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HIGH ENERGY PHYSICS

solutions

From Light to Action: the Canadian Light Source

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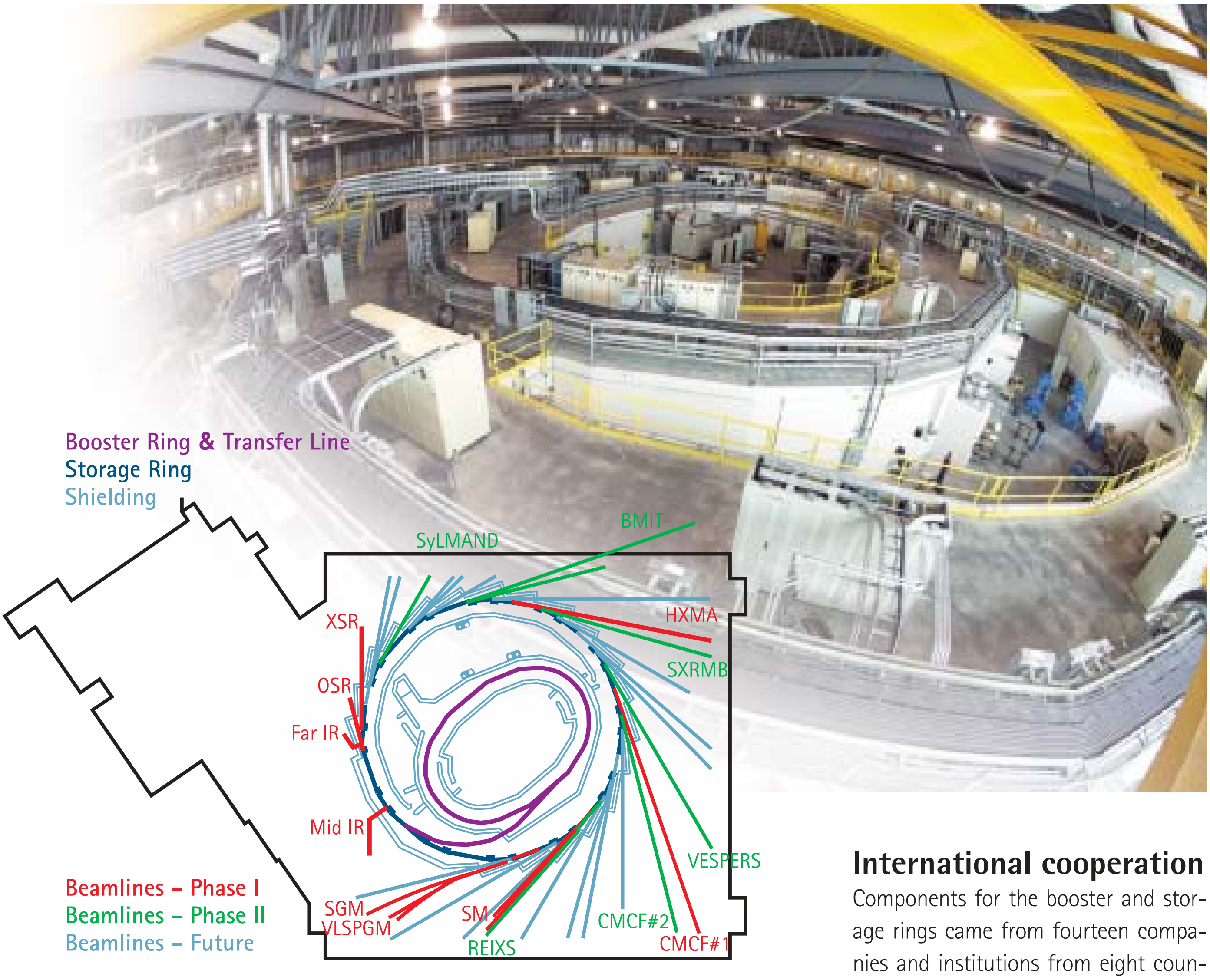
On a snowy day in October, 2004 over 500 dignitaries and invited guests were on hand to witness the official "switching on" of the Canadian Light Source at the University of Saskatchewan in Saskatoon. The event symbolically marked the end of a 30 year quest to design and build a synchrotron in Canada.

Unique design

The Canadian Light Source (CLS) is technologically unique in many ways. The Canadian-designed third generation, 2.9 GeV light source uses an innovative compact storage ring lattice to deliver billions of high intensity photons with a fraction of the foot print and cost of other synchrotrons. This compact design is accomplished by operating the 72 storage ring magnets at fields that push the limits of conventional magnet technology. A superconducting radio frequency cavity designed at Cornell University

CLS Components and Suppliers

- *Dipole magnets:* *Tesla Engineering (UK)*
- *Quadrupole and sextupole magnets:* *Sigma Phi (France)*
- *XY corrector magnets:* *Budker Institute (Russia)*
- *Injection kickers:* *Danfysik (Denmark)*
- *Power supplies:* *IE Power (Canada)*
- *Superconducting RF cavity:* *Accel (Germany)*
- *Cryosystem:* *Linde (Switzerland)*
- *Vacuum chambers:* *FMB (Germany)*
- *Support structures:* *Hitachi (Saskatoon, Canada)*
- *Insertion Device vacuum chambers:* *Advanced Photon Source (USA)*
- *Vacuum pumps:* *Varian, Inc. Vacuum Technologies (USA)*
- *Position monitor electronics:* *Bergoz (France)*
- *Undulator magnets:* *Canadian Light Source*
- *Wiggler magnet:* *Budker Institute*



and built by ACCEL of Germany enables a stored current of up to 300 mA.

Unique partnership

The CLS is also unique in its funding and mandate. The CAN $174 million cost of capital construction and the facility's first seven beamlines is the biggest single investment in Canadian science in the last thirty years. It was paid for by an unprecedented partnership that includes federal, provincial and local governments, universities and industrial partners.

Unique focus

With a board of directors representing various funding partners, the management structure emphasizes the facility's national character and its focus on serving researchers from academia and industry. Its long-term target for industrial usage is 25 per cent. Historically, synchrotrons have had about 10 per cent industrial usage.

International cooperation

Components for the booster and storage rings came from fourteen companies and institutions from eight countries. Four undulators (two conventional planar, one Apple II type elliptically polarized undulator in which all four jaws move independently and one hybrid in vacuum device) were designed, built and shimmed at the CLS. A super-

CLS Basic Storage Ring Specifications

Configuration	Double Bend Achromat
Circumference	170.88 m
Periodicity / straights	12
Length of straights	5.2 m
RF frequency	500 MHz
RF Voltage	2.4 MV
Maximum Energy	2.9 GeV
Nominal Current	300 mA (1 RF cavity) ~ 600 mA (2 RF cavities)
Vacuum Pressure	1 x 10^{-10} torr
Critical Energy (bend magnets)	7.5 keV

conducting wiggler was built by the Budker Institute of Physics in Novosibirsk, Russia. Memoranda of understanding with a number of other synchrotrons were crucial to the successful completion of the Phase I facility.

Surpassing expectations

The CLS produced its first light December 9, 2003. Since that time, the storage ring has completed commissioning and the first seven beamlines are receiving light. The synchrotron is delivering beam lifetimes of 13.5 hours (1/e) with 100 mA stored beam, and beam currents up to 175 mA with lifetimes of 8.3 hours have been achieved—surpassing all expectations for the machine's first year of operations. With completion of the Phase I project, efforts are now turning to beamline pre-operation commissioning and the start of the CAN $50 million Phase II project, which will see a second set of seven beamlines added to Canada's national synchrotron facility. As of September 2005, 37 researchers have visited the CLS to take part in the first experiments, with positive results and data obtained. The race is on for the bottle of champagne that will go to the authors of the first published paper.

CLS Basic Machine Parameters

Parameter		Design	Model	Machine
Length	m	178.88	170.88	170.88
ν_x		10.22	10.22	10.22
ν_y		3.26	3.26	3.26
χ_x (adjusted)		-	0.7	0.4
χ_y (adjusted)		-	2.0	2.5
ε_x	nm-rad	18	13	15
ε_y	nm-rad	-	-	0.2
δ ($\Delta p/p$)	%	0.11	0.11	
Straights:				
β_x	m	8.1	7.1	~7
β_y	m	4.6	4.5	~4.5
η_x	m	0.15	0.26	~0.25
η_y	m	-	-	→0
RF:				
Frequency	MHz	500,000	500,000	500,000
Voltage	MV	2.4	1.8	1.8
α		0.0038	0.0041	-
σ_{bunch}	ps	33	40	39
Orbit position:				
X_{rms}	µm	40	40	30
Y_{rms}	µm	80	80	70
Stability:				
X_{rms}	µm	-	-	<5
Y_{rms}	µm	-	-	<5
Current	mA	500	-	175
Lifetime	1/e hr	6	-	8.3

Phase 1 – Insertion Devices

ID Type	Poles	Period	Min. gap (mm)	Output (eV photons)
Undulator	19	185	25	5.5 - 250
Undulator	53	45	12.5	250 - 1900
In-vacuum Undulator	145	22	5	6000 - 18000
SC Wiggler	60	35	15	10000 (critical energy)
Apple II EPU	43	75	15	100 - 1000 (circularly polarized), 100 - 3000 (linearly polarized)

A New Tool for Canadian Science

Synchrotrons have been described as "Swiss Army Knives of science" for their versatility. Synchrotron techniques have been applied to a host of research problems, ranging from molecular-level materials analysis and protein crystallography, to soft-tissue imaging and heritage preservation. The Canadian Light Source at the University of Saskatchewan is no exception, with a suite of beamlines available to conduct cutting-edge research in environmental, materials, and life sciences by academic and industrial researchers.

The CAN $174 million CLS capital project included the construction of the synchrotron and a cadre of seven "Phase I" experimental beamlines, covering the electromagnetic spectrum from far-infrared terahertz radiation to "hard" x-rays with photon energies in excess of 40 keV. These beamlines were the results of proposals from members of the Canadian synchrotron community and provide a balanced array of tools for cutting edge academic and industrial research.

Three of the beamlines have their origins in the facilities maintained by the Canadian Synchrotron Radiation Facility at the Synchrotron Radiation Center in Stoughton, Wisconsin.

All seven Phase I beamlines, as well as two diagnostic beamlines, are now receiving light at their end stations and the majority of them are now collecting data as part of the commissioning process. The data received at the end stations thus far indicate that the CLS is running beyond expectations.

First users

In May 2005, the CLS hosted its first user to use a beamline for original research. Allen Pratt from Natural

CLS Executive Director Bill Thomlinson (left), Valentina Zakaznova-Iakovela (PDF, University of Western Ontario, centre), Allen Pratt (Natural Resources Canada, right).

Industrial Research Active at CLS

While the CLS experimental and technical staff has been bringing light to beamlines, the industrial science team has also been extremely active, conducting numerous demonstration projects illustrating the power of synchrotron techniques to tackle problems in the environmental and resource sectors.

A number of hard x-ray experiments were conducted on the X11A beamline at the National Synchrotron Light Source (NSLS) in both environmental and material science, particularly the study of arsenic and its effect on the biosphere. A number of environmental samples were examined in order to determine the origin of legacy tailings from a gold mine. The results showed that x-ray absorption spectroscopy (XAS) could be used to differentiate between tailings formed by roasting (largely As^{3+} and As^{5+}) and those formed in a cyanide leach (As^{-1}).

For environmental studies, the ability to look at a sample in situ is where XAS shines in the field of characterization. CLS researchers used XAS to characterize the reduction products formed in an arsenic bioreactor and were able to track the arsenic oxidation following exposure to ambient air.

CLS industrial scientists are also active in life science studies with particular application to the agri-food industry. Researchers from the CLS have carried out infrared mapping of seeds to determine the location of nutrients. They have also used XANES to develop a better understanding of the uptake of trace nutrients such as selenium from animal mineral supplements. Both studies could lead to better, high quality feeds for livestock.

The CLS Experimental Hall, with Mid-Infrared experimental hutch and SGM beamline in foreground.

Resources Canada CANMET Labs became the First Synchrotron User at the CLS when he used soft x-rays from the Variable Line Spacing Plane Grating Monochromator (VLS-PGM) beamline to study the arrangement of atoms on the surface of pyrite (fool's gold). Pratt hopes that this increased understanding of pyrite's surface chemistry will lead to more environmentally friendly and efficient ways to separate pyrite and gold from ore. Shortly thereafter, University of Western Ontario researcher Stewart McIntyre used the VLS-PGM to study lead and lead corrosion. Lead corrosion is an important issue for Canada's nuclear power plants and their aging lead cooling pipes.

Other early users have conducted preliminary experiments on the synchrotron's Spherical Grating Monochromator and Hard X-ray Microanalysis beamlines, with promising results.

For further
information please contact:
matthew.dalzell@lightsource.ca,
sandra.ribeiro@lightsource.ca
or visit:
www.lightsource.ca

Phase 1 – Beamlines

Beamline	Energy (eV)	Resolution ΔE / E @ E	Flux (γ/s/0.1%BW) @ 500 mA	Techniques available
	Wavelength (cm-1 for IR, otherwise Δ)		Spot size Hor x Vert	
Far Infrared Spectroscopy (Far IR)	0.0012 - 0.496	0.0008 - 4 cm-1	5 x 10^{13} @ 100 μm	High spatial resolution far IR spectroscopy of condensed phase materials; Ultra high spectral resolution (<0.001 cm-1) spectroscopy of gas-phase molecules.
	10 - 4000		50 μm x 50 μm	
Mid Infrared Spectro-Microscopy (Mid IR)	0.06 - 0.74	0.2 - 16 cm-1	1 x 10^{14} @ 10 μm	Spectromicroscopic imaging at diffraction-limited spatial resolution; Spectromicroscopy at grazing angle of incidence; Spectromicroscopy with Attenuated Total Internal Reflection (ATR); Photoacoustic Spectroscopy.
	450 - 6000		γ / 2.5	
High Resolution Spherical Grating Monochromator (SGM)	200 - 1900	10^{-4} @250 eV 2x10^{-4}@1900 eV	2x10^{13} @ 250 eV 5x10^{11}@1900 eV	X-ray Absorption Spectroscopy (XAS); X-ray Photoelectron Spectroscopy (XPS); Auger Electron Spectroscopy (AES); X-ray Excited Optical Luminescence (XEOL) Spectroscopy; Photoemission Electron Microscope (PEEM).
	62 - 6.5		50 μm x 100 μm	
Variable Line Spacing Plane Grating Monochromator (VLS PGM)	5.5 - 250	< 10^{-4}	10^{12} @10 eV 0.2mm x 0.2mm 7x10^{11} @ 250 eV 0.05mm x 0.5mm	X-ray Absorption Spectroscopy (XAS); X-ray Photoelectron Spectroscopy (XPS); Auger Electron Spectroscopy (AES); X-ray Excited Optical Luminescence (XEOL) Spectroscopy; Photoemission Electron Microscopy (PEEM).
	2254 - 49.6			
Soft X-ray Spectromicroscopy (SM)	250 - 2000	8000	108 in 50 nm	Scanning transmission X-ray Microscopy (STXM) Photoemission Electron microscopy (PEEM).
	50 - 6.2			
Canadian Macromolecular Crystallography Facility (CMCF#1)	6500 - 18000	10^{-4}	10^{13} γ / sec	Single crystal X-ray diffraction; Multiwavelength Anomalous Dispersion (MAD).
	1.9 - 0.7		50 μm x 150 μm	
Hard X-ray MicroAnalysis (HXMA)	3500 - 40000	10^{-4}	10^{14} γ / sec	X-ray Absorption Fine Structure (XAFS); Microprobe; Diffraction; Reflectivity; Diffraction Anomalous Fine Structure (DAFS).
	3.5 - 0.3		10 μm x 10 μm	

ESRF: a Light for Science

The European Synchrotron Radiation Facility (ESRF) located in Grenoble, France – a joint facility supported and shared by 18 European countries – operates the most powerful synchrotron radiation source in Europe.

Thanks to the delivery of X-rays (light which has a much shorter wavelength than visible light), synchrotron radiation sources, which can be compared to supermicroscopes, reveal invaluable information in numerous fields of research: Biology, chemistry, medicine, earth & material sciences, physics, environment, and industry (notably pharmaceutical, cosmetics, petrochemistry, and microelectronics).

Varian announcement

Varian turbomolecular pumps, as well as ion pumps are widely used in High Energy Physics and General UHV research. With ESRF, Varian Vacuum Technologies has demonstrated once again its products are designed to offer unmatched reliability, performance, and cleanliness in order to meet the needs of its customers .

Thanks to its research & development department, as well as its flexible and fully automated manufacturing tools, Varian Vacuum Technologies customized for ESRF, TSPs, ion pumps, and DUAL ion pumps controllers. Moreover, Varian Vacuum Technologies ensures the complete refurbishment, including vacuum firing, of the ion pumps sold 15 years ago.

For further information
please contact:
yann.lacroix@varianinc.com
or by phone:
++33 1 69 86 38 84

The major characteristic of the ESRF's X-ray beam is its extreme brightness (number of photons produced per second per surface, solid angle, and energy bandwidth - 3x10^{21} units) which opens up new fields of applications: it makes possible to examine samples of microscopic matter, analyse ultra-dilute solutions, or even to observe what happens during chemical or biological reactions over very short timescales.

Synchrotron radiation facility principles: a ring of light

Electrons emitted by an electron gun are first accelerated in a linear accelerator (linac) and then transmitted to a circular accelerator (booster synchrotron) where they are accelerated to reach an energy level of 6 billion electron-volts (6 Gev). These high-energy electrons are then injected into a large storage ring (844 metres in circumference) where they circulate in a vacuum environment maintained by ion pumps, at constant energy, for many hours.

Inside the storage ring

The storage ring includes both straight and curved sections. As they travel round the ring, the electrons pass through differents types of magnets. These includes:

Bending magnets

When the electrons pass through these magnets, they are deflected from their straight path by several degrees. This change in direction causes them to emit synchrotron radiation.

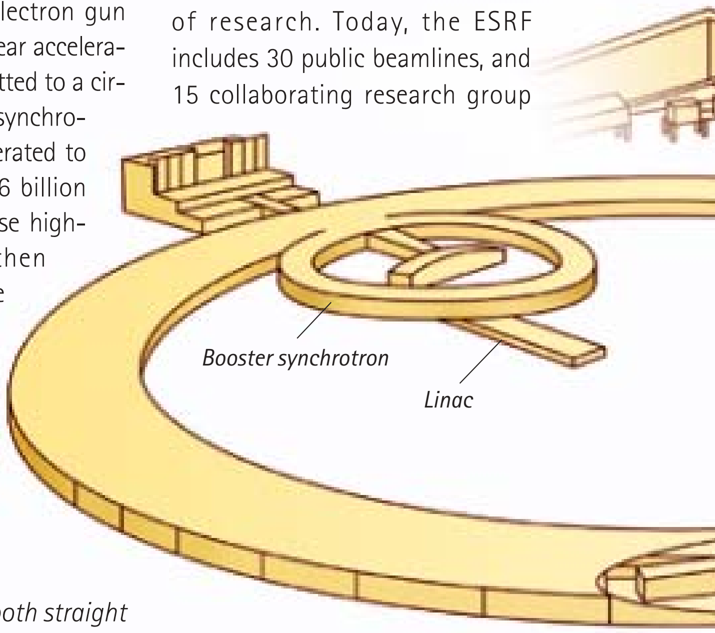
Undulators

These magnetic structures, made of a complex array of small magnets, force the electrons to follow an undulating, or wavy, trajectory. The beams of radiation emitted from the different bends overlap and interfere with each other to generate a much more intense beam of radiation than that generated by the bending magnets.

Focusing magnets

These magnets, placed in the straight sections of the storage ring, are used to focus the electron beam to keep it small and well-defined. A small and well-defined electron beam will produce the very bright X-ray beam needed for the experiments.

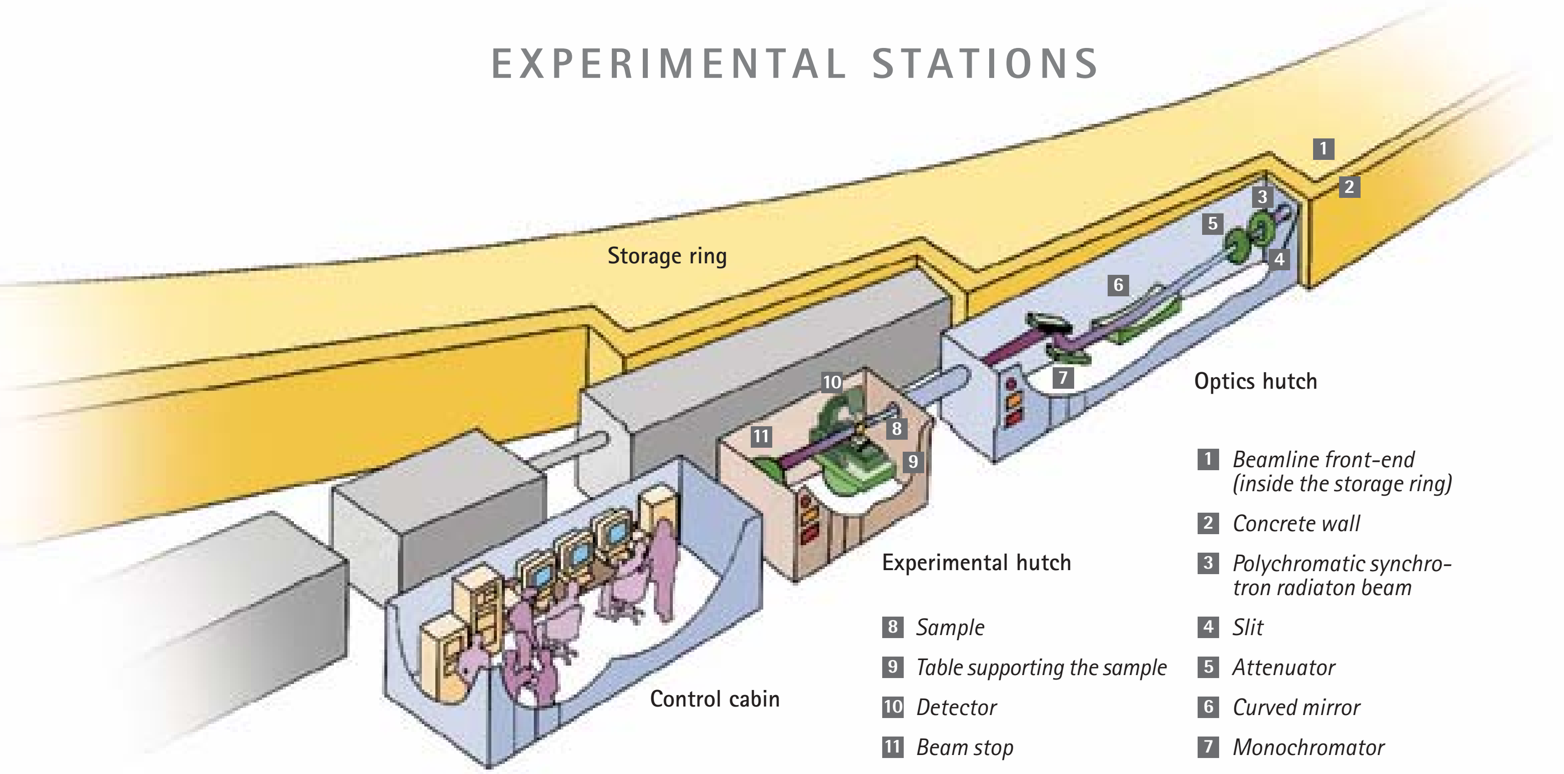
The synchrotron beams emitted by the electrons are directed towards the beamlines which surround the storage ring in the experimental hall. Each beamline is designed for use with specific technique or for specific type of research. Today, the ESRF includes 30 public beamlines, and 15 collaborating research group (CRG), in which experiments run throughout the day and night.



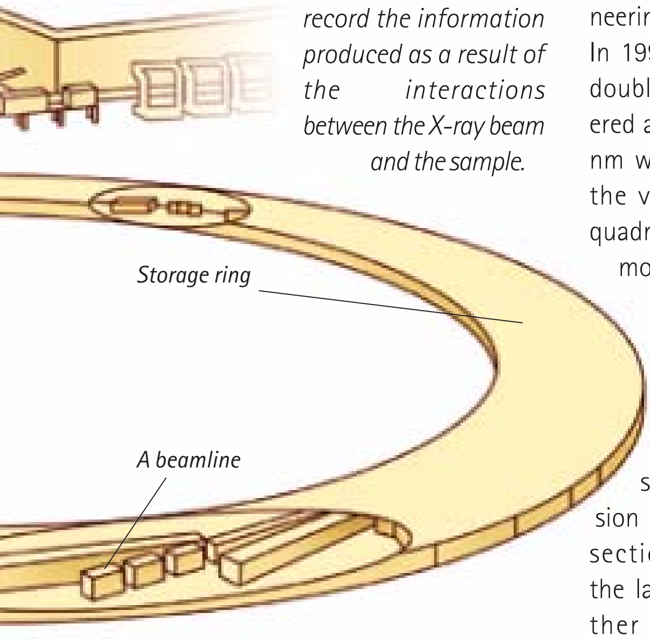
Each beamline includes

***An optics cabin**, housing the optical systems used to tailor the X-ray beam to have the desired experimental characteristics.*

EXPERIMENTAL STATIONS



An experimental cabin *which contains the support mechanism and sample environment for the sample to be studied. One or more detectors record the information produced as a result of the interactions between the X-ray beam and the sample.*



A control cabin *which allows the researchers to control their experiments and to collect the data.*

From infancy to maturity

The ESRF's brightness has increased dramatically and is now at least one hundred times higher than its design parameters. This stems from upgrades carried out to the lattice, the radio frequency system, and the insertion devices, as well as from other engineering developments.

In 1994, the original zero dispersion, double bend achromat lattice delivered a horizontal emittance close to 7 nm with less than 10 % coupling to the vertical plane. Using different quadrupole and sextupole settings, a modified lattice with a 4 nm emittance was implemented and operated in user service mode in 1995. The shrinking of the emittance was obtained by introducing small dispersion in the straight sections. In 1996, the lattice was further modified to reduce the vertical emittance in all insertion devices straight sections, opening the way up to very low gap insertion devices. Further work was undertaken to understand and minimise the vertical emittance.

The radio frequency system of the ESRF ring was initially designed for a standard 100 mA. Between 1992 and november 1995, the beam current in user service mode was raised progressively from 100 to 200 mA. In august 1997, a third pair of radio frequency cavities provided the margin and redundancy required for the long term operation at 200 mA. In those days, for reasons of beam stability, the 200 mA was only delivered in 1/3 filling mode with a lifetime of around 10-20 hours. In 2004, the uniform

and 2/3 filling modes correspond to 66% of user service mode with a lifetime of 80 hours being delivered in uniform. Raising the current to 300 mA or even higher is an active subject of development for the years to come. At the same time, a vigorous and ongoing effort was set up to develop and upgrade the insertion devices. In 1994, the minimum gap of an undulator was 20 nm. As soon as 1994 , the first insertion devices segment with a 16 nm gap was installed, followed by many others. Later 11 nm gap undulators were built followed in 1999 by the first in-vacuum undulator operating at a minimum gap of 5 nm. The magnetic gap reduction implied a shrinking of the undulator period and a shift of the undulator spectrum to higher photon energy. However, the effective jump in performance from longer and smaller gap insertion devices took more time than expected for two mains reasons. Firstly, higher brightness at higher photon energies involves a higher white beam heatload. The front end was unable to withstand the power delivered by a 5 m long , 11 nm gap undulator operated with a ring current of 200 mA. So, in 2000, a new front end was tested and the beamline monochromators were upgraded using diamond crystals and/or cryogenic cooling. The second reason was that, as the insertion devices vacuum chambers being developed needed to be compatible with a large quantity of existing undulator segments, the insertion devices chamber could not be equipped with an antechamber, and the pumping performed from the extremity induced a large pressure bump in the middle of the insertion devices vessel, resulting in excessive Bremsstrahlung downstream in the beamline. To remedy this effect, the in-vacuum undulator technology was developed as well as the non evaporable getter (NEG CERN licence) coating of the insertion devices vacuum chambers. In 2004, 10 of the 28 straight sections equipped with insertion devices have received a NEG coated vessel and a NEG coating facility is operating in house.

This major upgrade in performance since 1994 has also been accomplished thanks to a dramatic progress in many other areas such as beam diagnostics, control, alignment, vacuum, operation...

Facility specifications:
ESRF in 2004 (1994)

Current:	200 (100) mA
Emittances:	4 & 0,03 (7 & 0,7) nm
Insertion devices gap:	5-11 (20) mm
Insertion devices length:	1,6 (1,6-5) m

For further
technical information
about ESRF please contact:
Kersevan@esrf.fr, hahn@esrf.fr,
bersier@esrf.fr
or refer to:
www.esrf.fr

With courtesy of ESRF communication department.

6, rue Jules HOROWITZ, BP 220,
F-38043 GRENOBLE Cedex 9, France
Tél. : + 33 4 76 88 20 00
Fax : + 33 4 76 88 20 20