ISA

Institute for Synchrotron Radiation Aarhus University

Newsletter

No.1. January 1990

This newsletter is the first of a planned series, in which the activities of the Institute for Synchrotron Radiation at the Aarhus University will be presented. This first issue has a special character, in that it also serves as an introduction to ISA.

The main objective in the formation of ISA is to establish a center which makes the experimental facilities and potential of the storage ring ASTRID available to users from public as well as private, national as well as international organizations.

On these pages, the existing and coming facilities will be presented, including a description of some of the planned scientific and technological activities. The more technical information and parameters are found in separate inserts.

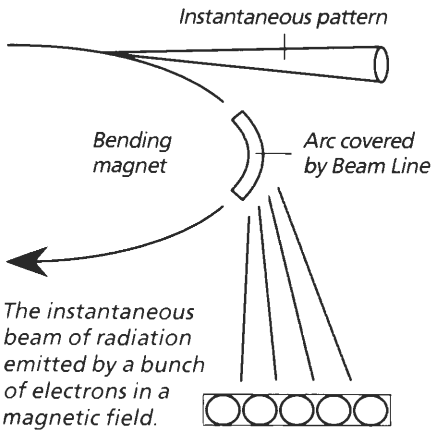
Synchrotron Radiation

An introduction

Synchrotron radiation is the name given to the electromagnetic radiation which is emitted by electrons being deflected by an electromagnetic field.

In a storage ring such as ASTRID, the electrons in the beam move under no external forces in the straight sections, but in the bending magnets strong magnetic fields force the electrons to follow a circular path with constant radius.

An accelerated electric charge will emit electromagnetic radiation, and since the electron velocity is very close to that of light, the radiation is emitted within a narrow cone in the direction of motion. Since the electron moves on a circular path in the magnet, the effect will be similar to light from the headlights of a car making a turn. An RF-acceleration system compensates for the energy lost to synchrotron radiation.



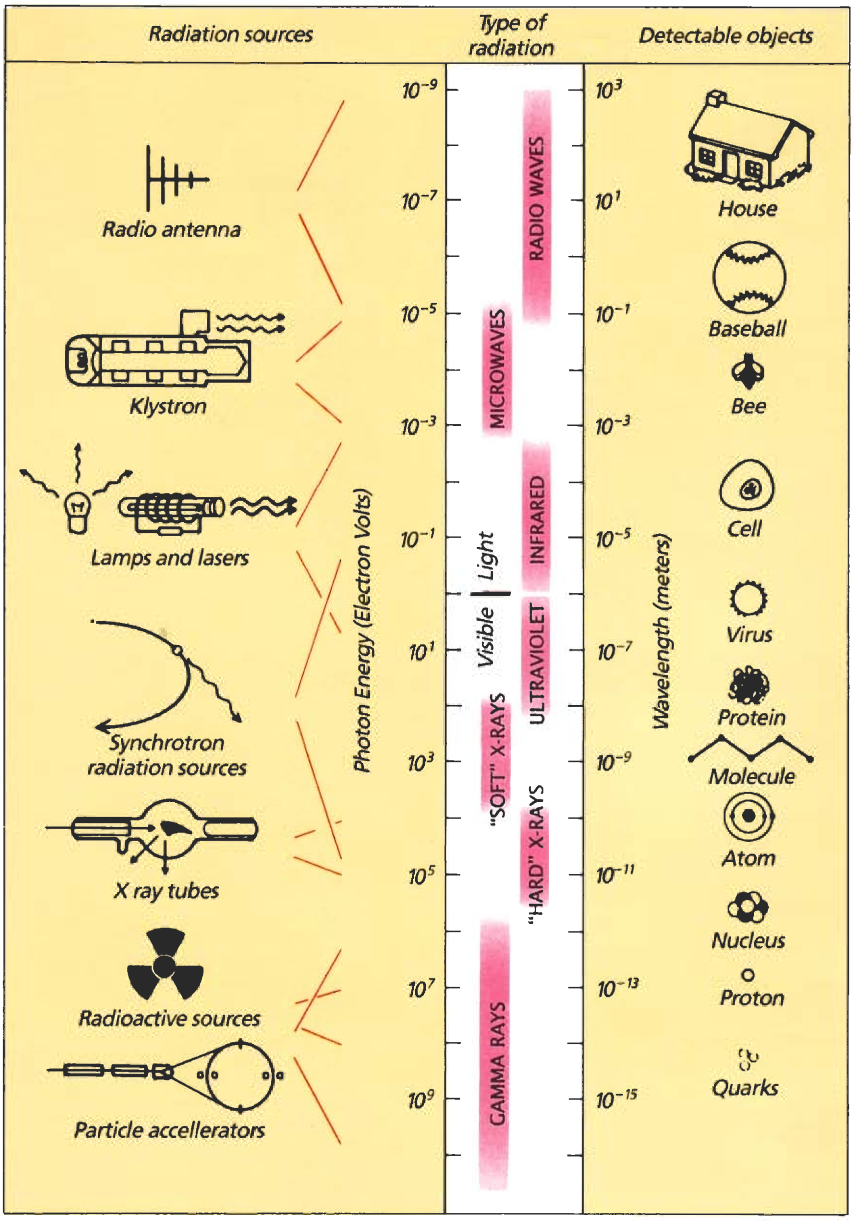
At any point at beam level in the laboratory, the light from one bunch of electrons, will therefore appear only as a short flash of radiation, but since there are many bunches and the beam circulates with a high velocity, the flashes come with a frequency of some 100 MHz.

Synchrotron radiation can be characterized by the critical energy of the radiation. The intensity of the radiation emitted decreases slowly below this energy, whereas the decrease is very rapid above the critical energy.

The synchrotron radiation is linearly polarized in the orbit plane.

Radiation emitted by an electron moving in an magnetic field.

Energy of electron (GeV)	E_o
Magnetic field (Tesla)	B
Critical energy (keV)	$E_c = 0.66BE_o^2$
Critical wavelength (Å)	$\lambda_c = 12.4/E_c$
Angular spread of light (mrad)	$0.511/E_o$



Spectrum of electromagnic radiation

ASTRID as a source of Synchrotron radiation

When ASTRID is used as a source of synchrotron radiation, electrons with an energy of 100 MeV are injected from the race-track microtron. When a sufficiently large current (100-200 mA) has been accumulated, injection is terminated and the RF-cavity in the ring accelerates the electrons to their final energy of 600 MeV. When this beam energy is reached, the RF cavity will continue to run in order to replace the energy lost to synchrotron radiation. The entire process of 'filling' the ring is expected to last 10-20 minutes.

Several effects cause the beam intensity to decrease exponentially with time. First of all, the electrons collide with the gas molecules remaining in the vacuum system leading to large scattering angles and energy losses. Secondly, electrons scatter on other electrons within the same bunch. Finally, synchrotron radiation itself causes momentum changes, which leads to beam losses. These effects together lead to a beam lifetime of the order of one day. When the beam intensity has decreased significantly, the remaining beam is dumped, and the ring is filled again from the injector.

Synchrotron radiation is emitted in the 8 45° bending magnets, in which the electron follow a circular trajectory

ASTRID beam characteristics

	Middle of straight section	*Dipole entrance*	*Dipole center*
Hor. size (mm)	*1.54*	*0.44*	*0.50*
Vert. size (mm)	*0.21*	*0.29*	*0.06*
Hor. div. (mrad)	*0.92*	*0.98*	*0.96*
Vert. div. (mrad)	*0.91*	*0.91*	*0.95*

of radius 1.25 m. The synchrotron radiation intensity is determined mainly by the number of circulating electrons, ie. the current in the ring, and hence a current as high as possible is stored in order to satisfy the users of the radiation. Furthermore, a small source size and a small divergence of the radiation leads to a large number of photons in a given narrow energy-range on a spot on the sample. The source size is at a minimum just where the radiation is emitted, namely in the dipoles. In particular the vertical beam size between the two 45° bending magnets makes this the ideal source-point for a high-resolution monochromator such as the SX-700.

ASTRID Synchrotron radiation parameters

Electron energy	*600 MeV*
Horiz. beam emittance	*0.16 mm mrad*
Electron current	*200 mA*
Critical energy	*0.38 keV*
Critical wavelength	*32 Å*
Beam lifetime	*24 hours*
Number of bunches	*14*
Time between bunches	*9.5 ns*
Bunch length (RMS)	*0.1 ns*
Energy loss/turn	*9.4 keV*

ASTRID compares very well with other synchrotron radiation sources in the ultraviolet and soft X-ray region. The synchrotron radiation in this region is much more intense than that from a large X-ray generators, typically 100 times more intense than the characteristic radiation, and 10000 times more intense than the continuous radiation from an X-ray tube.

An extension of ASTRID with so-called insertion devices is planned. Such devices consist of either a large number of magnets with a moderate field (undulator), or a few very strong magnets (wiggler). An undulator will boost the intensity, and especially the so-called brilliance of the soft radiation, whereas the wiggler will extend the energy of the usable radiation to higher values.

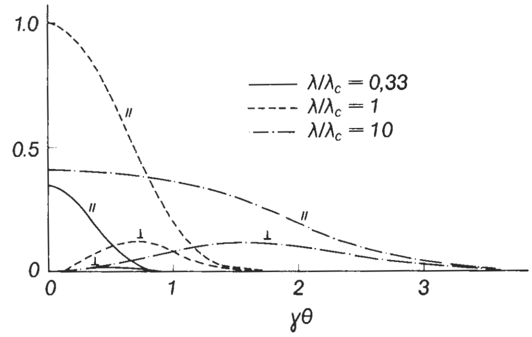
The time structure of the electron beam, and thus of the synchrotron radiation is determined by the RF system. Furthermore bunches can be suppressed to increase the time interval between bunches. The radiation will thus be emitted in short pulses, thereby enabling time-resolved experiments.

SX-700 Monochromator

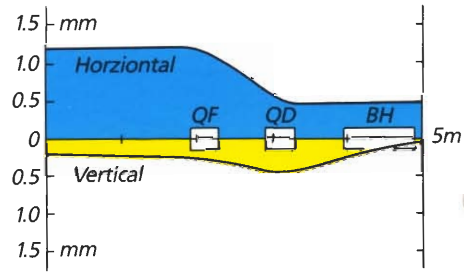
An SX-700 monochromator has been bought from ZEISS for permanent use on beamline 5.

The SX-700 is a high-transmission monochromator covering the energy range 6-1000 eV with an excellent resolution in the order of 100 meV. This instrument thus covers the range of several conventional monochromators.

In order to make the SX-700 available to users before ASTRID can produce synchrotron radiation, it has been set up at BESSY, Berlin, where a special arrangement has made it possible to establish a Danish beamline. BESSY and ISA have agreed to share the available beamtime equally.

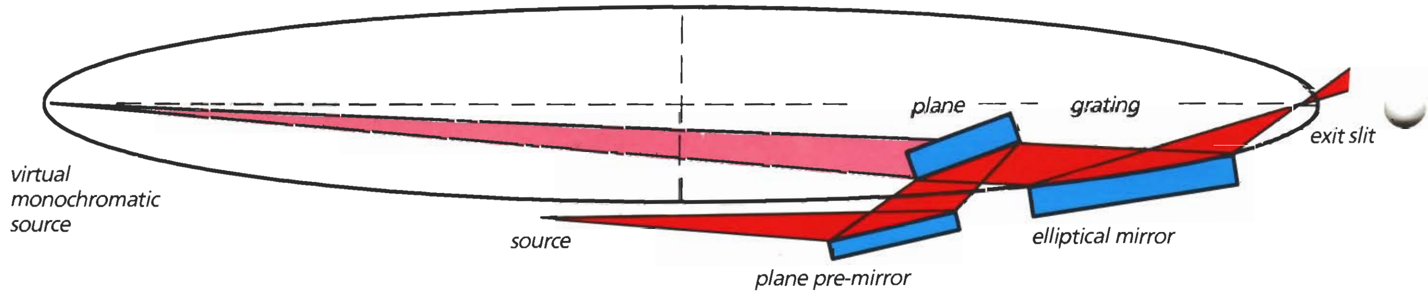


Intensity of the polarization component parallel (//) and perpendicular (⊥) to the beam orbit as a funtion of angle to the orbit plane.

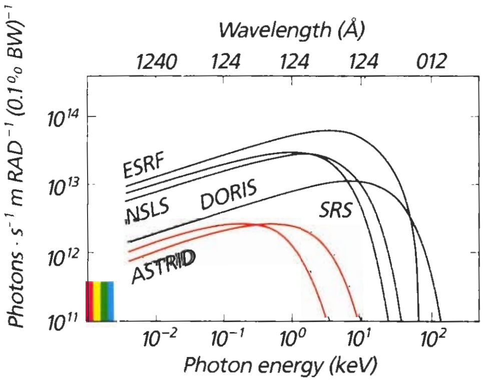


Horizontal and vertical electron-beam size in 1/8 of the ring.

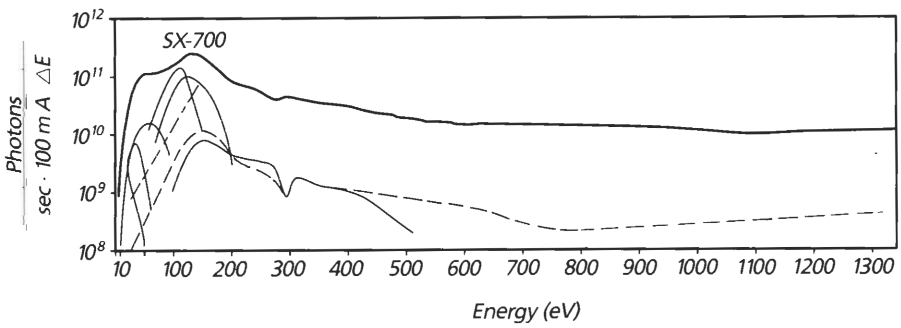
Future ISA groups will thus have the opportunity of getting started quickly, and obtaining experience on the monochromator as well on the the associated surface analysis setup. After two years at BESSY, the beamline will be transferred to Aarhus. An ISA physicist will be permanently stationed at BESSY during the two-year period.



Geometry of SX-700 optical components.

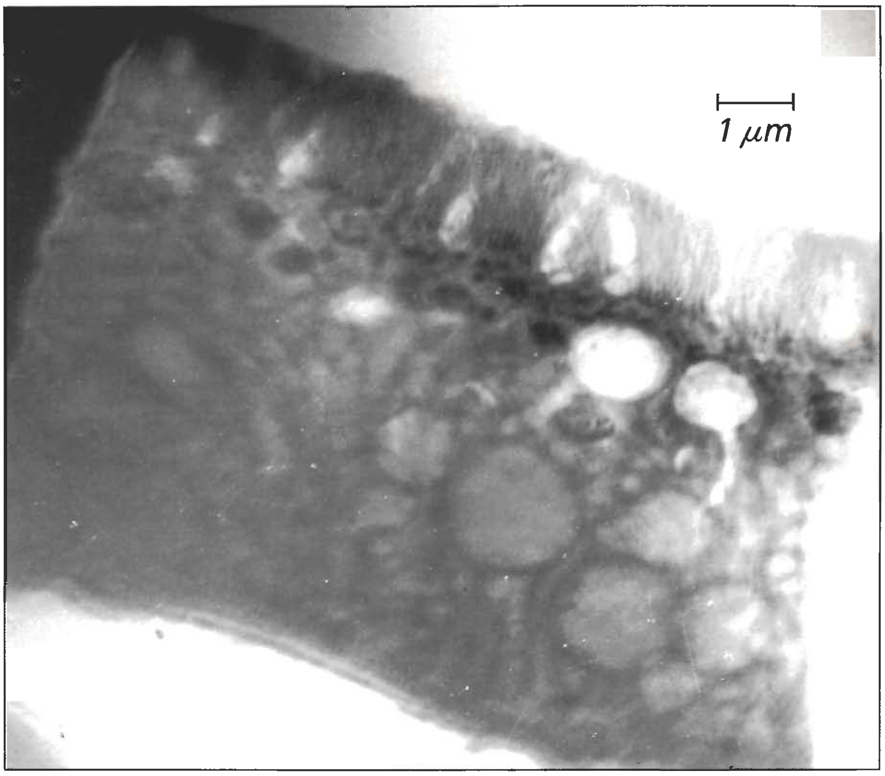


The radiation spectrum from ASTRID and some high-energy synchrotron radiation sources. The visible part of the spectrum is indicated.



Transmitted intensity from the SX-700 compared to other types of monochromators commonly used in this energy range.

Biology and Medicine



X-ray microscope picture of section of rat kidney.

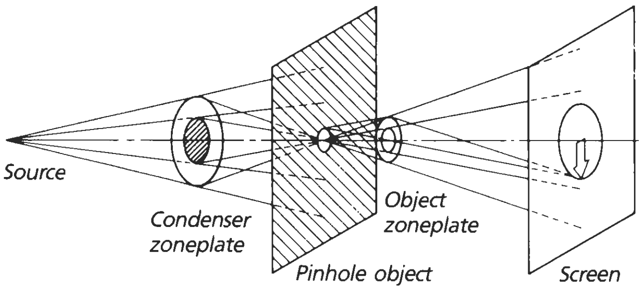
X-ray microscopy

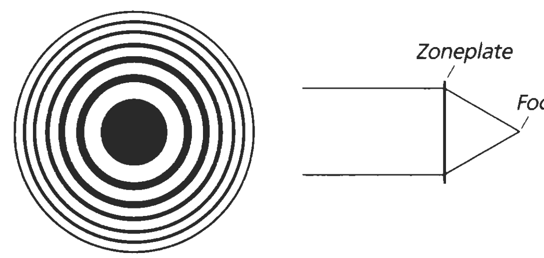
Microscopy is an essential tool in examinations of biological samples. Presently, the resolution in light microscopy is limited by the wavelength of visible light, and electron microscopy requires extensive sample preparation. An X-ray microscope can achieve better resolution than conventional light microscopes, and will require little or no sample preparation.

One beamline on ASTRID will be used for an X-ray microscope. The instrument which will be placed on this beamline will be an imaging microscope operating at X-ray energies in the 'water window', which is the range between the absorption edges for carbon and oxygen. In this range, natural contrast between water and protein is obtained. This is of great importance, since a minimum of sample preparation is involved, i.e. no staining is necessary. Furthermore, it opens possibilities for imaging living cells in a wet environment.

The best resolution available today is of the order of 500 Å, but a resolution of 100 Å are expected with the advancement of X-ray lens (zone plate) fabrication techniques.

Besides using these focussing techniques for microscopy, they may also be employed in small-spot ESCA, which may provide chemical information of the sample surface with an micron lateral resolution.





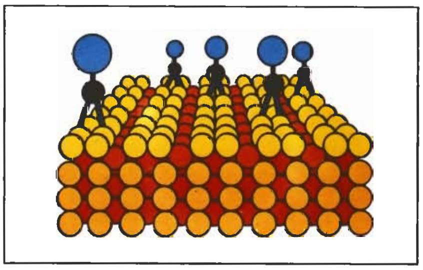
Physics

Surface Physics

A surface physics program is planned, which will be be running at the Danish SX-700 beamline at BESSY, until it is transferred to Aarhus when ASTRID is operational as a source of synchrotron radiation.

The purpose of the project is to investigate interrelationships between electronic and geometrical properties of clean and adsorbate-covered surfaces.

The first systems to be studied are simple- and transition-metal surfaces with alkali adsorbates. These systems are of considerable technological importance in connection with electron-emission devices and in the promotion of catalytic reactions. There is also much current interest in these systems, due to observations of a pronounced coverage-dependence in the nature of the chemical bond formed upon adsorption, and adsorption induced reconstruction of the substrate for some surfaces.



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The methods used will be many of the established surface analytical techniques plus some especially well suited for synchrotron radiation.

Laser Physics

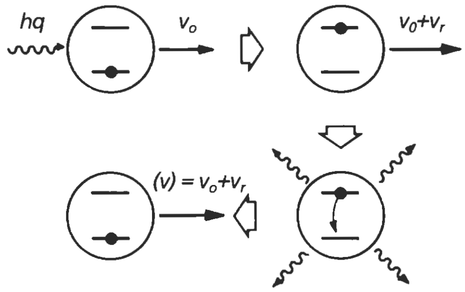
The laser physics program at ASTRID aims at utilizing the unique possibilities offered by storage of accelerated, fast ions. A laser is an ideal tool when working with stored ions, as the interaction between light and matter is sufficiently gentle not to destroy the storage, in contrast to violent atomic collisions.

The elements of the planned research program with heavy ions at ASTRID focuses on the following topics:

- laser cooling of fast particles
- high resolution rf-laser double resonance spectroscopy
- fundamental tests of special relativity
- collective phenomena in cold plasmas

Laser cooling of fast, stored ions will be a major topic for the first experimental heavy ion session with ASTRID planned for the spring of 1990.

In high resolution laser spectroscopy and in many areas of fundamental physics, a well characterized phase-space is an important parameter. The technological limit on beam temperature is determined by the temperature of the plasma of the ion source. In order to achieve lower temperatures, cooling must be employed. One cooling scheme is based on laser interactions with the beam.



Sketch showing absorption and isotropic emission of a photon, resulting in momentum transfer in the direction of the incoming photon.

Momentum is transferred from a running light field to the particle upon absorption of a photon. The momentum is later redistributed randomly by spontaneous emission processes. Repeated scattering processes transfer momentum to the the ions as a function of their velocity with acceleration rates as high as 100 keV/s close to a resonance between the laser field and the transition frequency of the ion or atom. In this way, the laser acts as a snowplow traversing the velocity profile of the particles, leaving them with a narrower profile at a slightly higher velocity.

By using a standing laser field, even higher cooling rates can be achieved. The resulting force, called the dipole force, does not saturate and can be 100 times as strong as the scattering force.

Both methods have been observed in the laboratory, and the experiments will be continued on ASTRID.

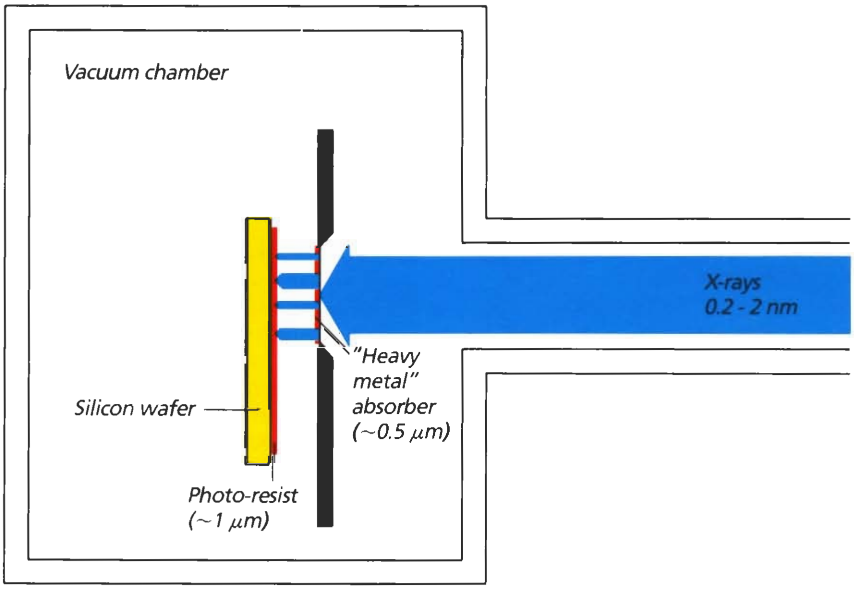
Materials Technology

X-Ray Lithography

For industry, synchrotron radiation is a very important tool in research and development. One very promising application is in the production of microelectronics. Up till now, most production facilities use ultraviolet light to transfer the pattern from the mask to the silicon wafer. This limits the minimum dimension of chip features to a few micrometer. For smaller dimensions, the shadow pattern will be blurred by diffraction of the light. Soft X-rays, with their shorter wavelengths, strongly reduce the influence of diffraction. By using strong synchrotron radiation sources for chip production, dimensions down to 0.2 micrometer have been obtained with very short production times.

Detector development

The accelerated particle beam in ASTRID may be extracted over a period of time. The high-energy electron or ion beams thus available are useful for a number of purposes. An important use is testing new detecting systems in the fields of high-energy physics and astrophysics.

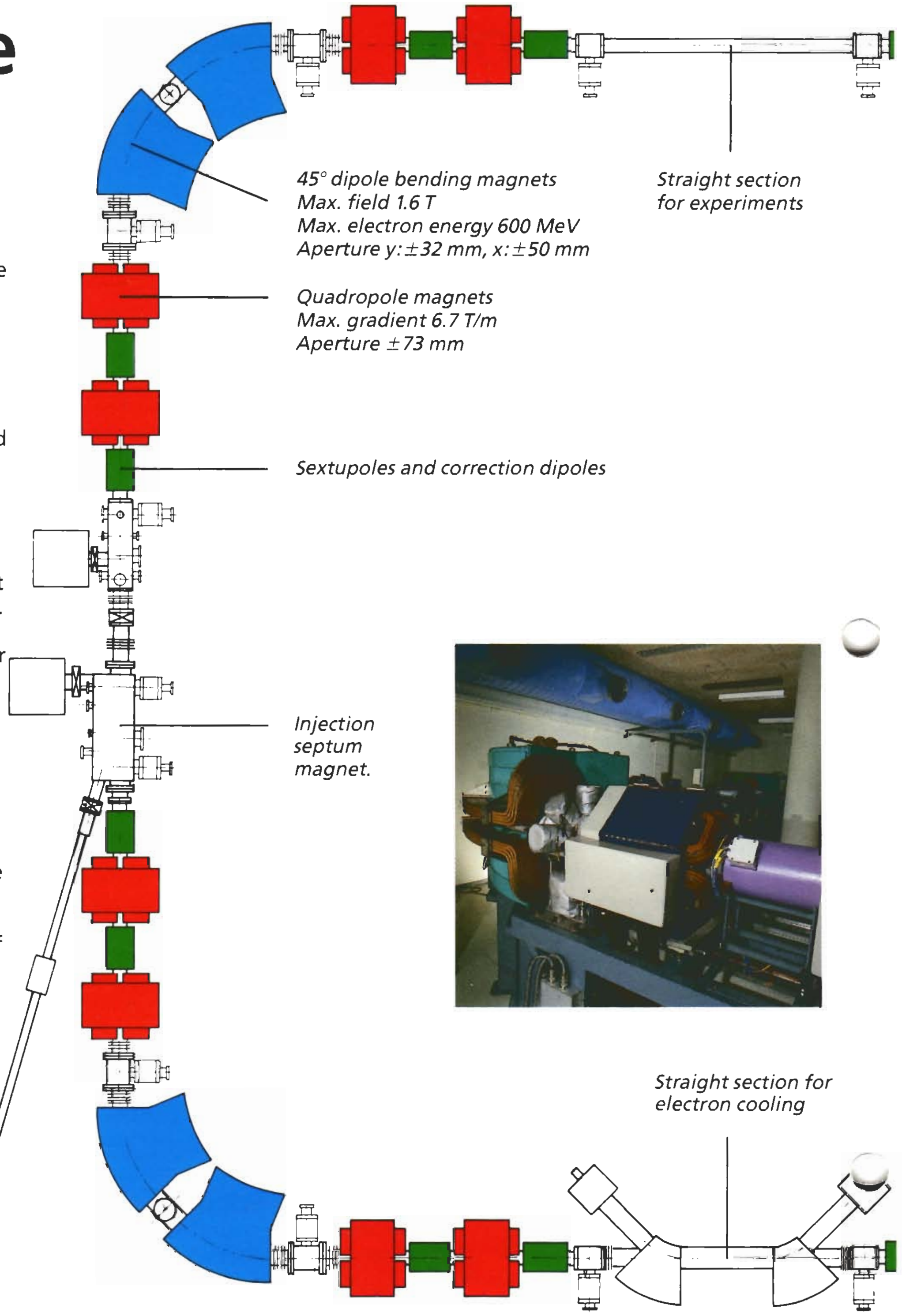


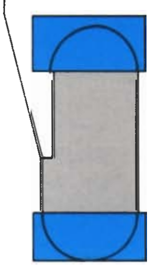
The storage ring

ASTRID is a storage ring for electrons and ions. The 'ring' consists of a system of vacuum chambers forming a square with four 8 m long straight sections connected by four 90° bends, all pumped down to the lowest possible pressure. The ultra-high vacuum is necessary to avoid collisions with atoms in the rest-gas, thereby obtaining a long lifetime of the stored beam. The beam is kept on a closed orbit by a system of bending and focusing magnets. In the focusing quadropole magnets, the field is non-uniform and acts as a lens, confining the stored particles to a tight beam when travelling around the ring. The field of the bending dipole magnets is uniform and perpendicular to the plane of the orbit, and causes the particles to be bent around the corners on a circular path. Hence the closed orbit consists of a series of straight and circular segments.

In one of the straight sections, the particles run through an RF-cavity, where the beam can be accelerated. During this process, the strength of the magnets must be increased in proportion to the beam energy. The acceleration also causes a bunching of the circulating beam.

The ions are preaccelerated in an isotope separator, whereas the electrons are produced and accelerated in a microtron before being injected into the ring. The injection is done by means of two special magnets, a septum and a kicker, which bend incoming particles into the closed orbit. A large circulating current can be reached by accumulation of many pulses from one of the injectors.





Heavy Ion Injector

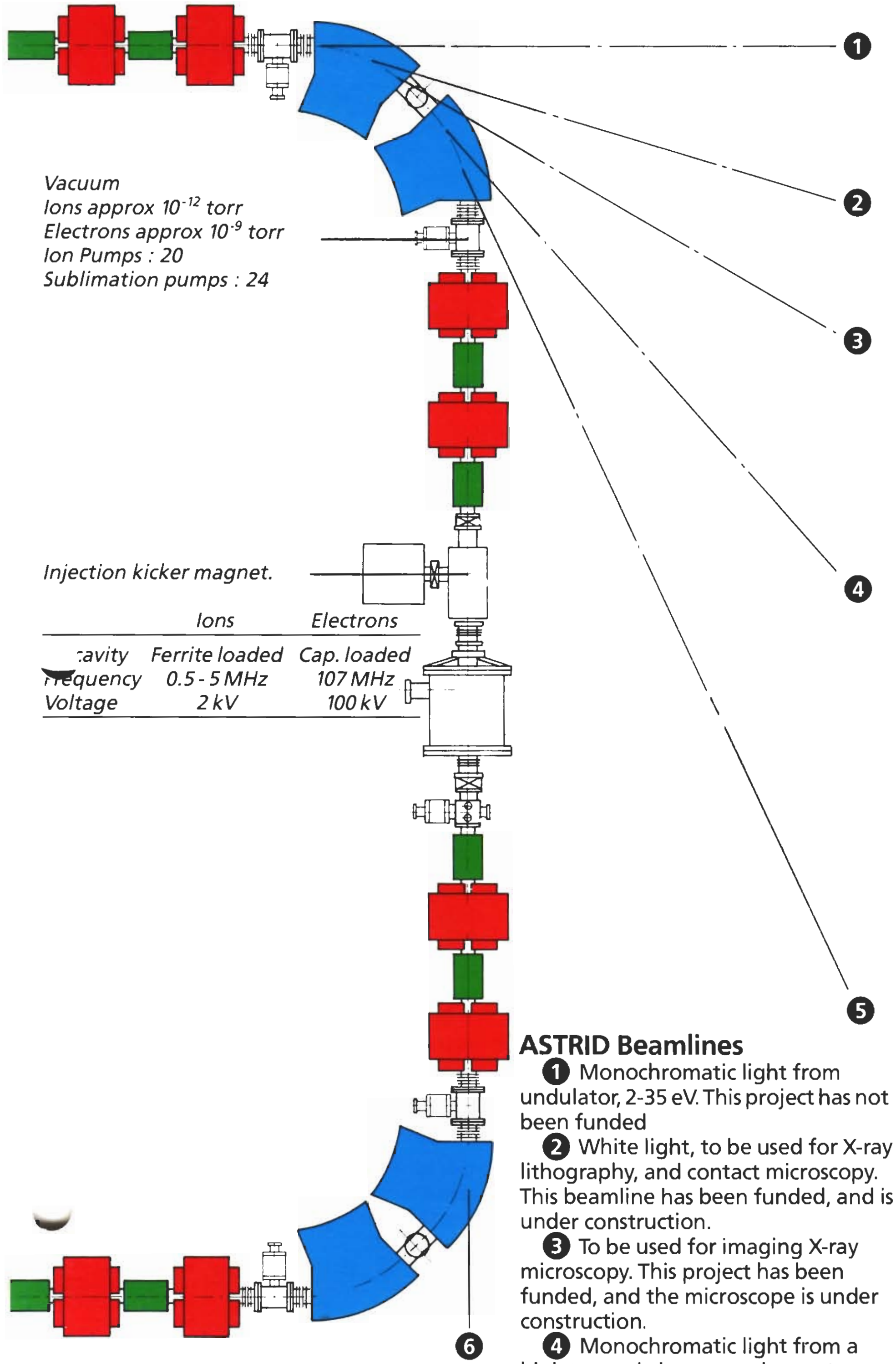
The ion injector is an isotope separator constructed by the Institute of Physics. Ions produced in the universal ion-source are accelerated by an electrostatic potential before they enter the storage ring via the injection beam line.

Electron Injector

The electron injector for ASTRID will be a race-track Microtron (RTM). This type of injector is compact and economical as compared to a linear accelerator, and it has proven its ability as an injector at several locations. The RTM constructed here was originally developed by M.Eriksson and his group at MAX-lab in Lund for use with the MAX storage ring.

The electron beam is produced by an electron gun and preaccelerated before it enters the acceleration cavities via a bending magnet system. After the first transit, the beam is reflected back through the cavities by the 180° dipole, and then the 'race' begins. A total of 19 passes of the cavities are planned, giving a final energy of about 100 MeV. After the 19th track, the beam is deflected 14° away from the RTM by a small septum magnet.

RTM parameters	
Injection energy	*70 keV*
Resonant energy gain	*5.3 MeV*
Number of turns	*19*
Final electron energy	*100 MeV*
Energy spread	*100 keV*
Pulse current	*10 - 20 mA*
Pulse length	*1 μs*
Repetition frequency	*10 Hz*
Emittance	*0.1 mm mrad*
RF frequency	*2998.6 MHz*
Dipole field	*1.15 T*



Electron cooling

Electron cooling has been prepared for the ion operation. The principle in electron cooling is to let a very cold, ie. low energy spread, electron beam merge with the heavy ion beam on a small part of the ring. The energy of the electron beam is such, that the mean velocity of the two beams is equal. Scattering processes will tend to make the temperature of the two beams equal, which will result in a lower temperature of the heavy ion beam.

An electron cooling system has been set up for single-pass measurements on the tandem accelerator in Aarhus. This system can be moved to the storage ring when needed.

ASTRID Beamlines

❶ Monochromatic light from undulator, 2-35 eV. This project has not been funded

❷ White light, to be used for X-ray lithography, and contact microscopy. This beamline has been funded, and is under construction.

❸ To be used for imaging X-ray microscopy. This project has been funded, and the microscope is under construction.

❹ Monochromatic light from a high transmission monochromator, eg. a TGM. This beamline has not yet been funded.

❺ Beamline with a large range monochromator (SX-700, 6-1000 eV). This beamline has been funded, and the SX-700 is now operational on a beamline at BESSY.

❻ Beamline with a superconducting wiggler (8T), and crystal monochromator (1-10 keV). This beamline has not yet been funded.

When the microtron is not used as injector to the ring, it may be used for separate projects such as:

- Free electron laser.
- Positron production.
- Isotope production for medical use.
- A strong source of gamma radiation.

A brief history of ISA:

1984:
As a result of Danish participation in the research at CERN in Geneva, it is decided to build a small (4x4 m) storage ring for ions at the Institute of Physics in Aarhus. During the design phase it is decided, that by increasing the size to 8x8 m and adding the necessary beam optical elements, it would also be possible to store electrons, which would give Denmark its first synchrotron radiation source. A group of physicists from Aarhus, Copenhagen, Odense and Risø formulates the scientific case for the project. Danish industry expresses interest and support.

1985:
The project is partially funded. Construction starts with help from colleagues at CERN (Geneva), MAX (Lund) and BESSY (Berlin).

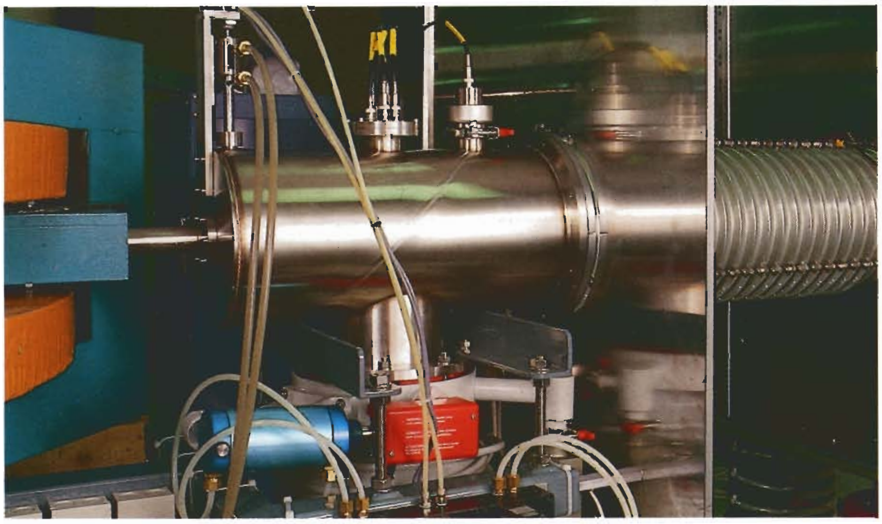
1986:
The Danish government proposes to establish instrument centers around large facilities in order to make these installations available and strengthen collaboration between public and private research institutions.

1987:
The Faculty of Science in Aarhus proposes to form an institute for synchrotron radiation. In order to increase the stored currents to 1-200 mA, a new 100 MeV electron injector is planned. Six beamlines are planned in the first stage, and the possibility of inserting an undulator and wiggler is included in the planning. The center should thus be able to deliver Synchrotron radiation in the energy range from a few eV to about 5 keV. The center will be responsible for the ring in both modes, i.e. with heavy ions and electrons.

1988:
The new electron injector, injection system, three beamlines and a monochromator (SX-700) is funded by SNF (The National Scientific Research Council) and the Program for Technological Development.

1989:
Completion of the ring for heavy ion operation was obtained by the end of the year.

Organization



ISA is organized as a separate entity within the Faculty of Science. It has a staff of scientists, engineers and technicians which will maintain and run the ring with associated beamlines, and perform research and development. A director is responsible for scientific and administrative matters. User committees will be formed, and regular user meetings will be held with the purpose of using the existing resources, and proposing new ones.

Invitation

Anyone with an interest in the facility, or with proposals for new activities is invited to take part in an existing programs, or to form a new user group. The ISA staff will advise users in setting up and running experiments.

Funding sources:

- Byggedirektoratet
- SNF's apparaturfornyelsespulje
- SNF
- Ib Henriksens Fond
- Carlsberg Fondet
- Tuborg Fondet
- Thomas B. Thriges Fond
- Det Teknologiske Udviklingspro-gram
- Dfl annuum
- Aarhus Universitets Forskningsfond

Financial

Total investment in ISA (mill. Dkr.)

Buildings	11.0
The storage ring	14.2
70 man years (sept 89)	21.0
100 MeV microtron	5.0
Injection 3 Beamlines (1,4,5) Monochromators	16.7
Remaining 25 man years	8.0
Total	74.7

Not yet funded

3 Beamlines (2,3,6) Ondulator Wiggler	17,3

During the planning and construction of ASTRID, extensive assistance and advice has been received from various institutions and individuals. This help is gratefully acknowledged. A short list of some of the institutions which have contributed to the design of ASTRID is listed below:

- CERN, Geneva
- BESSY, Berlin
- MAX-laboratory, Lund
- KTH, Stockholm
- DESY, Hamburg

Further reading

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Møller, S.P.:
ASTRID, a Storage Ring for Ions and Electrons. Proc. Eur. Particle Conf., Rome 1988, World Scientific Publishing Company, p.112.

Møller, S.P.:
A Micropole Undulator for ASTRID, internal report.

Aarhus Storage Ring Specifications, internal report. ASTRID/RS/SPEC 86-7.

Interest in ASTRID should be expressed to

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