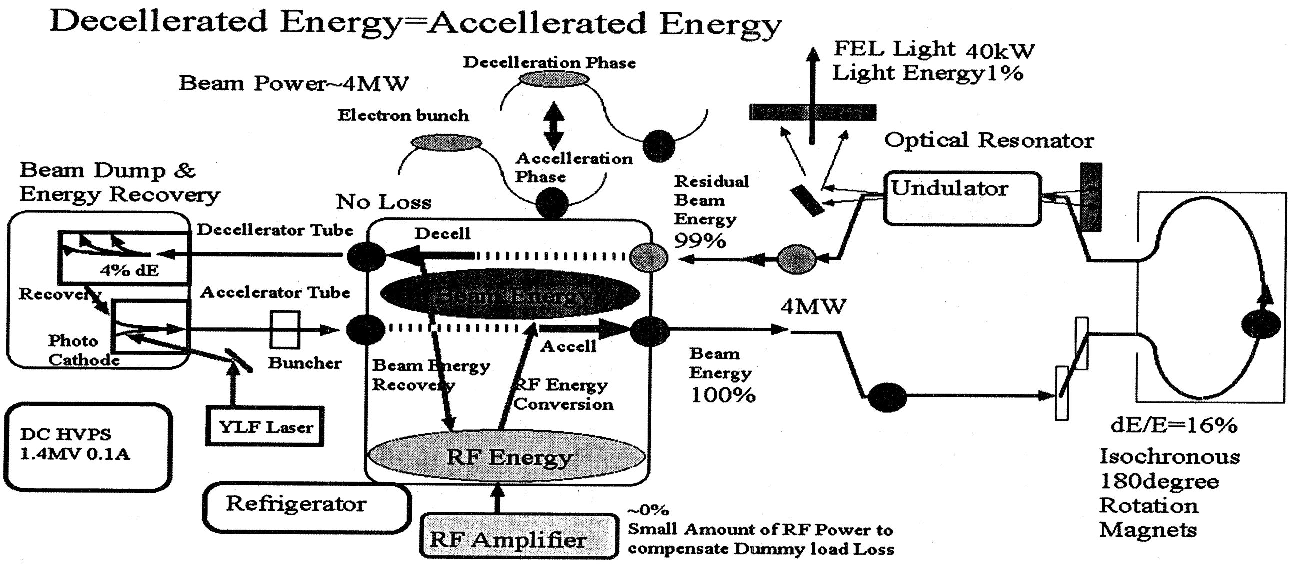

Figure 4: A Reflextron energy recovery geometry of a 180 degree bending and its conceptual explanation.

As shown in fig.6, 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 10kW or 100kW, 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 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.

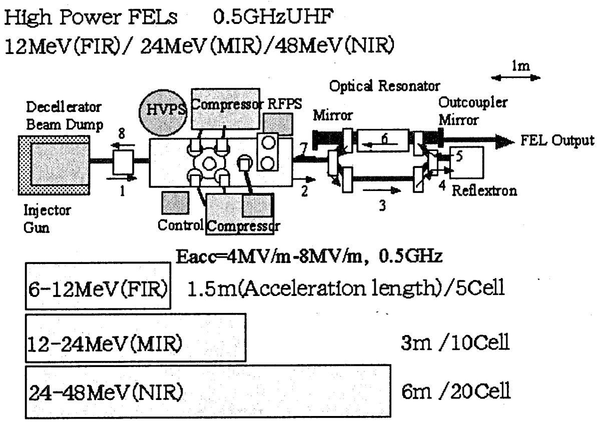

Figure 5: Three industrial FEL models for lasing in the FIR, MIR, and NIR wavelength regions with the reflextron geometry. All of them use the 500MHz UHF band cavities of 5, 10 and 20 cells, respectively.

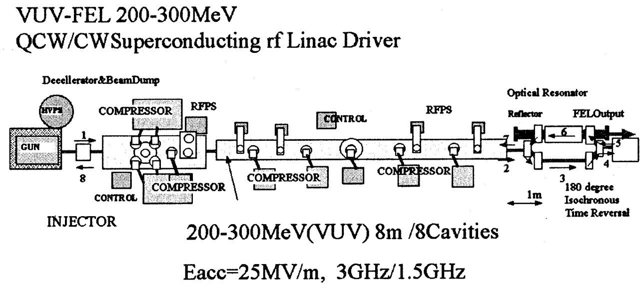

Figure 6: An ultraviolet industrial FEL (UV FEL) ranging from 0.3 to 0.1 micron wavelengths will be planned to use a S or L band cavity of 200-300MeV electron energy with the reflextron geometry and 1.65K He^3 GM refrigerators.

A 10kW or higher industrial FEL which can lase at around a fiber-transmittable wavelength of 1.3μm 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.

An ultraviolet FEL (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 lithography, photochemical processing, polymer surface modification, optical mass spectrometer, and so on.

2.6 New Refrigerator and New Superconductors

The 1.65K He^3 GM refrigerator as a recondenser or a cooler has been developed at the JAERI FEL to cool down L or S bands Nb cavities for a tabletop superconducting rf linac-based FEL, energy recovery X ray light source and energy recovery X ray FEL near future. A thermal design of the zero-boil off cryostat for the S- and L-bands linac-based X-ray light source and FELs looks similar with the 4K high duty, or quasi-CW and UHF linac-based cryostat except for having 3 heat shields of 80K, 20K, and 4K and low-duty.

Whenever a novel superconductor like MgB2 [8] and halogen-based compound doped C60 fullerene [9] will become usable near future to make a high frequency superconducting cavity of S- and L-bands, the JAERI stand-alone and zero-boil off cryostat concept will be suited better, and used to manufacture the novel superconductor material-made accelerating cavity cryostats. Because their critical temperatures have been measured to be very high, a compact, durable and powerful cooling engine like the GM refrigerator will be usable for the superconducting S and L bands cavities. After the new superconductor-made cavities could become available, all difficulties like a vacuum leakage problem relating with superfluidity, very expensive capital and operational costs for the 1.9 K liquefier and so on in the superconducting S and L bands Nb cavities would be solved by using the higher critical temperature superconductor cavities and inexpensive and reliable 20K and 80K double-staged GM refrigerator with a single heat shield.

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. As discovered the new lasing mode, we could make the FEL pulse ultra-short and very efficient without the energy recovering. 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 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 the beam power at a few MeV or less electron energy.

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Table 1a. Summary of the industrial FEL applications.

Field	Applications		Examples
Nuclear Engineering and Science	Isotope Separation	Uranium Enrichment	Atomic Method for Uranium Enrichment, Molecular Method for Uranium Enrichment
		New Materials	Isotope Separation for ^{90}Zr, ^{50}Ti, ^{53}Cr and so on.
	Nuclear Fuel and Nuclear Waste Reprocessing		Atomic Separation for U、 Pu and other Radioisotopes
	Nuclear Engineering		Radioactive components processing (remote-processing) Nuclear fuel cutting (remote-processing) Reactor disassembling (remote-processing)
	Nuclear Fusion		Plasma heating, Current Drive, Plasma diagnostics(Temperature, Density) Laser Fusion, Muon Catalysis Nuclear Fusion (Laser Enhancer)
	Basic Sciences		High Energy Accelerators, mm Wave Radio astronomy (Local oscillator) Gravitational Wave Observatory Laser Interferometory
Basic Chemistry, Material Sciences, Solid-state Physics	Photo-electron Spectroscopy		Spectroscopy for Metal Band Structure、 elementary excitation modes、 impurity levels、 semiconductors、 half-metals and so on.
	Far infrared spectroscopy		New superconductor theoretical models, High Tc Superconductor materials, Superconductor gap energies
	New material purification and Isotope seperation of monoisotopic materials		Isotope separation of H, B, C, O, Si and so on. Improvements of Material properties(heat conductivity etc.)
	Biotechnology		DNA structual disassembling DNA, nerve fiber and other biomaterials cutting and processing, Ultra fast X ray analysis of protein 3D structure
	Photo-excited chemical reaction enhancing and cutting hydrogen-bonds		Research and Development for Mesoscopic materials (<submicron sized materials)
	THz Sciences and Technologies		THz fast elements(detector, mixer, laser or oscillator) utilizing quantum well, quantum wire, and quantum dot, Decomposition and ultra sensitive detection of environmentally-harmful materials

Table 1b. Summary of the industrial FEL applications(continued).

Field	Applications	Examples
Medicals,	Utilization of non-thermal, and photochemical reaction processes for mdeical applications	Cancer therapy, Medical treatment for Arteriosclerosis, Cholesterol decomposition, bone cutting, Laser surgery, gallstone demolishing Laser surgery for myopia(short sight)and the cornea laser florescent endoscope, sterilization、 pasteurization
	Utilization of thermal process for medical applications	Laser surgery, Photo-coagulation, Birthmark, melanin skin deposition endoscopic laser surgery
	others	laser functionality recovering, laser rehabilitation, Laser anesthesia. 、 laser acupuncture and moxibustion,Laser CT(computer tomography), Laser measurements of rare element concentration in a living body laser doppler effect measurement of blood flow, diagnosis for abnormal metabolism, laser dentsitry (therapy, preventive medicine of a tooth decay, tooth processing) laser cell welding and laser cell-bonding, gene-injection
Lasermanufacturing , Thin film, Surface process, Semiconductor	Laser manufacturing	Laser manufacturing, Laser drilling, laser-cutting, laser-welding Laser surface-modification、 laser quenching、 laser anneling Laser welding processes(laser alloyng, laser sticking, surface fusing), Laser boring, Civil engineering, Plant construction、
	Thin film and surface processing	Photo cemical vapour deposition(laser chemical evaporation) Lasr initiated etching, Lithography, Laser ablation (thin film deposition), Doping (precise concentration contorl of impurities, high concentration doping) , Laser marking, laser stamping, sterilization (Wafer, rinsing water) , laser local anneling
Energy Beaming	Remote Energy Beaming	Space debris orbit control, High altitude unmanned airship and airplane, Interplannet probe vehicle, Energy Beaming to communication Satellites, (Electricity charging, Laser propulsion, Heat source), Orbital Solar Power Station (Laser Beaming、 Heat Beaming)
Environmental Science	Ultra-sensitive detection and decompsition for Environmental harmful materials	Remote and widely-range ultra-sensitive detection for Furan、 Dioxin FIR Lidar, Tritium remote sensing, and selective decomposition, vibrational state level spectroscopy, thermal decompsition through vibrational levels, environmental hormone and harmful materials, Remote and wide-range laser sensing for chemical agents depleting of the ozone layer, laser monitoring the effects of (global) warming