OVERVIEW OF SYNCHROTRON RADIATION AND FREE-ELECTRON LASER PROJECTS

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Abstract

A general overview of recent activities at synchrotron radiation and free-electron laser projects is presented.

1 INTRODUCTION

Whenever relativistic light charged particles such as electrons or positrons are bent in a magnetic field *synchrotron radiation* (SR) is emitted. Since the first observation of SR just over 50 years ago, a series of facilities have been developed to provide SR beams for research: a 1st generation, in which SR was used 'parasitically' on machines built for high energy physics, a 2nd generation of dedicated SR sources, and more recently a 3rd generation of low emittance machines with many insertion devices for higher brightness SR. In this normal type of SR the electrons emit incoherently, i.e. with random phases. The electrons can be made to emit in phase, i.e. coherently, in two ways: i/ if the electron bunch is short with respect to the radiation wavelength; because of difficulties of producing very short bunches this technique is limited to the far infrared/mm wavelengths; ii/ the electron density is modulated along the bunch with the period of the radiation wavelength. A device in which this modulation is created, and coherent emission takes place, is called a *free-electron laser*.

2 SR FACILITIES

Table 1 lists operating SR facilities and those under construction or being proposed, excluding machines dedicated to industrial use [1]. Here we concentrate mainly on the status and development activities of the various projects. More technical details of performance limitations and possible solutions is given in ref. [2].

2.1 Activities at Existing Facilities

Dedicated facilities operate up to 7000 h/yr and provide SR to users for up to 5600 h/yr, typically 80-85 % of the total operation time, with an efficiency of ≥ 90 %.

A survey of current development topics at SR facilities shows that increased current (54%), methods of overcoming instabilities (46%), reduced emittance (38%), better reliability (38%), improved lifetime (29%) and increased energy (25%) are all actively being pursued, less so improved efficiency (17%) and different time structures (17%). The dominating activities however are closed-orbit stability (67%) and insertion device development (71%). The percentages indicate the proportion of facilities actively working on a particular topic. In the following, some brief examples of activities in these areas is given.

2.1.1 Energy

An increase in operating energy provides more SR flux at higher photon energies, and also gives better lifetime and generally better stability. The Taiwan Light Source (TLS) is now operating routinely at 1.5 GeV compared to the initial 1.3 GeV. The NSLS X-ray ring has been running about half of the time at 2.8 GeV rather than 2.58 GeV. At the PLS the linac has recently been upgraded and full energy injection at 2.5 GeV is planned in the near future. The Photon Factory (PF) operates at 3 GeV for a few weeks per year for X-ray users. ELETTRA operation at 2.4 GeV is also being studied.

2.1.2 Emittance

Reduction in emittance is being pursued at many facilities in order to increase the SR brightness. The most substantial gains are possible at older "2nd generation" sources, helping to maintain their competitiveness compared to the newer sources. At the PF a major re-construction of the lattice was carried out last year. The ring was re-started in Oct. '97 using the old optics with an emittance of 130 nm, while studies of the low emittance optics went ahead in parallel. Regular user operation commenced in May '98 with an emittance of 37 nm rad, higher than the minimum achieved (29 nm rad) to provide a longer beam lifetime. At Hefei a new High Brightness Light Source (HBLS) configuration that reduces the emittance from 150 to 27 nm rad is part of a recently funded upgrade. At SPEAR a major upgrade is being proposed (SPEAR III) which will reduce the emittance from 160 nm rad to 17 nm rad at 3 GeV as well as allow higher current operation and lengthen some ID straights. Optics which give a factor of 2 reduction in emittance (to 45 nm rad) are also being studied at the NSLS X-ray ring.

2.1.3 Lifetime

The main drawback of low emittance, particularly in low energy rings, is the poor beam lifetime that results from collisions between electrons within the same bunch (Touschek effect). One of the ways this can be alleviated is to enlarge the bunch volume. Since an increase in the transverse dimensions results in an unwanted reduction in SR brightness, a more attractive option is to increase the bunch length. One of the possibilities is to use an r.f. cavity operating on a multiple of the main r.f. frequency. Higher harmonic cavities have been operated for some time in older rings with lower r.f. frequency: ALADDIN (4th harmonic, 200 MHz), NSLS VUV ring (4th harmonic, 211 MHz) and UVSOR (3rd harmonic, 270 MHz). More recently 1.5 GHz 3rd harmonic cavities have been installed in MAX II and are also under development at TLS, ALS and ELETTRA. Other than an increase in the beam lifetime (typically a factor of two),

Table 1. Main parameters of existing and proposed SR facilities. Type: P(artially) Ded(icated), Par(asitic); Status: Op(erational), Comm(issioning), Constr(uction), Prop(osed); C = circumference; E_{inj}, E_{op} = injection, operational energy (most typical energy underlined); I_b = actual/nominal max. beam current (mA), ε_x, ε_y = horiz., vert. emittances (nm rad) (at typical energy); Op.h. = total no. hours scheduled operation in '98; User% = percentage of Op.h. for SR users in '98; Eff. = op. efficiency (%) for users in '97; ID/NID = no. installed/total no. ID straights. († FY97)

Facility	Type	Status	C (m)	E_{inj}	E_{op}	I_b	ε_x, ε_y	Op.h.	User%	Eff.	ID/NID
Brazil											
LNLS UVX	Ded.	Op. '97	93	0.12	1.37	100	100, 0.4	3625	63	96	0/4
Canada											
CLS	Ded.	Prop.	147	2.9	2.9	500	16.3, -	-	-	-	-/10
China											
BEPC	PDed.	Op. '91	240	1.3	2.2	70	76, 0.76	600	88	-	2/-
HNSRL	Ded.	Op. '91	66	0.2	0.8	150	150, 13	4600	50	89	2/3
SSRF	Ded.	Prop.	345	2.2	2.2	400	3.8, -	-	-	-	-/16
Denmark											
ASTRID	PDed.	Op. '94	40	0.1	0.58	175	140, 14	6800	47	95	1/1
ASTRID II	Ded.	Prop.	76	0.5	0.6-1.4	200	10, 1	-	-	-	-/5
England											
DIAMOND	Ded.	Prop.	346	3.0	3.0	300	14, 0.14	-	-	-	-/16
SRS	Ded.	Op. '81	96	0.6	2.0	250	150, 5	6440	88	90	3/5
France											
DCI	Ded.	Op. '75	95	1.85	1.85	325	1600, 190	3823	98	90	1/2
ESRF	Ded.	Op. '92	844	6	6	200	3.8, 0.03	6800	83	96	27/28
SOLEIL	Ded.	Prop.	337	2.5	2.5	500	3.1, 0.03	-	-	-	-/14
SuperACO	Ded.	Op. '85	72	0.8	0.8	420	20, 20	3440	91	89	6/6
Germany											
ANKA	Ded.	Constr.	110	0.5	2.5	400	76, 1.5	-	-	-	0/5
BESSY I	Ded.	Op. '81	62	0.8	0.3-0.8	750	50, 2.5	2000	90		3/3
BESSY II	Ded.	Comm.	240	1.9	1.7 (1.9)	100	6, < 0.02	-	-	-	1/14
DELTA	PDed.	Comm.	115	1.5	0.4-1.5	200	15, 0.06	2700	-	-	1/4
DORIS III	Ded.	Op. '73	289	4.5	4.5	120	400, 12	6384	84	91	10/11
ELSA	PDed.	Op. '88	164	1.6	1.6,2.3	80	400, 8	4000	38	-	0/1
PETRA	PDed.+Par.	Op.	2304	7	12	40	25, 0.75	4400	23	-	1/1
India											
INDUS I	Ded.	Comm.	19	0.45	0.45	100	73, 0.73	-	-	-	0/1
INDUS II	Ded.	Constr.	172	0.7	2.0-2.5	300	37, 3.7	-	-	-	0/5
Italy											
ELETTRA	Ded.	Op. '94	259	1.0	2.0	300	7, 0.1	6528	81	93	6/11
Japan											
HiSOR	Ded.	Op. '97	22	0.15	0.7	-	400, -	-	-	-	2/2
New Subaru	Ded.	Constr.	119	1.0	0.5-1.5	100	67, 6.7	-	-	-	0/4
PF	Ded.	Op. '82	187	2.5	2.5, 3.0	400	37, 0.37	4250	80	94	6/7
PF-AR	Ded.	Prop.	377	2.5	6	100	163, 1.63	-	-	-	-/8
SPRING-8	Ded.	Op. '97	1436	8	8	100	7, 0.07	4000	75	97	8/38
TERAS	Ded.	Op. '81	31	0.31	0.75	250	1700, 1700	2000	80	100	2/2
Tohuku U.	Ded.	Prop.	194	1.2	1.5-1.8	300	7.4, -	-	-	-	-/12
UVSOR	Ded.	Op. '83	53	0.6	0.75	240	120, 3	3000	80	99	3/3
VSX	Ded.	Prop.	200	0.3	1.0	200	1, -	-	-	-	-/2
Korea											
PLS	Ded.	Op. '95	281	2.0	2.0	200	12, 0.08	5000	80	91	1/10
Russia											
KSRS SIB.1	Ded.	Op. '83	8.7	0.075	0.45	230	800, -	-	-	-	0/0
KSRS SIB.2	Ded.	Op. '96	124	0.45	2.5	72	100, 1	2500	-	-	0/9
VEPP-2M	PDed.	Op. '72	18	0.6	0.7	300	460, 4.6	-	-	-	2/3
VEPP-3	Par.	Op. '73	74	0.35	2.0	250	270, 2.7	-	-	-	1/2
VEPP-4M	Par.	Op. '98	366	1.8	6.0	100	400, 120	-	-	-	2/4
Spain											
LSB	Ded.	Prop.	252	2.5	2.5	250	8.5, 0.1	-	-	-	-/10
Sweden											
MAX I	PDed.	Op. '86	32	0.1	0.55	250	80, 8	6000	58	95	1/2
MAX II	Ded.	Op. '95	90	0.5	1.5	250	9, 0.9	5000	90	80	5/8
Switzerland											
SLS	Ded.	Constr.	288	2.4	2.4	400	4.8, 0.05	-	-	-	0/9
Taiwan											
TLS	Ded.	Op. '93	120	1.3	1.5	200	27, 0.66	5500	76	90	3/4
U.S.A.											
ALADDIN	Ded.	Op. '85	88	0.108	0.8-1.0	240	110, 3.7	5200	85	95	4/4
ALS	Ded.	Op. '93	197	1.5	1.5, 1.9	400	6, 0.03	6520	85	96	6/10
APS	Ded.	Op. '97	1104	7	7	100	8, 0.08	5900	78	-	18/35
CAMD	Ded.	Op. '92	55	0.18	1.3-1.5	200	235, 2.35	3000	83	-	0/2
CHESS	Par.	Op. '80	795	5.3	5.3	190	200, 20	5333	75	-	2/2
NSLS VUV	Ded.	Op. '83	51	0.75	0.8	850	160, 3	6853†	75†	96†	5/7
NSLS X-ray	Ded.	Op. '82	170	0.75	2.58, 2.8	350	90, 0.1	7014†	81†	98†	2/2
SPEAR II	Ded.	Op. '73	234	2.25	3.0	100	160, 1.6	6900	77	96	6/10
SURF II	Ded.	Op. '74	5.3	0.01	0.3	200	-, -	-	-	-	0/0

an additional benefit of these devices is the strong reduction in longitudinal coupled bunch instabilities due to increased tune spread within the bunch (Landau damping), which also reduces the effective energy spread. {Harmonic cavities are also used to reduce the bunch length for FEL operation at UVSOR and recently also at SuperACO (5th harmonic, 500 MHz)}.

An alternative method of increasing the bunch length used at ASTRID and at BESSY-I is phase modulation of the r.f. The effect on the energy spread in this case is however not clear.

2.1.4 Closed orbit stability

The closed orbit determines the position and angle of the SR beam source points, and so its stability at the level of a fraction of the electron beam size and divergence is crucial for maximum utilization of the SR brightness. Work is in progress on a wide range of topics - electron and photon beam position monitors (BPMs) and their electronics, mechanical stability of BPMs and the vacuum chamber in general, elimination of electrical noise sources, local and global feedback systems. A detailed review of these topics is given in [3].

2.1.5 Coupled bunch instabilities

Coupled bunch instabilities driven by higher order modes (HOMs) in the r.f. cavities are very troublesome for the operation of SR sources. Apart from the possibility of beam loss, or beam size increase, longitudinal instabilities also cause an increase in the energy spread which reduces undulator radiation intensity, particularly of the higher harmonics. Such instabilities can be overcome by a variety of techniques: harmonic cavities (see 2.1.3), precision adjustment and stabilization of r.f. cavity temperatures, damped cavities and feedback systems. At the PF all of the 4 cavities have recently been replaced with damped cavities which has largely eliminated coupled bunch instabilities up to 400 mA. With feedback systems, the trend is towards digital systems, because of the availability of powerful commercial DSP technology, providing greater flexibility, and better diagnostic features. Digital longitudinal feedback systems are operational at ALS, PEP-II and Dafne, and are due to be installed soon in PLS and TLS. Analog transverse feedback systems operate in ALS, PLS and TLS; a digital system is under development at ELETTRA.

2.1.6 Insertion devices

A topic of continuing development is that of insertion devices (IDs), especially at the newer facilities where there are more vacant straight sections in which IDs can be installed (see Table 1). One area of particular interest is the production of radiation with variable polarization. Permanent magnet "APPLE-2" undulators are under development at ALS, BESSY II, ELETTRA, Spring-8 and TLS. There are also several devices which incorporate electromagnets to allow a rapid switching of the polarization. At the NSLS X-ray ring a combined permanent magnet/electromagnetic wiggler is operational with 100 Hz switching rate. Two new electromagnetic devices have been installed this year at ELETTRA and SuperACO. The one at ELETTRA is a C-shaped structure incorporating both horizontal and vertical fields, and allows a switching rate of 100 Hz. The SuperACO device consists of separate horizontal and vertical fields with an adjustable phase between them which allows a wider range of polarization states to be generated, and can operate at 1 Hz. At the ESRF a novel undulator with combined permanent magnets and electromagnets with a 5 ms switching time will be installed this summer.

In-vacuum short-period devices are of great interest as a way of providing high brightness radiation beams at the highest possible photon energies. A device of this kind was installed in the NSLS X-ray ring in May '97. The permanent magnet device has a 11 mm period, and at the minimum gap of 3.3 mm (3 mm beam aperture) produces radiation with a fundamental of 4.6 keV . A similar device is being constructed at the ESRF and will be ready at the end of this year. A number of in-vacuum devices are also operational, and others being commissioned, in Spring-8.

Various other new devices include: a figure-8 undulator being commissioned in Spring-8; a prototype quasi-periodic undulator (QPU) tested at the ESRF; a variably polarized QPU being constructed at ELETTRA; a 3 T permanent magnet device under test at the ESRF.

2.1.7 Top-up injection

A development topic which may be of great importance for future light sources is "top-up injection" i.e. frequent injection in order to maintain a constant beam current. In this way lifetime limitations can be overcome and better orbit stability obtained, because of the constant head load on machine components. If this can be achieved also with undulators closed and beamline shutters open, then a constant thermal load on the optical elements can also be maintained. This is being given high priority at the APS and tests are due to be performed this summer. Top-up injection is already performed in the CESR positron ring where some users collect data during filling. Some tests were also performed a few years ago at TLS.

2.2 SR Facilities Being Commissioned and Under Construction

The latest member of the 3rd generation SR facilities "club" is BESSY II which started commissioning this year and very quickly achieved the first stored beam on April 22nd. User operation is scheduled from January '99.

Spring-8 achieved first beam in March '97 but was only authorized to operate with 20 mA at that time. Permission was received this year to increase the current to 100 mA, and this was first achieved on May 13th.

The SIBERIA-2 ring of the Kurchatov Synchrotron Radiation Source (KSRS) in Russia has achieved 72 mA at 2.5 GeV, limited by the available r.f. power. Higher current will be possible after the commissioning of a second r.f. generator this summer. Regular user experiments are planned to begin in early '99.

The DELTA ring at the Univ. of Dortmund is partly dedicated as an SR user facility (50%), and partly to SR/FEL (30%) and accelerator physics (20%) development. The ring presently operates at 1.5 GeV with 40 mA, limited by r.f. power, and at 450 MeV for FEL studies. More r.f. power will be added this summer to reach 200 mA. A number of beamlines are under construction and will be commissioned by the end of '98.

In India the circulation of the first beam in INDUS-1 is expected in a few months time. Meanwhile the construction of the building for the 2-2.5 GeV ring INDUS-2 started last year and prototype magnets and aluminium vacuum chambers have been fabricated.

Construction of the ANKA project in Germany is proceeding rapidly after its official start in March '97. Orders have now been placed for all major components. The completion of the building is scheduled for November this year and first beam should be achieved in Dec. '99.

Final approval of the Swiss Light Source (SLS) was obtained in June '97 and building construction started in June this year. For the beginning of operation in summer 2001, the installation of 5 beamlines is foreseen.

In Japan the New SUBARU project is nearing the start of commissioning. This 0.5-1.5 GeV ring uses the existing 1 GeV Spring-8 linac and is being built to carry out R&D towards new light sources and to promote industrial and medical applications. The ring has two 14 m long straights one of which will be used for a free-electron laser, and two 4 m straights, one of which will accommodate an 8 T superconducting wiggler.

2.3 Proposed SR facilities

In Europe, there are four proposals for 3rd generation light sources. DIAMOND (England), LSB (Spain) and SOLEIL (France) are all relatively large projects based on 2.5-3 GeV storage rings that have been under consideration for some time. A more recent proposal is the smaller 1.4 GeV dedicated source ASTRID II (Denmark). The FODO structure provides low emittance (10nm rad) together with 5 straight sections for IDs.

In Japan, the SR user facility proposed by the Univ. of Tokyo, the VSX project, has recently been revised from a 2 GeV light source to a smaller 1 GeV ring with racetrack shape providing a low emittance of 1 nm rad and two 30 m long straights. Tohoku Univ. is also proposing a 1.8 GeV storage ring. At KEK, the increase in energy of the linac for the B Factory means that the Accumulator Ring is no longer required. The conversion to a dedicated 6 GeV light source, the PF-AR (Photon Factory Advanced Ring for Pulsed X-rays), is being proposed.

The Shanghai Synchrotron Radiation Facility (SSRF) awaits final approval, but received R&D funds in June last year. An increase in energy from 2.5 to 3-3.5 GeV is seriously being considered.

Funding for the proposed 2.9 GeV Canadian Light Source is also anticipated in the near future.

3 FEL PROJECTS

Compared to SR facilities, free-electron lasers (FELs) are relatively new and, at least at short wavelengths, still under development. In a FEL an electron beam traversing an undulator interacts with a co-propagating photon beam of the correct wavelength which induces bunching of the electron beam, giving rise to coherent emission. One technique for doing this is the oscillator configuration in which radiation trapped in an optical cavity interacts with many electron bunches on successive passes. The majority of FELs at longer wavelength are of this type, because of the availability of mirrors with sufficiently high reflectivity. To reach shorter wavelength not only requires electron beams of increasing quality in general, but mirror reflectivities become very poor beyond the UV. In principle this can be overcome using the alternative "self-amplified spontaneous emission" (SASE) technique, already successfully demonstrated at infrared and longer wavelengths, which eliminates mirrors but requires a very high quality electron beam and a long undulator.

The main areas in which FELs can compete with alternative sources are generally the IR/Far IR (> 10 µm) and beyond the UV (< 200 nm). The first region is where FELs have been most successful so far and a number of user facilities are in operation. No FEL operates yet below 200 nm, although many short wavelength experiments are underway or planned, using both storage rings and linacs (see [4]). Another major activity is the development of high powered FELs for industrial use.

3.1 FEL User Facilities

Several FEL user facilities are in operation in Europe, Japan and the U.S., all based on the oscillator configuration, but using various types of accelerator and covering 4 decades of wavelength range (see Table 2). The FELI facility has the shortest wavelength FEL operating with a linac (280 nm), and covers the range up to 40 µm with 4 different systems; an extension to 80 µm is foreseen. The Stanford FEL Center operates the only FEL based on a superconducting linac. Here independently tuneable beams can be supplied to two or three users simultaneously, by multiplexing the linac energy and/or switching between undulators, between macropulses. FELIX is planning an upgrade to extend long wavelength operation from 100 µm to 300 µm. CLIO is also planning to improve long wavelength performance and is also proposing CLIO-2 for the 50 µm - mm range. SuperACO is the only storage ring based facility; 350 nm radiation is used for experiments both by itself and also in synchronism with SR for two-colour "pump-probe" experiments. The Univ. of California at Santa Barbara (UCSB) operates two FELs driven by an electrostatic accelerator; a third FEL covering the range 30-63 µm is under development. The microtron driven Frascati FEL Facility (F-CUBE) is presently shut-down to extend the operating range spectral range to include 400 µm - 1 mm.

Table 2. Main parameters of operating FEL user facilities. E = electron energy; λ = FEL wavelength; Δt = micropulse length; P_{micro}, = max. output micropulse power [MW]; P_{mean} = max. average output power [W]; Op.h. = total hours scheduled operation in '98; User.h. = scheduled hours for users in '98; Eff. = op. efficiency (%) for users in '97.

Facility	Accelerator	E (MeV)	λ (μm)	Δt (ps)	P_{micro}	P_{mean}	Op.h.	User.h	Eff.
AFEL, *U.S.A.*	linac	14 - 20	4 - 20	~ 10	50	1	~ 400	~ 100	-
CLIO, *France*	linac	21 - 50	3 - 50	0.5 - 6	≤ 100	≤ 1	~ 3000	~ 2400	-
Duke Mk.III, *U.S.*	linac	26 - 40	2.8 - 6.3	-	1	1	-	-	-
Duke OK-4, *U.S.*	storage ring	240-750	0.226-0.41	-	0.5 - 3	0.15	-	300	-
F-CUBE, *Italy*	microtron	2 - 5	2-3.5 mm	50	10 kW	0.06	-	-	-
FELI, *Japan*	linac	20 - 165	0.28 - 40	2 - 3	10	0.3 - 1	2400	2000	85
FELIX, *Holland*	linac	15 - 50	5 - 100	-	≤ 100	0.3	3200	3000	> 90
Stanford, *U.S.A.*	s/c linac	15 - 40	4 - 100	0.3 - 3	1	1	2000	1500	~ 80
SuperACO,*France*	storage ring	600-800	0.35 - 0.63	20 - 50	1 kW	0.2	650	~ 325	-
UCSB, *U.S.A.*	electrostatic	2 - 6	63-2.5 mm	1 - 20 μs	6 kW	0.1	-	2889†	-
Vanderbilt,*U.S.A.*	linac	24 - 45	2 - 9.4	~ 0.75	5.8	1.5 - 3	2100	1900	~ 80

(† 1997)

Several other operating FELs are expected to become user facilities. The Institute of Scientific and Industrial Research (ISIR) at Osaka Univ. is modifying its L-band linac based FEL for user experiments in the 20-160 μm range. The Compact Infrared FEL (CIRFEL) developed by Northrop Grumman and Princeton Univ. in the US will also function partly as a user facility and is presently being upgraded to extend the wavelength range (8-20 μm) and increase output power. The FEL of the Center for Research and Education in Optics and Lasers (CREOL) of the Univ. of Central Florida operated for the first time in Nov. '97 at 355 μm and is intended to become a user facility in the 220-800 μm range. The Jefferson Lab. IR FEL (see below) will also serve partly as a facility for basic research. Finally, a project has recently been funded at Rossendorf (Germany) for a FEL user facility in the 20-150 μm range based on a new 20 MeV superconducting linac, ELBE.

3.2 Storage Ring FEL Projects

For many years the shortest FEL wavelength was 240 nm, set by the former VEPP-3 FEL project in 1988. The lack of progress since then has mainly been due to the limited gain available in the storage rings used for these tests (NIJI-IV, SuperACO, TERAS, UVSOR) compared to the mirror losses, which deteriorate due to the damage caused by the higher harmonics of the undulator radiation emission. Progress was made in 1996 at UVSOR when using a special helical undulator magnet to reduce mirror damage, a minimum of 238 nm was reached.

More recently the Duke Univ. storage ring FEL succeeded in lasing at 226 nm in April '98 with the ring operating at 500 MeV. The bunch current was only about 1 mA and hence the laser output power was very small. In the future higher bunch currents and ring operating energy will increase this to 1 W. The ring is presently shut down for the construction of a new user facility building.

This was followed in May by the successful lasing on NIJI-IV at 228 nm. NIJI-IV is a compact racetrack ring with 30 m circumference, dedicated to FEL development.

First lasing is expected soon by the FELICITA I project on the DELTA ring at Dortmund. After starting at 470 nm, with the ring at 450 MeV, the wavelength will be reduced in stages to below 200 nm.

Efforts also continue at SuperACO in parallel with its user activity to reduce the operating wavelength.

Finally, a new European collaboration involving Sincrotrone Trieste, CEA/LURE, CLRC-Daresbury Laboratory, Univ. Dortmund, ENEA Frascati and Max-lab has just started to develop a UV/VUV FEL on the ELETTRA ring in the 350-190 nm range.

3.3 High Power FELs

There are several FEL projects that are designed for applied research/industrial use. The Japanese Atomic Energy Research Institute (JAERI) is developing a kW IR FEL based on a 16 MeV superconducting linac with energy recovery. First lasing was reported in Feb. '98, and in March/April a macropulse power of 100 W was obtained at 24-28 μm. Jefferson Lab. together with a Laser Processing Consortium is developing a 3-6 μm "IR Demo FEL" with kW-level average power for applied research and manufacturing applications, based on a 38 MeV superconducting linac with energy recovery; first lasing and 150 W average power were obtained in June this year. BINP, Novosibirsk is also developing a high power IR FEL for the Siberian Centre of Photochemical Research based on a racetrack accelerator-recuperator.

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