Recent Highlights from Synchrotron Radiation Facilities.

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Abstract

A brief overview of synchrotron radiation facilities world-wide is presented. Different kinds of synchrotron radiation sources and their matching to the particle beam parameters are then discussed. The recent development at some facilities and the expected impact in different fields are finally overviewed.

1. Introduction.

The synchrotron radiation facilities are used for basic research in a large number of disciplines like atomic and molecular physics, solid state physics, surface physics, astronomy, medicine, biology, chemistry, geology etc. The synchrotron radiation is also used for more technically oriented applications in material science, electronics, drug characterising etc.
The methods used cover a wide range. Emission studies are carried out where electrons, photons (fluorescence and luminescence), ions and molecular fragments are detected. The direct beam can also be used as a probe in scattering, diffraction and absorption studies. Apart from these material-characterising methods, we can also change materials and structures in photo-chemistry, doping, X-ray lithography and micro-mechanics.
Science in many of these areas are now flourishing due to the present strong development in synchrotron radiation technology. At an accelerator conference like EPAC we will not try to treat the experimental areas but rather focus on the driving force behind this evolution, the development in machine physics and in undulator technology.
Today, we have some 50 synchrotron radiation storage rings in the world, each equipped with some 10-30 experimental stations. A list of the synchrotron radiation facilities world-wide can be found in table 1 [1]. The first highlight in this field is the large and growing activity of synchrotron radiation based science. It should be observed that the synchrotron radiation facilities are also distributed outside the accelerator dense areas which should imply that advanced technology and science is transferred almost all over the globe.

We can now identify four generations of synchrotron radiation rings, three of them are currently in operation while the fourth generation type still is discussed and different solutions tried for the next leap.
Some of the first generation rings are still very active producing synchrotron radiation. These rings were originally designed for high energy physics research and were used parasitically for synchrotron radiation research. Some of these rings are not just still active, they are continuously being upgraded and have in many respects an imposing performance and potential.
The second generation of synchrotron radiation rings were specially designed for the production of synchrotron radiation, mainly using the dipole magnets as light sources. To-day, these rings are the work-horses for the synchrotron radiation production around the world.
Now, we see the third generation rings coming up. The emphasis is here put on insertion devices, and then especially undulators, as radiation sources. The performance of these machines is several orders of magnitudes higher compared to what we could get earlier.
The fourth generation machines are currently planned at several places [2] and experiments are carried out to reach the diffraction limit for the light sources.

2. Figures of merit.

There are mainly two properties characterising a SR source. The first is the flux defined as

$$\Phi = \frac{N_f}{0.1\%, mrad}$$ (photons/(s, 0.1 % energy spread, mrad horizontally))

The brilliance B is the peak flux density in phase space

$$B = \frac{N_f}{0.1\%, mm^2, mrad^2}$$

The flux is a function of electron current and electron energy only. When calculating the brilliance we have to take into account the phase space defined by the diffraction properties and that given by the electron beam emittance.

The photon angular spread defined by diffraction can generally be approximated for gaussian distributed photon beam to

$$\sigma'_{ph} = \sqrt{\frac{\lambda}{2L}}$$ where σ' is the RMS angular spread, λ the emitted light wavelength and L the source length.

The diffraction relation for gaussian distributions

$$\sigma_{ph}\sigma'_{ph} = \frac{\lambda}{4\pi}$$ yields the apparent source size

$$\sigma_{ph} = \frac{1}{\pi}\sqrt{\frac{\lambda L}{8}}$$

The electron beam phase space area or emittance $\varepsilon = \sigma_e \sigma'_e$ should thus preferably be less than $\frac{\lambda}{4\pi}$. If this is the case, we call the source diffraction-limited. This demand is so far difficult to fulfil, especially for shorter wave-lengths. To reach this limit will be the challenge of the fourth generation machines.

Even if the electron beam emittance is close to $\frac{\lambda}{4\pi}$, we need to match the phase space form of the electron beam emittance to that induced by diffraction. The mismatch between these phase-space forms for a dipole source is seen in fig. 1, where L is in the mm range which gives σ_{ph} in the µm range while the electron beam size is orders of magnitudes larger.

For an undulator, with L in the meter region, σ_{ph} is some order of magnitude larger which yields a better match to the electron beam size. This fact plus the larger number of emitting sources explain the high brilliance attainable from an undulator in a low emittance storage ring.

If we now look for the trends in synchrotron radiation research we can see the following development:

i. Higher energy resolution.

For many experiments, not only a higher flux is sufficient to attain a high energy resolution. Generally, the performance of the energy-analysing system will depend on the beam size at the energy analysing slits. Within this constraints, we must keep the photon flux high to get decent measuring periods.

ii. Higher spatial resolution.

So far the experimental information attained has been averaged from rather large samples in the mm region. For a detailed spatial information in the material studied, for instance in microscopy applications, a small probe beam is necessary.

In soma cases, like in high-pressure or small crystal experiments you need a small probe beam to get a high counting rate.

iii. Higher temporal resolution and shorter measuring periods for dynamic studies.

A high brilliance is the figure of merit for all the examples chosen above, and this is even more pronounced when you want a combination of them.

3. Activity at first and second generation sources.

The main production in synchrotron radiation research is today carried out at these facilities. Large user communities and instrumentation have been built up here. Large investments are still being made and the performance is steadily increased. SPEAR is now equipped with a new dedicated injector booster, DORIS III is operated with a by-pass housing several long insertion devices and has gained in performance by now using positrons, SRS is equipped with new wiggler beams etc. The first and second generation

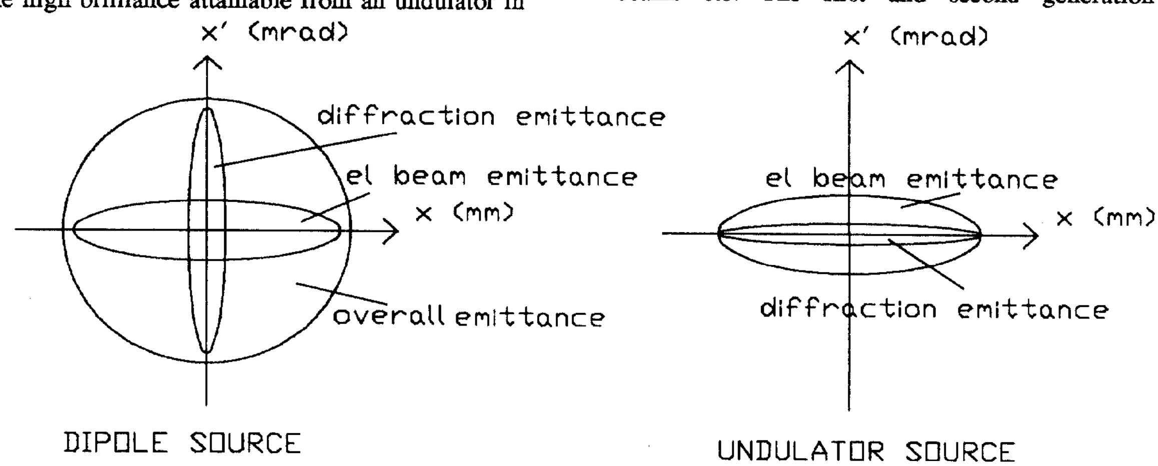

Figure 1. Photon and electron beams in phase space.

synchrotron radiation rings seem to stay in business for quite a while.

4. Third generation storage rings.

Several third generation rings are now operational. Super-ACO has been operating since long and lots of experience has been gained in the operation of insertion devices. Super-ACO is also benefiting from the use of positrons which gives the machine a long beam life-time and a stable beam.
ESRF is the first operating third generation x-ray storage ring. Emphasis is put on undulator radiation in the X-ray region. The technical specification is quite demanding in terms of brilliance and beam life-time. This project is described in more detail in special reports at this conference, but let me bring up some important results achieved.
All specification goals have been attained. In many cases, like beam current, beam life-time, beam stability and reproducibility, the results are even much better than specs. These results are attained with an electron beam.
As a result of this, the new demanding experiments which motivated the construction of the ESRF, have now started up. Just now, we are facing the high potential in terms of high performance and large capacity being realised. New 3rd generation X-ray rings, APS in USA and SPring-8 in Japan will soon start up and further increase the scientific capability world-wide.
We are also facing s similar development in the soft X-ray and VUV spectral region. ALS in Berkeley, SSRC in Hsinchu and Elettra in Trieste have started up and are now steaming up towards their full performance. You will also find detailed reports at this conference for these facilities.
New 3rd generation storage rings in this spectral region are close to starting up. BESSY II and DELTA in Germany, MAX II in Sweden, PLS in Korea and FELL in USA are now in the construction phase.
The commissioning of the 3rd generation facilities has been a success. We were all a bit anxious of eventual new problems arising related to the tough beam specifications. One explanation to this success apart from the skilled accelerator groups commissioning the rings is the tight international co-operation between the experts in the field.

5. Insertion devices.

As important as the storage ring development is that of the insertion devices. These items are in fact defining the 3rd generation ring specifications. Let me just give three examples.
i. Smaller gaps.
The undulator gap is defining the spectral region of the facility. Some years ago, a 40 mm gap was considered as conservative. Most of the third generation sources are now defined for a 20 mm gap. Lately, undulator gaps as small as 6 mm are used at some labs and other labs are following. The use of short period undulators imply a wider spectral region for the facilities.
ii. Circular polarised sources.
New research fields utilising dichroism effects in the VUV to X-ray region, call for circular polarised undulators. Special devices offering circular polarised radiation have been in operation for a couple of years at soma labs. Such devices have now been further developed many labs like Photon Factory (Yamamoto), ESRF (P. Elleaume), ELETTRA (R. Walker), SSRL (Carr, Sasaki).
iii. Harmonic shimming.
The operation at higher harmonics has so far been hampered by undulator phase errors. New methods are now developed (P. Elleaume, ESRF). With this shimming, the synchrotron light yield at higher harmonics will increase substantially thereby increasing the spectral region of the system.

6. Conclusions.

We are now facing a strong development in the synchrotron radiation based sciences. This is in its turn triggered by the development at existing accelerators and even more pronounced by the advent of the 3rd generation sources taken in operation. Right now, we can see this trend continue for all foreseeable time. New concepts like the introduction of non-zero dispersion straight sections, smaller beam coupling and further development of the insertion devices indicate that the brilliance figures will continue to increase at the 3rd generation facilities.

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References:

1. H. Winnick, SSRL, private communication.

2. M. Cornacchia, H. Winnick (editors), SSRL Report 92/02

Table 1.
Storage Ring Synchrotron Radiation Sources (March 1994)

LOCATION	Inst	Electron Energy (GeV)	Notes
BRAZIL			
Campinas	LNLS-1	1.15	Ded*
	LNLS-2	2	Design/Ded
CHINA (PRC)			
Beijing	BEPC	1.5-2.8	Partly Ded
Hefei	HESYRL	0.8	Ded
ROC-TAIWAN			
Hsinchu	SRRC	1.3	Ded
DENMARK			
Aarhus	ASTRID	0.6	Partly Ded
ENGLAND			
Daresbury	SRS	2	Ded
	DIAMOND	3	Design/Ded
	SINBAD	0.6	Design/Ded
FRANCE			
Grenoble	ESRF	6	Ded
Orsay	DCI	1.8	Ded
	SuperACO	0.8	Ded
Discussed	SOLEIL	2.15	Design/Ded
GERMANY			
Bonn	ELSA	1.5-3.5	Partly Ded
Dortmund	DELTA	1.5	Ded/FEL*
Dresden	ROSY	3	Plan/Ded
Hamburg	DORIS III	4.5-5.3	Ded
	PETRA II	7-14	Partly Ded*
Berlin	BESSY I	0.8	Ded
	BESSY II	1.7	Ded*
INDIA			
Indore	INDUS-I	0.45	Ded*
	INDUS-II	2	Design/Ded
ITALY			
Frascati	ADONE	1.5	Shut down
	DAFNE	0.51	Parasitic*
Trieste	ELETTRA	1.5-2	Ded
JAPAN			
Hiroshima	HISOR	0.4-1.0	Design/Ded
Kyushu	SOR	0.7	Design/Ded
Nishi Harima	Spring-8	8	Ded*
Okasaki	UVSOR	0.75	Ded
Osaka	Kansai SR	1.8	Design/Ded
Sendai	TSSR	1.5	Design/Ded
Tokyo	SOR-ring	0.38	Ded
	HBLS	1.5-2	Design/Ded
Tsukuba	TERAS	0.8	Ded
	NIJI IV	0.5	Ded/FEL
	Photon Factory	2.5	Ded
	Acc Ring	6	Partly Ded
	Tristan	8-32	Plan/Ded
KOREA			
Pohang	P L S	2	Ded*
NETHERLANDS			
Eindhoven	EUTERPE	0.4	Plan*
RUSSIA			
Moscow	Siberia I	0.45	Ded
	Siberia II	2.5	Ded*
Novosibirsk	VEPP-2M	0.7	Partly Ded
	VEPP-3	2.2	Partly Ded
	VEPP-4	5-7	Partly Ded
	Siberia-SM	0.8	Ded*
Zelenograd	TNK	1.2-1.6	Ded*
SPAIN			
Barcelona	Catalonia SR Lab	2.5	Authorised
SWEDEN			
Lund	MAX I	0.55	Ded
	MAX II	1.5	Ded*
SWITZERLAND			
Villigen	SLS	1.5-2.1	Design/Ded
USA			
Argonne, IL	APS	7	Ded*
Baton Rouge, LA	CAMD	1.2	Ded
Berkeley, CA	ALS	1.5	Ded
Durham, NC	FELL	1-1.3	Ded/FEL
Gaithenburg, MD	SURF II	0.28	Ded
Ithaca, NY	CESR	5.5	Partly Ded
Raleigh, NC	NC Star	2.5	Design/Ded
Stanford, CA	SPEAR	3-3.5	Ded
Stoughton, WI	ALADDIN	0.8-1	Ded
Upton, NY	NSLS I	0.75	Ded
	NSLS II	2.5	Ded

* In construction