Non-Thermal Laser Machining with ERL-FELs for Nuclear and Other Heavy Metal Industries

Eisuke J. Minehara

Advanced Photon Source Development Unit, Japan Atomic Energy Agency,
2-4 Shirakata shirane, Tokai, Naka, Ibaraki 319-1195 JAPAN, E-mail:minehara.eisuke@jaea.go.jp

The JAEA free-electron laser(FEL) successfully demonstrated capabilities of sub-ps ultra-fast pulse lasing, over 6% high conversion efficiency, 1GW high peak power, a few kW average power, energy-recovery superconducting linac (ERL) operation and wide tunability in far-infrared wavelength regions up to now. Using high power lasing and ERL technologies, we plan to develop a more powerful and more efficient FEL than 20kW and 25%, respectively, for nuclear, chemical, semiconductor, defense, shipbuilding, and other heavy metal industries. In order to realize such a tunable, highly-efficient, high average power, high peak power and ultra-fast pulse FEL, we need the efficient and powerful FEL driven by the JAEA compact, stand-alone, zero boil-off ERL. Our discussions on the ERL-FEL technologies will cover the application of non-thermal peeling, cutting, and drilling to decommission the nuclear power plants, and to prevent stress-corrosion cracking in nuclear, light- and heavy-metal industries. We also survey other possible applications for the industrial ERL-FELs, the JAEA compact, stand-alone and zero-boil-off cryostat concept and operational experience.

I. 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 (Ref 1) of the current century for all, the JAEA FEL group has developed an industrial FEL driven by a compact, stand-alone and zero-boil-off ERL (Ref 2). Our discussions on the versatile tool will cover many requirements for the industrial FELs, especially from the nuclear and other heavy-metal industries, some positive answers from the JAEA compact, stand-alone and zero-boil-off cryostat concept, non-stop cooling, and operational experience over these 14 years, our discovery of the new, highly-efficient, high-power, and ultra-short pulse lasing mode (Ref 3), and the ERL technology.

A very efficient and powerful FEL has been long required to use for almost all industrial applications, for examples, nuclear industry, pharmacy, medical, defense, shipbuilding, solid-state physics, chemical industries, environmental sciences, space-debris orbit control, power beaming, and so on (Ref 1) instead of conventional lasers, and other light and heat sources. Since the industrial FELs will become popular in the world near future, the JAEA FEL facility has tried to develop a compact, stand-alone and zero-boil off superconducting RF linac-based FEL with and without an energy-recovery geometry (Ref 2). Long-holding requirements and hopes for the industrial FELs, and some possible answers from the JAEA compact, stand-alone and zero-boil-off cryostat concept and operational experiences over these 14 years will be discussed in details. The JAEA cryogenics will be explained briefly as an easy maintenable and easy operable machine, and the future directions and plans discussed.

Our original strategy to develop the industrial FELs at JAEA simply consists of three steps; the first step 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 (Ref 2); and the third increasing total system efficiency using a beam-energy recovering. After we found the new FEL lasing mode of high efficiency in the beginning of 2000 (Ref 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 for a small machine will be discussed in the following.

II. INDUSTRIAL FREE-ELECTRON LASERS

II. A Requirements for Industrial FELs

A variety of requirements and hopes for industrial FELs from their potential users and developers 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 them out as typical examples of costs, reliability, compactness, easiness in production, operation and maintenance, the operational and maintenance intervals, fulfillment for radiation safety code, pressure vessel code, other official regulatory rules and so on in Japan and other countries. 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 public and private buildings. In addition to them, we can easily find other important requirements of readiness to use any time, ease to use, no specialist required in the operation and maintenance, safety in the operation and maintenance, very long maintenance intervals like a MTBF value, and no regulations from any legal and official codes and rules. Most of them have been answered positively by the JAEA cryogenics design concept and others up to now (Ref 2) in Japanese domestic ones.

II. B Compact, Stand-Alone, Zero-Boil Off Cryostat and Its 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 superconducting 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 JAEA FEL since the beginning of the program in 1989 (Ref 4). The JAEA 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 superconducting-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 have been optimized to minimize the heat invasion by utilizing a finite-element method of temperature distribution calculation in the cryostat. Calculated and measured stand-by losses are from 2.5W to 4.5W at the JAEA cryostats, consistent with each other, and the zero-boil off one usually cuts around 80% or more of the loss in the conventional case.

A compact 4 K He^4 GM-JT (Gifford-McMahon refrigerator with a 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. A compact 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 higher frequency L and S bands cavities and 2K or 1.8K temperature cryogenics. 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 intrinsically the same efficiencies but the available efficiency of the recondensors slightly lower. The capital cost of the liquefier and coolant transferring system is the same with or slightly cheaper than the GM-JT refrigerator as long as the system is as small as the existing JAEA system.

We have introduced an 8W 4K refrigerator being originally developed for the Japan Railways' Maglev train (JR Superconducting Linear Motorcar Train), and modified it to an 12W one to cool down to 4.2K our 500MHz UHF cavity cryostats about 16 years ago. Except for initial troubles of the recondesers, we could successfully keep running the whole system over these 20 years. There have been no trouble or no malfunctioning in the 4 shield coolers for about 15 years, and no failure recorded to dry up liquid He inside any He vessel of the 4 modules since the beginning in 1992. As very typical operation statistics, we successfully run the system without any trouble for 355 days in the 1996 Japanese fiscal year and without warming up for about 500 days from November 1999 to March 2001.

The compact, stand-alone, zero-boil-off cryostat, and non-stop cooling operation with no dry-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 have continued to perform a cold maintenance in exchanging a displacer unit of the shield coolers every 3 or 4 years and to keep the whole cryostat cool without de-conditioning the superconducting RF cavities. Because the domestic pressure vessel code does not allow one 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 very easily available for the stand-alone, zero-boil off cryostats like the JAEA FELs, and MRIs. We have run the cold maintenance 5 times over a few months as an aging test of the cold maintenance. Once we accidentally introduced wet air contamination into the cold refrigerator, we found and confirmed that the contamination could only be remove by replacing the displacer of the refrigerator. Because we have not found any accumulated contamination or dirt, or 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 after each failure" 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 May 2001 to now, we have successfully kept non-stop cooling or running cool over about 7 years using cold maintenance technology.

II. C Novel Ultrashort-Pulsed and Highly-Efficient Lasing Mode

A novel lasing mode was discovered to realize ultra-short pulsed and highly efficient lasing in FELs at the JAEA FEL facility in the beginning of 2000 (Ref 3, 5). As at that time the world-highest 2.34kW average power and about 1GW peak power were obtained at JAEA FEL, they will be replaced by their new records soon. As it is well known that an FEL conversion efficiency from the beam power equals $1/2N_w$ 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 were expected to be effectively a small number of periods, and efficient operation after FEL saturation because of pulse-shortening and spiking mechanisms. As reported the pulse width of the new mode was measured to be a few cycle lasing of 3.4 cycles and 255 fs at 22.4 micron (Ref 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.

The new lasing can open up new possibilities in FEL science and technology in that we can drastically increase 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.

II. D Energy Recovery FELs at JAEA

Figs. 1 and 2 show the energy recovery circular loop at the JAEA FEL facility under operation and 10kW upgrading.

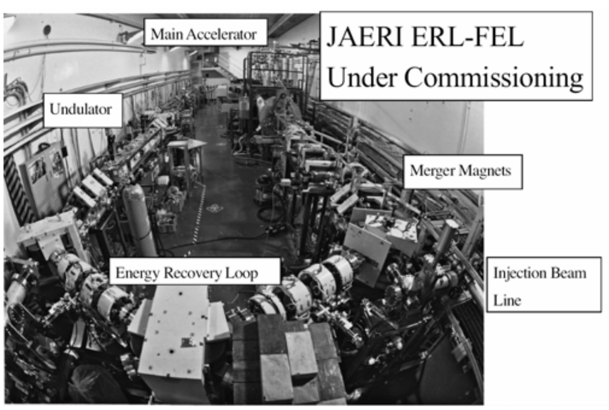

Fig 1. Photograph of the energy recovery circular loop at the JAEA FEL facility under 10kW upgrading.

Energy recovery concept had been discussed and tried at Stanford University, Los Alamos National Laboratory and Jefferson laboratory since 1980's (Ref 6). The 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-ERL FEL is needed to run the ERL- 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 ERL- 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.

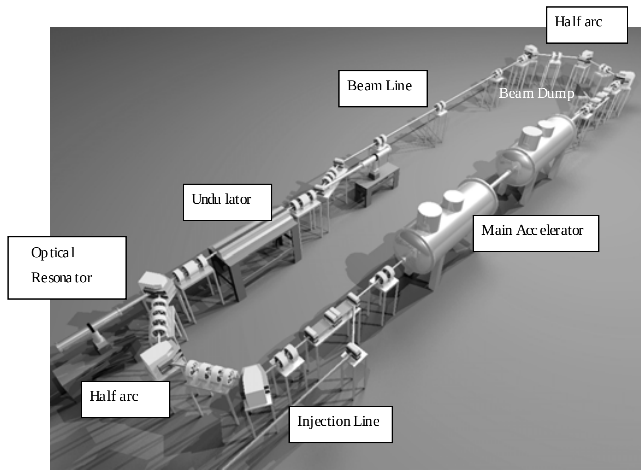

Fig 2. The energy recovery circular loop at the JAEA FEL facility under part-time operation and 10kW upgrading.

Another energy recovery geometry and conceptual explanation shown in the Fig.3 have a 180-degree isochronous bending magnet to decelerate the electron beam anti-parallel with the acceleration direction. According to the original Canadian patent (Ref 7) in 1970's, the geometry and magnet were called a reflextron. In the 180 degree bending geometry, average or centroid velocities of the electron pulses in both the acceleration and deceleration are 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

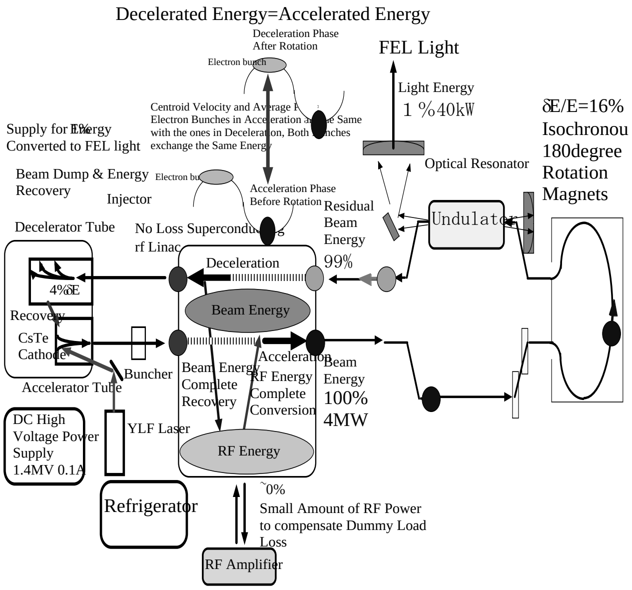

Fig 3. A Reflextron energy recovery geometry of a 180 degree bending and its conceptual explanation.

difference can be occurred between the deceleration and acceleration.

The JAEA has hopes to make a prototype of the industrial FELs for nuclear industrial applications using the reflextron or equivalent geometry because the reflextron and equivalent ones have intrinsically many better features discussed above to realize an ideal ERL- FELs.

II. E Industrial FELs and Their Applications

Four industrial FEL models having the reflextron or similar geometry are illustrated in Figs. 4 and 5. Three of them are infrared FELs, and the fourth ultraviolet or visible FEL. As shown in Fig.4, 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 10MeV in 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 (MIR FEL) ranging from 50 to 8 micron wavelengths will use the 500 MHz UHF band cavity of 12-24 MeV electron energy as 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 (NIR FEL) ranging from 12 to 2 microns uses the same 500 MHz cavity of 24-48 MeV electron beam energy with the reflextron.

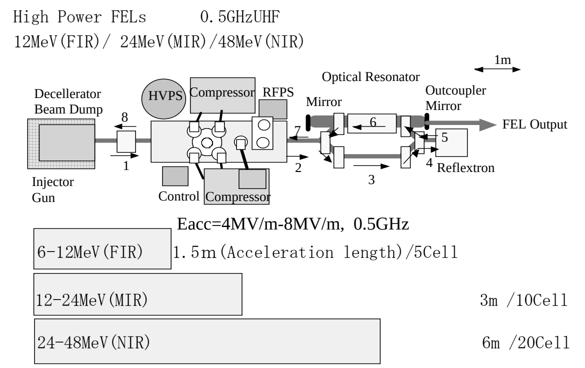

Fig 4. Three nuclear industrial FEL models for lasing in the FIR, MIR, and NIR wavelength regions with the reflextron geometry. All of them use the 500MHz UHF band cavities of 5, 10 and 20 cells, respectively.

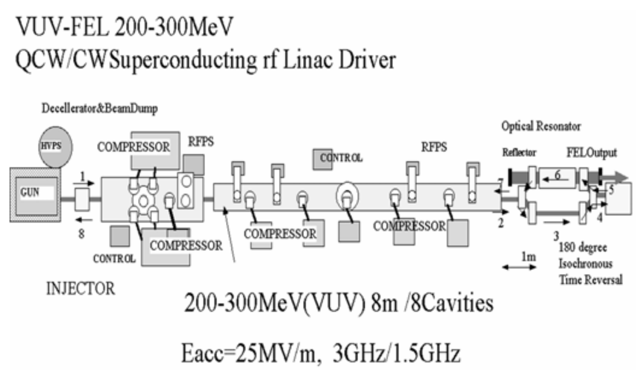

Fig 5. An ultraviolet and visible industrial FEL (UV FEL) ranging from 0.3 to 0.1 micron wavelengths will be planned to use a S, L, and UHF band cavity of 100-200MeV electron energy with the reflextron geometry and 1.65K He^3 GM recondenser and 1.9K He^4 central liquefier.

As shown in fig.6, 1.3 micron high peak power and high average power JLAB FEL light could instantly cut the 316L stainless-steel bar sample like boiling water reactor components and stainless-steel thick bar without high pressurized blow-off gas. All conventional laser cutters must need a focused and very high pressurized gas flow to blow off narrow part of the laser-heated and melted metal material. A 10 or 20 kW industrial FEL which can lase 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 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.

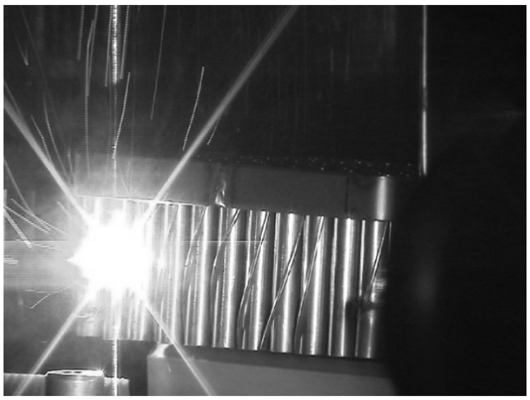

Fig 6. High peak power and high average power JLAB FEL light could instantly cut the 316L stainless-steel bar sample like boiling water reactor components and stainless-steel thick bar without high pressurized blow-off gas.

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 prevention of cold worked stress-corrosion cracking of the vital components like pressure vessel shroud and recirculating pump piping in the nuclear power plant. The cold worked stress-corrosion cracking sample like BWR shroud is shown in Fig. 7. An ultraviolet and visible FEL (UV FEL) ranging from 0.7 to 0.2 micron wavelengths will be planned to use S, L, and UHF band cavities of 100-300MeV electron energy with the reflextron geometry. The FEL will be applied to lithography, photochemical processing, polymer surface modification, nuclear decommissioning, and so on.

II. F New Refrigerator and New Superconductors

The 1.65K He^3 GM refrigerator as a recondenser or a cooler has been developed at the JAEA FEL facility to cool down L or S bands Nb cavities for a tabletop superconducting rf linac-based FEL, ERL X-ray light source and ERL 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

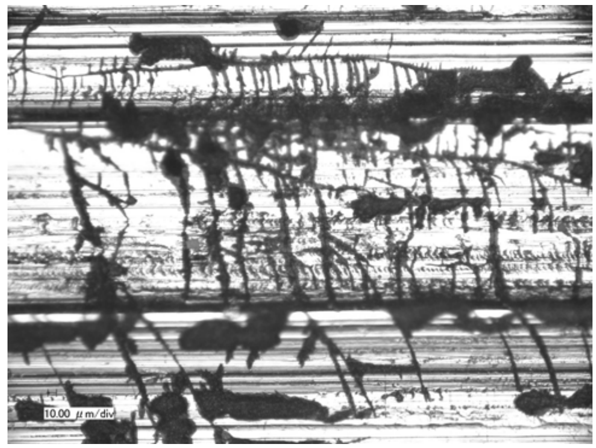

Fig 7. Cold worked stress-corrosion cracking of the 316L stainless-steel sample like BWR shrould and others.

of 80K, 20K, and 4K and low-duty one.

Whenever a novel superconductor like MgB2 (Ref 8) and alkaline metal-doped C60 fullerene (Ref 9) becomes usable near future to make a high frequency superconducting cavity of S and L bands, the JAEA stand-alone and zero-boil off cryostat concept will be suited better, and used to manufacture the novel supercondutor 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 become available, all difficulties like a vacuum leakage problem relating with He^4 cryogenic coolant super-fluidity, very expensive capital and operational costs for the 1.8 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 two-staged GM refrigerator with a single heat shield. As another pulse-tube cryogenic refrigerator has been developed recently to realize higher efficiency and vibration-free mechanical structure, a near future ERL-FEL could be cooled down to very low temperature around 2K or 1.8K.

III. CONCLUSIONS

FELs driven by superconducting RF linacs 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 remain in a beam power after the lasing by the ERL. As discovered with 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 drastically more efficient, and to realize industrial FELs for the nuclear decomissioning soon. The reflextron like 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 at the same position, and we can recover very efficiently the beam power at a few MeV or less electron energy.

ACKNOWLEDGMENTS

The author gratefully express his thanks to Drs. G. Neil, M. Shin, S. Benson, G. Williams, J. Kevin, J. Gubeli and many other colleagues in JLAB FEL facility and all members of JAEA ERL-FEL one for their valuable and kind suggestions and helps on the FEL machining trials, and Profs. H. Horike and T. Fukuda of Osaka University for his continuous encouragement. This work has been supported in part by Grants-in-Aid for Scientific Research (A19206103).

REFERENCES

1. J. Hecht and D. Teresi, “ Laser, Supertool of the 1980s” 1982, Ticker & Fields, 383 Orange Street, New Heaven, Connecticut 06511, U.S.A..
2. E. J. Minehara et al., Nucl. Instrum. Methods Phys. Res. Sect.A445, 183 (2000).
3. N. Nishimori et al., Phys.Rev. Lett. 86, 5707 (2001).
4. E. J. Minehara et al., pp159-161, in the proceedings of Particle Accelerator Conference, 1995, Dallas.
   E.J. Minehara et al., Free Electron Laser Challenge 2 (SPIE) Vol.3614, pp.62-71, 1999.
5. R. Hajima et al., Nucl. Instrum. Methods Phys. Res. Sect.A483, 113 (2002).
6. G. R. Neil et al., Phys. Rev. Lett. 84, 662 (2000).
7. E. A. Heighway, “Magnetic Beam Defection System”.Canadan Patent993124, issued 1976.
8. J. Nagamatsu et al., Nature 410, pp63 - 64 (2001).
9. R. F. Service, Science, 2001 August 31, vol. 293, p1570.
10. E. J. Minehara, Nucl. Instrum. Methods Phys. Res. Sect.A557, 16 (2006).