Executive Summary:

The LabSync project is a design study project targeted at the development of laboratories that contain powerful light sources covering a broad range of frequencies. At the start of the project in 2008, there were essentially two routes for such compact radiation sources. The first route was based on the interaction between matter and electrons (as in the Mirrorcle) while the second route was based on the irradiation between light and matter (as in the Lyncean). Since laboratory users are usually more familiar with the“ standard way to generate x-rays using the bombardment of targets with electrons, the project consortium was build on a partnership with the Mirrorcle teams from Japan, including Ritsumeikan University as well as Photon Production Laboratories. The other partners included KULeuven (Belgium), Bestec (Germany), University of Ferrara (Italy), SPECS (Germany) as well as CNRS-Grenoble (France).

During the first two periods of the project, the Mirrorcle system was the main focus of the project. One of the main advantages of this system is that through the insertion of different targets into the electron trajectory course, radiation of different wavelengths can be created. This spectrum covers the soft x-ray regime via transition radiation as well as the hard x-ray regime via bremsstrahlung and thus enables a system configuration whereby both beams can be generated simultaneously. By designing the beam optics appropriately it is then even possible to bring these different sources of radiation simultaneously onto the same sample spot. An additional degree of freedom is the energy of the electrons used and Mirrorcle systems with energies of 1 MeV, 4 MeV, 6 MeV as well as 20 MeV are available. With these systems, the consortium explored the following areas: i) medical x-ray imaging including phase contrast and parametric radiation, ii) radiation therapy applications and iii) materials and in-situ thin film characterization studies.

While the Japanese partners focused on improvements to the Mirrocle products, the other partners concentrated on evaluation and characterization of the different beams (Far-Infra-Red, Soft x-rays, Hard X-rays) generated mostly by the 6 MeV and 20 MeV systems. This information was then used to make the first designs for beam-lines as well as end-user stations. Also the background radiation escaping from the different systems was measured in order to evaluate the necessary radiation protection measures. Finally a first design for a complete compact synchrotron laboratory system based on the Mirrorcle was proposed.

For the third period the focus shifted away from the Mirrorcle to other smaller light sources. As the hard x-ray source, the potential of liquid metal jet sources was explored through simulations and experiments performed at the Bruker facilities on a source manufactured by Excillum. For mammography applications it was concluded that liquid metal jet sources with K-edge filtering could achieve a higher physical image quality than conventional sources. In addition a study was made that showed that such sources can be used for x-ray experiments in a high magnetic field of 30 T whether pulsed on in continuous mode. As an alternative to the 6-20 MeV radiation therapy, the potential of nanoparticle enhanced electron emission to create double strand breaks in DNA was explored. This method then delivers already a significant dose of LET electrons when low energy x-ray sources are used (20 - 100 keV).

As a soft x-ray (EUV) source, a laser plasma source with high repetition rate was developed and tested. This activity also included the development of debris filters as well as a monochromator beamline. This design was then used to complete the multi-diagnostic chamber. This chamber layout finally contains the following elements: i) XPS using different x-ray sources (Al K or Cr K) as well as a wide angle lens (60 deg) necessary for depth profiling , ii) UPS using traditional and EUV sources, iii) SEM and SAM and iv) in-situ SPM with parallel STM and nc-AFM capabilities.

Project Context and Objectives:

To understand the fundamental processes in life sciences European scientists are requesting access to more and more performing tools. In particular, there is a demand for high-quality light sources operating in the infrared, soft X-ray and hard X-ray wavelengths. To this end, Europe has invested a great deal of effort into state-of-the-art synchrotron and free electron laser facilities. These large-scale facilities have already had a significant impact on scientific output. However, one big drawback of these facilities is that beam-lines are run under a user facility programme with high turnover rates. As such, non-standard experiments are difficult – if not impossible - to execute.

Such user facilities cannot be coupled to the large existing systems that exist locally such as those related to hospitals (radiation therapy), pharmacological factories (drug design) and urgent analyses (quality checks). As such, there is a pressing need to bridge the gap between the traditional laboratory sources and the large-scale user facilities. For some time, scientists have been looking for compact light sources able to generate tuneable light of a high enough "quality" to perform a number of important experiments on a local laboratory scale.

The Mirrorcle prototype could fill the gap between large-scale equipment and existing laboratory source and is also tuneable within a wide range of frequencies. The prototype has been in existence for about 10 years and the project foresees Japanese and European researchers worker together to design additional features and improve the functionality of Mirrorcle. Although the matter – electron beam mechanisms that underlie the Mirrorcle are well known, the peculiarities related to the use of nanoscale-sized, very thin targets and large beam divergences pose significant challenges and opportunities. In fact, several prototype beam-lines and end-user stations will be designed by European partners with the aim of obtaining state-of-the-art infrared, soft X-rays and hard X-rays experimental set-ups that can be used in a variety of fundamental, applied and medical sciences. These design activities are also relevant for other x-ray emission schemes with large divergences such as those based on the laser beam – electron beam interactions.

LABSYNC will develop a plan for how to improve the overall functionality of the existing Mirrorcle technology, including technical specifications of the beam-lines and estimated costs. When the design study produces positive results good accelerator performance, good optics and large X-ray brilliance the design may be implemented during a follow-up project. The different Mirrorcle systems with their wavelength range are illustrated below.

The project objectives were the following (summarized) for the first two periods.

Objective 1: Characterization of the Mirrorcle devices

As a starting point the compact accelerator and the storage ring will be fully characterized.

Objective 2: Infra-red characterization and optimization of the mirror systems

The 20 MeV relativistic electrons in the storage ring emit synchrotron radiation (SR) in the infrared region. This SR will be measured and the output will be optimized.

Objective 3: Characterization of soft x-ray source, optimization of thin foil targets and full output characterization

Soft x-ray photons are generated through the interaction of electron beams with a stack of very thin foils. This so-called "transition radiation" will be characterized and different stacks of foils will be tested and optimized.

Objective 4: Characterization of the white beam hard x-ray source, optimization of wire targets and full output characterization

Hard x-rays are generated when thin wire targets (25 micron size) are put in the electron trajectories. The spectral features are similar to those of an X-ray lab source, consisting of Bremsstrahlung. The wire targets will be optimized to obtain the largest number of photons.

Objective 5: Characterization of hard monochromatic x-ray source, optimization of parametric x-ray crystals and full output characterization

Parametric x-rays are monochromatic x-rays produced by the diffraction planes of a single crystal target. The targets will be optimized to cover a wide energy range of monochromatic radiation.

Objective 6: Design of a FIR beamline with FT spectroscopy

The design of a FT-FIR system, operational in an as "wide-as-possible" frequency range is the goal in this objective. We will try to optimize the FIR collection in the storage ring, and the transport of the FIR radiation to the experimental environment.

Objective 7: Design of XPS based on the soft x-ray source

We will design a beam line for X-ray Photoemission Spectroscopy. By changing the energy of the penetrating X-rays, different depth of the sample can be analysed. This is important for in-situ real-time experiments that monitor the growth of nanomaterials.

Objective 8: Design of hard x-ray monochromatic beam line

We will design a hard X-ray monochromatic beam line for diffraction and spectroscopic experiments (X-ray absorption and fluorescence). To that end, x-ray tracing simulations of the optical elements paying special attention to the type of double bounce monochromator (water cooled or not), to the focusing mirrors, to high order harmonics rejection, slits to define the beam, etc will be carried out. A second station will be designed and located downstream of the X-ray diffraction beam line for studies of irradiation therapy with the monochromatic beam.

Objective 9: Design of beam line for medical imaging

The goal of this objective is to select an appropriate x-ray beam, spectrum and geometry for 2 high end clinical applications, to calculate the associated patient doses and its maximal exposure settings, and to design the detector modalities for radiological imaging.

Objective 10: Design of integration of FIR / Soft x-ray / Hard x-ray beam lines focussed on one plane in space/time

The compactness of Mirrorcle allow in principle to have these three different experimental techniques acting together in the study of the growth process of functional (or functionalized) surfaces and nanomaterials. A basic layout of such a beam line will be provided.

Objective 11: Installation of an active feed back system towards the potential user community

One of the most important goals of this proposal is to inform the scientific community about the potential of the new technology.

Although good progress and results were obtained in the first two periods of the project, the consortium decided that the Mirrorcle technology is not yet up to the specific requirements of the other partners. Therefore in Period 3, the consortium was changed and the objectives shifted towards other sources. The objectives changed accordingly.

B2. Project Objectives Period 3.

Objective 1: Explore low energy x-ray photon therapy using photo-emission and nanoparticles

We will develop a novel low energy x-ray irradiation therapy approach based on the use of core-shell nanoparticles. The high Z nanoparticles emit efficiently photo-electrons and Auger electrons when irradiated with low x-ray energy beam (E < 100 keV) leading to high LET effects. These effects will be simulated, the nanoparticles will be synthesized and the therapeutic effects will be evaluated.

Objective 2: Study of the implementation of a liquid-metal-jet anode x-ray tube on an extreme

conditions environment: high magnetic fields

We will study and design beamlines that make use of this source under the very restrictive conditions of high magnetic fields (both static and pulsed). We will make use of the continuous radiation to produce a tunable (photon energy) X-ray source enabling diffraction/absorption studies at specific energies.

Objective 3: Characterization of a liquid-metal-jet anode x-ray tube

To study the x-ray properties of a novel source based on a liquid-metal-jet anode by means of Monte Carlo simulation and experimental measurements.

Objective 4: Design of an EUV source with EUV monochromator beamline

This objective is is dedicated to the design of a EUV source emitting photons in the soft X-ray range together with a corresponding Monochromator Beamline focusing the monochromatized photon beam to the interaction center of a multidiagnosis endstation for sample characterization.

Objective 5: Design of a system concept for a multi-diagnostic endstation

This objective is dedicated to design a multidiagnosis endstation for sample characterization with Soft-X-rays integrating two alternative X-ray sources, a liquid metal jet source and an EUV source.

Project Results:

C1. Period 1

KULeuven (summary)

KULeuven has contributed to the characterization of the Mirrorcle; with experiments in the Far-InfraRed, medical images as well as the radiation dose measurements. A concept for a complete laboratory design based on the Mirrorcle has been worked out together with a research program.

During the visits in Japan, three type of measurements were performed related to the use of the far-infrared radiation and the hard x-ray. In the latter case, also the background radiation around two Mirrorcle systems was measured in order to determine the specifications for the radiation protection (such as the thickness of the required concrete walls).

With the Mirrorcle 6X, many samples were characterized with the far-infrared radiation during the first year. A comparison of the spectral flux between a blackbody radiator and the Mirrorcle 6X is given in the Figure below. Clearly at 15 cm-1, the flux of he Mirrorcle 6X is more than 250 larger than that of a blackbody and illustrates the capabilities of this system in the FIR range.

Radiation measurements were performed at two installations, namely the Mirrorcle 6X at the Ritsumeikan campus and on the Mirrorcle 20X at the Kusatsu installation. Doses and dose rates around the installation, both inside and outside the shielding bunker have been determined by means of TLD�s (thermo luminescence dosimeters), compensated GM (Geiger-Muller) detectors and ionization chambers. In addition the measured values were compared against numerical calculations of dose distributions. From the measurements of the emitted radiation (photons and neutrons) from the two installations it was possible to propose several design changes to the Mirrorcle shielding systems, in collaboration with the Ritsumeikan and Photon Production Laboratories.

In the current installation of the Mirrorcle 6X the whole system is enclosed into one radiation protection bunker. That includes the klystron, the microtron as well as the synchrotron source. In a first modification, it was suggested to separate the different elements in a better way so that there is not interference from the radiation emitted by the microtron to the measurements systems around the synchrotron. Since the Mirrorcle emits high-energy background radiation, a second configuration was proposed that limits further the amount of radiation that might interfere with the measurement equipment. In this proposed laboratory design, there is also a concrete wall around parts of the beamline as indicated in the adjacent Figure. In this Figure, the EXAFS beamline and the monochromated beamline include a reflection / diffraction element that is completely enclosed by concrete. In addition, the chance of radiation cross-contamination between the different beamlines can be reduced significantly using this design.

CNRS (summary)

CNRS has contributed to the characterization of the Mirrorcle with experiments in the hard x-ray regime, including Laue Diffraction, EXAFS and a detailed flux comparison between the Mirrorcle CV6, the Mirrorcle 20 SX models and a Cu x-ray tube. In addition, CNRS also followed the progress of other compact sources (such as Lyncean).

Hard X-ray metrology was carried out during our first visit to RITS in February 2008. There we managed to perform white beam Laue diffraction experiments on a SiO2 single crystal and EXAFS on a Mo thin foil. The first experiment was carried on the M-6X instrument and the latter one at the M-20SX. Figures of the results of these two experiments are shown below.

The conclusion of these experiments is that the X-rays issued from the Mirrorcle source are of the greatest quality in terms of resolution (certainly due to the smallness of the target used to generate X-rays) but the flux was low. The reason for that still remains a mystery. The flux and brilliance figures supplied by Yamada, and still appearing in the Mirrorcle web site, are not correct by orders of magnitude. It became quite clear that some kind of metrology has to be properly carried out mainly to understand why Mirrorcle performances are not as expected and thus how to improve them in view of applications. These tests are lengthy and required specific instrumentation that was not foreseen in the first place, neither by Yamada nor by the LabSync project. Since then, and suggested by us, Yamada and his team have made a substantial effort in measuring the flux and performance of the three Mirrorcle generators and compare these results with those of analogous experiments on X-ray tubes. As a matter of fact X-ray emission depends on the target, Cu, Be, Mo, etc, and the flux dependence as a function of the target type have been carried out as well. In our December 2008 visit we noticed that a lot of progress has been done between the last and this time and a good amount of information had been already collected. The important feature is that experiments in both Mirrorcles and X-ray tubes were carried out with the same monochromators and detectors and thus the final figures have a meaning in the relative values. As of today, and with the warning message that we wrote at the beginning, the flux of Mirrorcle can be considered of the same order of magnitude as a 1KW tube.

RITS and PPL have proposed ways to easy increase the flux by for instance, increasing the injection duty cycle from 400Hz to 40kHz, thus with an expected gain of a factor of 100. Clearly we have seen a very positive evolution since 2008 in the way of facing the real problems and advancing towards their solution. More tests are going to be carried out in order to improve the photon emission in the X-ray range and thus increase the flux up to the predictions.

BESTEC (summary)

BESTEC has developed the first design elements for a soft x-ray beam-line. A setup for the characterization of the soft x-rays has been assembled. The system is dedicated to the characterization of the Mirrorcle x-ray source but can also be used to measure the radiation from a laser plasma source. The system was installed and first results have been obtained.

The soft X-ray radiation tested here is that emitted from a laser plasma source. The soft x-rays are emitted from a gold plasma. The plasma is generated by an intense laser pulse (532 nm, ~10 ns pulse width, 20 Hz repetition rate, up to 500 mJ/pulse), which is focused (~15µm) onto a gold target. As a result also the soft X-ray radiation is pulsed with a pulse length in the ns range and the same repetition rate of 20 Hz. The soft X-ray radiation is emitted into a 4? solid angle and is supposed to have an intensity maximum around 100 eV. The soft X-ray source in this setup is imaged by a toroidal mirror 1:1 onto an in-UHV CCD camera. The tangential and sagittal radii of the mirror determine the deviation angle to 3.5° and the length of the entrance and exit arm of the imaging detector to 780 mm, each. The dimensions of the toroidal mirror and an additional aperture in front of the mirror limit the acceptance angle of the imaging detector to 2.5 mrad x 7.5 mrad.

The above figure shows the image of a single shot soft x-rays on the in-UHV CCD chip. The pixel size is 13 micron x 14 micron. Several filters were used in the imaging detector in order to attenuate the emitted light, which would otherwise saturate the CCD chip. From the filter properties and additional tests with a transmission grating we conclude, that the wavelength of the filtered radiation detected on the CCD chip is of the order of several hundred eV. From the obtained camera images, the source size, the relative position and intensity of the emitted soft x-rays were measured as a function of the laser pulse energy. The measurement of the source size and intensity could be optimized by varying the position of the focusing lens in the path of the laser focusing optics.

Since the laser plasma source emits in a 4? solid angle the optical elements for focussing and monochromatizing the radiation should have a rather large acceptance angle. The adjacent figure shows the flux of the monochromatized radiation at the focal point of an experimental station behind a soft X-ray monochromator beamline dedicated to this plasma source. The laser power was set to only 10% of the maximum value. The maximum intensity is found as expected around 100 eV.

SPECS (summary)

SPECS has developed the first elements for the multi-diagnostic end-user station that should combine the different types of radiation. Specifically a wide-angle lens - adapted to a diverging x-ray source -- for the SPECS PHOIBOS hemispherical electrostatic energy analyzer has been assembled and tested.

SPECS has started the activities on one essential part of the endstation being mostly independent of the actual source characteristics: the wide angle lens (WAL) of the electron spectrometer. The work done in the first twelve months has been focused on making experiments using an existing prototype of the lens mounted to a SPECS PHOIBOS 150 electron analyzer (giving the PHOIBOS 150 WAL) on one hand and electron optical simulations and ray tracing of the electron paths on the other. The aim has been to define the existing technical limits so far and to evaluate how to exceed the limits.

The SPECS PHOIBOS hemispherical electrostatic energy analyzer allows recording of energy spectra for negative particles (electrons) and positive particles (ions) in the kinetic energy range from 0 eV to 3.5 keV. The wide angle lens is mainly developed to record angular resolved and angle dependent X-ray excited photoelectron spectra within an acceptance angle range of +/- 30° in parallel. It can be used to perform non-destructive surface depth profiling. A picture of this system is shown in the adjacent figure.

The analyzer can be equipped with a flange mounted detector assembly. The 2D detector system (CCD or Delay-Line detector) uses both the energy and angular resolution for Angle Dependent XPS measurements without tilting the sample. The CCD system features a 12 bit digital CCD camera with a dynamic range of 1000. The detector design is especially optimized for the detection of low kinetic energy electrons.

The PHOIBOS spectrometer consists of an ultrahigh vacuum (UHV) housing and four major internal components, which are shown in Figures 2 and 3. The UHV environment is necessary to avoid collisions of the electrons to be detected with the gas molecules changing their energy and momentum.

The internal components are:

- The input lens system for receiving charged particles;
- 180° hemispherical analyzer (HSA) with 150 mm nominal radius for performing spectroscopic energy measurements;
- detector assembly for particle detection;
- Slit Orbit mechanism with an external rotary feedthrough.

Angle-Dependent XPS (ADXPS) is a powerful tool for performing non-destructive surface depth profiles in the top few monolayers. This has been demonstrated by the new PHOIBOS 150 WAL analyzer on a TaN/TaON film performing ADXPS measurements with a total acceptance angle of 60°. Parallel collection of the channels by angle is shown in the adjacent figure. The CCD image reveals the Ta 4f spin orbit splitting, showing the TaON and TaN component for an angle range of 20° - 80°. The TaN component is only visible for smaller take off angles.

UNIFE (summary)

The University of Ferrara has contributed to the characterization of the Mirrorcle with experiments in the hard x-ray regime, specifically with medical images. In addition, they have simulated the Mirrorcle bremsstrahlung from tiny targets as well as Parametric X-ray Radiation both in the diagnostic radiology context.

A thorough evaluation of a new system cannot only consist in a series of accurate experiments aiming at the measurement of pertinent physical parameters. It is of paramount importance to deeply understand the underlying mechanism of the various physical phenomena involved in system functioning. Monte Carlo (MC) simulations are widespread and reliable methods to achieve a detailed knowledge of the system to be evaluated and are also very useful when the experimental approach is unfeasible.

An accurate study of hard x-rays emitted from thin targets, irradiated by electron beams circulating in the MIRRORCLE storage ring was performed and published in the Medical Physics journal. This work, aimed at optimizing some of the parameters that are critical for the design of medical applications based on the MIRRORCLE light source. The goal was to evaluate the dependence of photon fluence and beam monochromaticity on electron-beam energy, target material and thickness. The transport of 6 and 20 MeV electrons in a thin molybdenum, rhodium and tungsten wire target was studied by means of Monte Carlo simulations using the MCNPX code. Configurations of the x-ray output port, different from the default forward-directed emission of the beam, were also investigated. A comparison with reference spectra for general diagnostic radiology and mammography was carried out. It was shown that the emitted x-ray beams can be far more intense than those generated by conventional x-ray tubes for radiography applications as shown in the figure below comparing spectra from W in the Mirrorcle 20 with those of conventional W anode at 100 kV. The profiles of the calculated polychromatic spectra resemble those generated by conventional x-ray tubes, with x-ray energies up to the energy of the incident electron beam. It is also worth noting that an appreciable improvement in the monochromaticity of the beams can be obtained by viewing the x-ray emission from an output port antiparallel to the direction of the incident electron beam. The optimum target thickness for tungsten target spectra is practically constrained by a trade-off between bremsstrahlung efficiency and focal-spot size requirements. A larger margin for optimization of target thickness is probably available for mammographic spectra. The constraint of a backward directed (or, to a lesser extent, orthogonal) output port is to be considered mandatory for minimizing the high-energy tail of the spectral distribution and keeping the radiation dose to a reasonable level. It is also fundamental to evaluate the impact of the high-energy tail of the emitted spectra in x-ray imaging applications, since the energy range involved is significantly beyond the diagnostic range.

To evaluate the potential of the MIRRORCLE system for medical imaging applications, a set of measurements were performed at the Photon Production Laboratory (Japan) during the first week of July 2009. We took there our own x-ray imager (to compare results with diagnostic x-ray tubes available in our laboratories) and various target materials, commonly used in diagnostic radiology, to be inserted within the MIRRORCLE system. X-ray images of known details were obtained for two configurations of the x-ray source, namely by using the standard output port, which corresponds to the forward direction of the x-ray beam, and an alternative output port at 30 degrees from the forward direction (see fig 1). As discussed in the MC simulation, by comparing the two configurations of the x-ray source we wanted to investigate the effects on the x-ray spectrum. The imaging study showed the potential of the MIRRORCLE machine as a powerful source of x-ray photons. Radiographs of test objects were recorded with exposure times of the order of seconds and, although the x-ray polychromatic spectrum is not currently optimized for diagnostic radiology, image contrast was compatible with values obtained in radiological tests. Moreover, the x-ray imaging experiment revealed an interesting effect of edge enhancement due to the wide x-ray spectrum used to obtain the radiographs.

Ritsumeikan and PPL (summary)

Ritsumeikan University has contributed to the characterization of three Mirrorcle machines (CV4, 6X and 20SX) with experiments in far infrared, the soft x-ray and the hard x-ray regime as well as the beam-dynamics. In addition they have participated in developing a novel design for future generations of Mirrorcle systems.

Photon Production Laboratory has designed developed many improvements to the Mirrorcle systems such as the new CV1, CV4 and CV10 system as well as the changes in configuration of the existing systems including the optimization of the diameter and the injection frequency.

Since 2008 January 1, we developed one more machine MIRRORCLE-CV4 as shown on the right side, in addition to the operating machines MIRRORCLE-20SX and MIRRORCLE-6X. The CV series is named to include machines with 8 cm orbital radius, while 20SX and 6X have 15 cm orbital radius.

We studied the characteristics of the above mentioned 3 machines and reached optimized machine designs. It was concluded that for producing brilliant hard X-ray, in the 1 to 4 MeV range, CV series is sufficient, and 20 MeV is not necessary. For producing brilliant EUV and soft X-ray, 20 MeV range machine is necessary. MIRRORCLE-6X is useful for brilliant far-infrared generation. This machine was named MIRRORCLE-6FIR.

Target fabrication methods have been greatly improved. Now, 10 ?m diameter sphere target is attached to a few ?m thickness yarn made of carbon nano tubes. Because of this improvement, an excellent resolution imaging was obtained. This technology is already established. Our effort will be extended to 1 ?m diameter target fabrication.

The X-ray intensities of both MIRRORCLE's and X-ray tube were measured by using the same monochromator and detector. The intensity was normalized with respect to the sourcedetector distance, the pixel size of IP, and the source size. We leaned that the X-ray density of MIRRORCLE is about same level as that of X-ray tube. We don't rely on the absolute value, but the relative value should be OK. CV4 is giving the highest brilliance, because we used very small target. Of course if we apply the same small target to 20SX we will get the same order brilliance. From these experiments we concluded that CV is more productive and economical.

Below is explained the reason why CV4 is more productive compared to 20SX although it is such low energy machine. The X-ray divergence is proportional to 1/?, thus CV4 X-ray density is 25 times lower. But, roughly speaking, 1) Since the orbital radius is 8 cm, while for 20SX it is 15cm, the stored beam current is twice larger when the injector beam current is the same. 2) The orbital radius is 8 cm, therefore the beam bunch size is almost twice smaller, and the electron- target collision yield is doubled. 3) The beam energy is lower, the total X-ray power lost by the target is 5 times lower, which yields 5 times longer lifetime. 4) Since both the beam momentum aperture and the dynamic aperture are larger, the lifetime of the scattered beam becomes twice longer. In total we gain 40 times due to the smaller orbital radius and beam energy, and lose 25 times due to the radiation spread. Another advantage is that since the necessary power to produce 4 MeV electron is 5 times lower than that for 20SX, we can increase the repetition rate 5 times. The net gain we expect is about ten times. We should be able to produce more X-ray, but since the quality of the present injector linac is poor, the beam injection efficiency is lower. We believe that after replacing the injector to microtron we will get ten times more X-ray flux than that of 20SX.

EUV absolute intensity and angular distribution were measured, and was found out that the beam divergence is extremely small. It is ±5 mrad horizontally and there is no divergence vertically. The radiation is more like laser as shown in the below Figure. The power is about 30 KW/mm^2/SR or 10^13 photons/s/mrad^2/mm^2/0.1% bw. We are preparing paper for submission.

The beam dynamics of MIRRORCLE-20SX and 6X was studied by using a thermograph or by scanning Si bolometer to measure the beam profile. We found that the beam size becomes mm size in 15 ms after the injection (see below). The radiation damping speed is extremely fast for this kind of beam energy and is mysterious. The beam lifetime is an order of minutes, which is extremely long for such small beam size.

CV series are the latest optimized design, which corresponds to 8 cm orbital radius and 35 cm square magnet yoke. Magnetic field is generated by permanent magnet. The hight of the yoke depends on the electron energy to be stored. The weight of the yoke is about 0.5 T, so that the entire system can be moved by a robot arm. The injection is nearly 100 %, the same as for other MIRORCLE. After successful commissioning of CV4, the standardized machines CV1, CV4, CV10 are now available from the Photon Production Laboratory Ltd. Machines can be selected according to the purpose of users. CV4 is the hard X-ray machine to be used for non-destructive testing of heavy constructions, such as cars, trains, airplanes, bridges, and power plants. CV1 will be useful for medical imaging, X-ray microscope, EXAFS, SAX, XRD and crystallography. CV10 will be for EUV and soft X-ray production, with use in EUV lithography and actinic mask defect inspection. CV10 can be also useful for generation of FIR and MIR, to be used for study of water-protein dynamics and for identification of chemical materials.

C2. Period 2

KULeuven (summary)

KULeuven has worked on the oxide thin film synthesis using molecular beam epitaxy which is the technique that will be combined with the multi-diagnostic beam line. KULeuven has also explored the developing a novel therapeutic approach whereby electron emission from Au nanoparticles is used, when these are irradiated with low energy photons (< 100 keV). In addition, electric field simulations of the Mirrorcle systems were performed to obtain a better understanding of the phenomena involved.

One of the main goals for KULeuven in LabSync is to explore advanced and novel in-situ diagnostic

methods on thin films samples. Therefore a significant part of the research activities includes the synthesis and characterization of such thin film samples in order to test them with the different systems developed in LabSync. The main thin film activities are related to the growth of oxides (Dy2O3 and V2O3) and metallic Dy3Ge5 alloy thin films.

The thin film research at KULeuven is related to the growth of systems relevant for several technological developments. This includes exploring novel gate oxides on semiconductors as well as novel gate metals on semiconductors. In both cases, the quality of the materials and in particular the interfaces are of crucial importance. Today we lack the appropriate experimental methods to map out the chemical, structural and physical phenomena that happen at the interface between these two materials, in particular with in-situ as well as realtime methods. The goal of LabSync in this respect is to design and to develop the instrumentation that will remedy this deficiency whereby the characterization methods and the growth methods are combined together into one system. The starting point for the thin films activities are the molecular beam epitaxy (MBE) systems available. These are ultrahigh vacuum (UHV) chambers with a base pressure better than 10-9 mbar and equipped with a number of effusion cells as well as electron beam evaporators. In order to make oxide films, an RF plasma source is added that is used to break up molecular oxygen into atomic species. The growth of the films on the substrate can be followed using in-situ reflection high-energy electron diffraction (RHEED). An image of such an MBE system that should be attached/combined with the end-user station is shown in the adjacent figure.

An additional activity of KULeuven is related to electric field simulations of the Mirrorcle systems. One of the goals is to understand quantitatively the values of the obtained x-ray flux and to evaluate designs where the flux could be improved. In these three dimensional simulations, it is possible to follow the trajectories of the injected electrons in the confining magnetic fields of the storage ring. In the Mirrorcle systems, the hard x-rays are then generated by the interaction of these electrons with targets that are put in their path. The simulations performed allowed to estimate how thick the targets may be before the electrons are lost.

CNRS (summary)

In this period, significant project efforts where concentrated on performing accurate flux measurements. This included the development and construction of a W-collimator and multipurpose electronics to control the positioning of the collimator. Also a more optimized detection system for measure the x-ray flux was developed. In addition, CNRS has studied and designed a compact dispersive XAS instrument, where the full absorption spectra (within a given energy band up to 1000

eV) can be simultaneously measured in a single shot, without moving any beamline component. The performances of the dispersive EXAFS beamline in terms of energy resolution and band width have been simulated. The flux calculations have been carried out with the help of Univ. Ferrara (WP6) scientists and the Monte Carlo code developed by them.

Within the framework of the LabSync consortium, a new type of monochromator was developed that can fit well within the specifications of a compact dispersive EXAFS beamline. In addition we have developed all the means necessary to determine the slope errors of monochromators and to link with the x-ray tracing software and to parameterize the design of a complete beamline.

In the first year report we concluded that a long tungsten (W) collimator should be the first optical element to be used in any beamline based on Mirrorcle generators. Indeed the full divergence of the X-ray beam, 1/, can not be used in any experiment other than imaging. In addition X-rays of very high energies, up to MeV, are shined by the generator which brings a considerable noise and a potentially dangerous background of radiation in key areas such as the monochromator and the sample. Therefore we have decided to reduce the print of the X-ray beam to that of the divergence that is ready encompassed by the monochromator bandwidth located down stream. The length of the tungsten collimator was calculated to have a transmittance of 0,18% for 1MeV photons. According to our calculations 10 cm of W are enough to stop the high energy photons or at least to reduce their pollution to a reasonable level of radiation. A collimator unit was studied and realized by the SERAS of Grenoble. Key specifications of the design are (i) compact, and (ii) modularity, and in addition it must support scanning features in order to study the spatial distribution of the emission of the X-ray source (the target emission inside the chamber). It is composed of two blocks of tungsten positioned on four axes made up of commercial translation/rotation stages borrowed to the CNRS for the final tests in Japan. A real scale drawing of the collimator with all the alignment rotations and translation is shown in the adjacent figure.

In the way to properly study Mirrorcle we realize that the detector system currently used at PPL, an image plate (IP), lacks of the dynamical range and flexibility that this type of studies demand. We built an inexpensive Si-diode detector, widely used to measure X-ray intensities, are not that expensive we decided to use Labsync funds. During this second year we have purchased two Si chips from Canberra and mounted in a housing that allow to properly work at PPL. This has been done in collaboration with M. Kocsis from the ESRF detector group. The thickness of the Si chips, 500 microns, makes them suitable to work in the energy window up to 30 KeV.

During this year, we studied and designed a compact dispersive XAS instrument, where the full absorption spectra (within a given energy band up to 1000 eV) can be simultaneously measured in a single shot, without moving any beamline component. In order to optimize the instrument we have decided to adequate its performances with respect to the energy resolution required in each part of the spectra: for the near edge features (or XANES) the resolution should be very good, of the order of 2 eV or better, whereas for the extended part of the spectra (or EXAFS) the experimental resolution should not better than 10 eV. This type of instruments already exists at 3rd generation synchrotron light sources such as the ESRF (beamline ID24), SOLEIL (beamline ODE), Diamond (beamline I20), etc. A very preliminary dispersive EXAFS experiment was carried by some of the components of the LABSYNC project. The results can be seen in http://www.photon-production.co.jp/en/application_e/XAFS_e.htm

The performances of the dispersive EXAFS beamline in terms of energy resolution and band width have been simulated. The flux calculations have been carried out with the help of Univ. Ferrara scientists and the Monte Carlo code developed by them. For the sake of compactness we have decided to fix the distance source-monochromator to 1m, and study several configurations of the distance monochromator-sample as well as different angle of scattering and types of monochromators. In the same spirit of compactness we will investigate the possibility to place the sample very close to the crystal.

For the design of this beam line, we voluntarily privileged a very compact geometry. This compactness is an essential element for the types of applications it is dedicated. To do this, we very strongly used pre-sizing work realized by the team. We have determined a "score" parameter to identify the best possible setting and optimum locations where positioning the various elements of the beam line. The location of the robotic structure is therefore naturally positioned in a prohibited area with a "score" of zero. The user samples will be also deposited in the forbidden area. We decided to operate in the Rowland circle. The focusing point of the beam line is therefore very near the monochromator, which minimizes the dimensions of the beam line and the cost. The distance between the bender and the 2D curved detector is reduced to less than one metre. This is shown in the detail drawing of the adjacent figure. Needless to say that the monochromator ensemble is not in the "air" and it is located inside a chamber that minimizes the scattering of unwanted photons at the sample position as well as the background at the detector.

BESTEC (summary)

A novel concept for a compact laboratory source and monochromator beamline for soft X-ray radiation with a continuously tunable photon energy range was developed. A laser plasma source in combination with a large-acceptance-angle monochromator beamline is proposed by BESTEC in order to meet the required specification.

Laser plasma sources emit soft X-ray radiation from thermal plasma, which is generated by the interaction of a focused, intense laser pulse with a target. The characteristics of the emitted radiation depend on the target material and the laser parameters. For the required photon energy range high Z materials e.g. Cu, Au, Sn are used. Laser pulses in the visible or NIR range with pulse lengths in the ns range and pulse energies of~200 mJ/pulse are necessary for this radiation characteristics. Due to their small source point (<50 µm at 100 eV and decreasing with increasing photon energy) laser plasma sources are the appropriate choice for spectroscopic applications.

Laser plasma sources using a copper target provide >1012 ph/pulse/sr @ 1%BW in the range up to 150 eV and >1011 ph/pulse/sr @ 1%BW in the range 250 - 600 eV (before the monochromator beamline). The flux delivered at the experiment depends linearly on the laser repetition rate (assuming constant laser pulse energy), the acceptance angle of the optical elements of the monochromator beamline, the energy resolution and the overall transmission of the beamline. A laser plasma source and monochromator beamline delivered recently to Carl Zeiss SMT provides >1010 ph/s @ 1% BW at the experiment using a Nd:YAG Laser with only 20 Hz repetition rate and collecting a solid angle of <0.005 sr.

At present a laser plasma source is developed for the Berlin Laboratory for innovative X-ray technologies (BLIX) at TU Berlin, which uses a laser with 100 Hz repetition rate, two beam exits for the soft X-ray radiation allowing for a solid angle of 0.08sr and 0.2 sr, each. The anticipated flux at the experiment is >2?1012 ph/s @ 1% BW and >8?1011 ph/s @ 1% BW for the two beam exits (assuming the same overall transmission of the monochromator beamline). These flux values are close but not yet within the required margins for the flux at the interaction center of the experiment.

A key parameter for a flux increase of the laser plasma source is the repetition rate of the laser. Appropriate laser systems with 500 Hz repetition rate maintaining sufficient pulse energy and a high focusability are under development on a commercial level and will be commercially available on request. With 500 Hz repetition rate and 0.2 sr acceptance angle a flux of 1?1013 ph/s @ 1% BW will be available at the experiment. Another important point is the increase of the solid angle accepted by the optical elements. This approach is based on a short distance between source and first optical element with a large acceptance area and an efficient debris filter system between the source and the first optical element.

Other important issues are operation cost and up-time as well as the position stability of the source point, which will be accounted for in the design phase of the source. Regarding detection schemes at the experiment we want to emphasize, that single event counting may become difficult due to the time structure of the soft X-ray radiation from the laser plasma source. Highly-sensitive integrating detectors will be of advantage.

SPECS (summary)

SPECS has developed a wide angle analyzer for XPS (the Phoibos 150) including electron trajectory simulations, the hardware design and realization, power supplies, detectors etc. This system has been integrated and tested together with a micro-focus 500 source in a compact analysis system. Significant resources were also spend on the design of a synchrotron end-station.

The previous report from the first period already showed the first development steps and first tests of the wide angle lens. Anyway the results were not completely convincing at that time with respect to the angle resolution, energy resolution and usable kinetic energy range of the analyzer. What has been left were the following topics:

- Optimizing lens mode
- Measurements with a new angular aperture

- Further development of data processing software
- Complete characterization of the transmission function
- More Measurements on real films
- Evaluation of usability of the wide angle lens for TOF
- Evaluation of usability of the wide angle lens for 15KV.

Except the last point all the others were closed during this year and the PHOIBOS 150 WAL analyzer is now a ready product that can be used plug and play. The angular acceptance and angular resolution of a hemispherical analyzer is usually tested during setup, where a slit array between the sample and the lens entrance is used to create a regular angular emission pattern. The slits of the array are oriented perpendicular to the entrance slit of the analyzer and create a line pattern on the detector. The width of the lines includes the contribution from the finite slit width and the finite width of the spot size amongst the angular resolution of the analyzer. Therefore, small spot excitation sources like a focussed electron source are used in such test measurements. The PHOIBOS 150 WAL allows angular dependent measurements in two different modes: snapshot mode and sweep mode. In snapshot mode all voltages are kept fixed and the width of the energy window on the detector is determined by the pass energy. In sweep mode the analyzer is swept over kinetic energy with a step width smaller than the energy window on the detector. In this mode the data can be taken either with full resolution of the camera, or with a predefined number of angular channels. The PHOIBOS 150 WAL is able to operate in a range of retarding ratio R = Ekin/Epass of at least 4 < R < 50 with the full angle acceptance range of ±30 degrees. A large available range in retarding ratio is of particular importance when using an X-ray source with fixed excitation energy, i.e. Al K?. An angular resolved sweep from 150 eV to 1500 eV with 3 eV pass energy is shown in the adjacent figure. The angular acceptance is 60 deg and there are 120 angular channels.

During the second period also a number of designs for the end-user stations were made. The general system setup is shown in Fig. 1. It shows the dimension of the complete system in comparison to typical user dimensions to demonstrate the reachability of all chambers and components. The analysis chamber contains as main parts the PHOIBOS 150 NAP analyzer mounted under magic angle geometry with respect to the sample / manipulator and the windowless beam entrance stage. This generic setup contains also a laser heater, a preparation chamber, a catalysis chamber, a load-lock chamber a source for UV radiation (UPS), a source for x-ray radiation (XPS), an electron source (SEM / SAM), a low energy electron diffraction system (LEED) as well as the beam entrance for the synchrotron light source.

UNIFE (summary)

UNIFE has focused on three parts namely i) the characterization of the Mirrorcle source by analyzing the experimental results obtained by the imaging details of diagnostic interest, ii) a thorough investigation of the edge enhancement effects produced by the Mirrorcle source and iii) the optimization of the parametric x-ray radiation and its application of diagnostic radiology.

The experimental data provided by the set of measurements performed at the Photon Production Laboratory (Japan) last year, were used for the characterization of the 6-MeV MIRRROCLE source. Results are summarized in two degree thesis and excerpts with relevant information are attached to this report. The measurement of the focal spot is discussed in the thesis of G. Gadda Measurement of the focal spot length of the Mirrorcle x-ray source. Since very long wire targets have been used as target materials inserted within the MIRRORCLE source, only the length of the focal spot has been measured, the width being equal to the wire thickness By using a specific test object, the extension of the focal spot in the direction parallel to the wire target is $l = (5,8 \pm 0,2)$ mm. In the thesis of E. Mastella X-ray emission using thin targets in compact accelerators, a thorough evaluation of the electron current that hits the target material has been carried out. Several methods have been used to calculate such current and all the value are within the range of about 1?A. Comparison with a standard x-ray tube in terms of photon flux confirms that MIRRORCLE performance has to be increased of about two orders of magnitude.

Based on the x-ray imaging experiment described in the first year report which revealed an interesting effect of edge enhancement, we investigated the phenomenon in depth and we provided a full explanation of it by demonstrating that such effects arise from the combination of x-ray absorption (kiloelectron- volt part of the spectrum) and secondary particle emission (mega-electron- volt part of the spectrum) within the sample. The adjacent figure shows a comparison between experimental and simulated data. The experimental data (continuous line) were taken from the

radiograph of an Al detail (in the top image the white line represents the line profile used for the comparison). Data from the Monte Carlo simulation (dotted line) are reported with their statistical uncertainty.

After the preliminary results on the diagnostic potential of PXR reported in Period 1, we extended our study to plan an experimental validation of our analytical model. We visited the Idaho Accelerator Centre (IAC) in the United States (http://www.iac.isu.edu/index.html) to discuss with Dr. K. Chouffani, an expert in the field, the feasibility of a PXR experiment in his laboratories. We then applied our model for the calculation of the PXR yield with various crystal targets. Results demonstrated that the Graphite crystal (002) exhibits the best yield factor both in Bragg and Laue geometry.

PPL and Ritsumeikan (summary)

Further characterization of the Mirrorcle prototype has been carried out during the project, including optimized accelerator designs. Also two new prototypes have been developed and tested during the second period, namely the CV1 and the CV4 machines. The specifications of the CV1 and CV4 machines have been provided in the second year report. In addition the radiation dose for all the different systems has been provided. Also a setup to make an x-ray source for the protein structure analysis operating at 12,7 KeV using a Xenocs mirror has been demonstrated. Finally also a source for X-ray absorption (XAFS) operating at 14 KeV has been developed.

As a result of demand for developing new MIRRORCLE machines, with smaller size and lower electron energy was developed the CV series. We started developing machines CV4 and CV1, for 4 MeV and 1 MeV electrons respectively, in April 2008. CV4 was originally designed for injection from LINAC. Then, to increase beam current, we replaced the injector by a microtron, which was designed and manufactured in our Lab, in September 2009. After that, CV4 was lent to a heavy industry, where it has been used as X-ray source for computer tomography for automobile engine diagnosis. MIRROCLE- CV4 achieved the world smallest resolution for a heavy construction. The manufacturing of a microtron for CV1 was completed in December 2009. The injector and the storage ring were gathered in January 2010, followed by a successful test of the injection. After that, we remade the machine, by vertical positioning of the injector and the storage ring, to decrease the machine location area, in June 2010. Then, CV1 was fixed in a small track, for providing NDT of bridges, and other immobile heavy constructions. Testing of real bridge was successfully performed.

In the optimized design of the CV series, the radius of the electron orbit is 8 cm, which is achieved by using 35 cm square magnet yoke. The magnetic field is generated by permanent magnet. The height of the yoke depends on the electron energy to be stored. The weight of the yoke is about 0.5 T, which allows moving the entire system by a robot arm. The injection is nearly 100 %, the same as for the larger MIRRORCLE's. The standardized machines CV1, CV4, CV10 are now available from the Photon Production Laboratory Ltd. Machines can be selected according to the purpose of users. CV4 is the hard Xray used for non-destructive testing of heavy constructions, such as cars, trains, airplanes, bridges, and power plants. CV1 will be useful for medical imaging, X-ray microscope, EXAFS, SAX, XRD and crystallography. CV10 will generate EUV and soft X-ray, for use in EUV lithography and actinic mask defect inspection. CV10 can be also useful for generation of FIR and MIR, for study of water-protein dynamics and identification of chemical materials.

Since 12.7 KeV radiation is most desired for analysis of protein structure, we are developing such a source. It is based on reflection of MIRRORCLE radiation from FOX2D MO curved mirror, which we purchased from Xenocs. The mirror is coated by graded multilayer coating, and it provides collimated beam, with a spectral purity of above 97% at 12.7 KeV at its output. Photo of the mirror, and its alignment illustration are shown in the adjacent figure

We also develop a source for X-ray absorption spectroscopy (XAFS) at 14±0.6 KeV, using Si(1,1,1) bent crystal for focusing. XAFS provides information about the local structure and unoccupied electronic states of a material specimen. For focusing the X-rays at optional position, it is useful if the radius of the bent crystal is tunable. We designed two types. One design represents a method of fixing one side. One side of the crystal is fixed by binding aluminum parts, and other side is pushed by micrometer head. The second design allows handling both sides, as shown in Fig. 4. The crystal is bound by pins. For bending the crystal, the unit is rotated around fixed point as the center of rotation. At present, we are working on preparation of the crystal, and next will be developing of a beamline for XAFS.

C3. Period 3

KULeuven (summary)

During the third period the tasks of KULeuven have mostly been related to i) the synthesis and characterisation of different nanomaterials, ii) the theoretical simulations of the electron emission efficiency of nanoparticles as well as iii) a first estimation of the therapeutic effects.

Two different wet chemistry methods to make nanomaterials, were explored during this third period. The first method was based on the sol-gel synthesis where a liquid layer is spin coated onto a substrate and subsequently annealed. This method was used to synthesize silica and AlPO4 nanomaterials. The sol-gel is a method that has been developed in our group without prior knowledge . The main purpose to choose this technique is that it allows an easy fabrication method for multicomponent materials like ternary and quaternary materials. With the traditional wet chemistry methods using synthesis in the liquid phase □ our second method □ that is much more difficult. As a test material to get the sol-gel process up and running most of the initial work has focused on AlPO4. A lot of time and energy was needed to optimise the various experimental parameters such as liquid mixture, annealing temperature and pressures etc. In this period, we have demonstrated that with this method, good quality ternary materials can be made. However one of the remaining challenges is to control the diameter and size distribution of the nanoparticles made with sol-gel. Our second method uses a synthesis in the liquid phase wherein the nanoparticles and grow. Both the Stoiber and the citrate reduction method were used in this case. Again silica nanoparticles as well as gold nanoparticles were grown with this method. Good quality nanoparticles could be made with a reasonable control on the particle size and dispersion.

Since the emission therapy method needs high Z materials in order to induce a high emitted electron flux, one may ask the question as to why low Z materials such as silica and AlPO4 where produced in this project. The main reason for this is that only a thin shell of material near the surface of the nanoparticles is participating in the electron emission. In that case it is thus enough to make silica nanoparticles and to coat these afterwards with a thin layer of a high Z material such as gold.

Most of the simulation activities were performed on gold nanoparticles of different radius typically 5 nm, 10 nm, 30 nm and 50 nm. The energy distribution was calculated as a function of distance and the oscillations observed in this behaviour were linked with the different electron shells of the gold atoms. This simulation was also performed for different photon energy typically 20 keV, 40 keV, 60 keV 80 keV and 100 keV. Surprisingly the 20 keV beam deposits much more energy than the higher energy beams and this can be understood by the large difference in the mass energy absorption coefficients for the different energies. Other quantities that were calculated include the interaction probability, the total amount of electrons generated (for the different sizes and different energies), the amount of electrons that come outside of the nanoparticles, the self-absorption and the relative energy enhancement. The most relevant results of the simulation are shown in the adjacent figure. Here the relative energy enhancement as a function of distance from the 5nm Au nanoparticle is plotted for different irradiation energies. The enhancement factor compares the energy deposited in the tissue with and without the presence of Au nanoparticles. Is clear that near the surface of the nanoparticle are large energy enhancement can be seen even at distances up to 10 micrometres. Surprisingly also is the fact that also the low energy photon beams (20 ▯ 40 keV) lead to a substantial increase in the energy enhancement.

Finally we started to estimate the therapeutic effect. Unfortunately the methods we used to measure the DNA damage did not work yet properly. Two experiments were performed namely one on genomic DNA and one on short DNA sequences but results were not conclusive so far.

CNRS (summary)

During the third period, CRNS has mainly evaluated the implementation of a liquid metal jet anode x-ray tube under the extreme conditions of an environment with high magnetic fields of 30 Tesla either in pulsed or in continuous mode.

In the third period, the specific activities have been concentrated in the validation of the liquid-metal-jet anode x-ray tube (manufactured by EXCILLUM) in the hostile environment of high magnetic fields. Although the need for this X-ray source is amply justified a key question still remains: can we use this source in a hostile magnetic environment? If so, how close to the magnet can this X-ray source be located in order to warrant its optimal functioning and prevent serious damages? The answer of these questions goes through computer simulations and calculations of the stray fields issued from magnets and configurations. Calculations have been performed for coils producing a continuous field (DC fields) or pulsed fields. For each one of them a 2D chart of the magnetic field distribution has been calculated on the basis of actual coils, either built or on the design table.

The above figure shows the magnetic field distribution outside of the coil along three directions, radial, vertical and along 45 degrees. (Left) Results for a large bore (50 mm) solenoid and wide access for neutron scattering experiments. (Right) Results corresponding to a split pair coil. The conclusion of this study is that the liquid-metal-jet anode X-ray source can be located at 1 m (for the pulsed fields) and 1.5m (for the DC fields) -at the shortest - from the magnets without experiencing serious disruptions of its functioning. This statement is equally applicable to any other X-ray source based on electron deceleration (or Brems).

BESTEC (summary)

In the third period, BESTEC focussed further on the design of an EUV source with EUV monochromator beamline

A compact laboratory source for soft X-ray radiation with a continuously tunable photon energy range was designed. The photons are emitted from a plasma, produced locally on a copper target by focused laser pulses. A customized large-acceptance-angle monochromator beamline for this source is proposed. First tests show consequences on the performance at increasing repetition rates. Appropriate measures to account for the implications of higher repetition rates up to 1kHz are discussed.

A prototype of a high-repetition rate source was tested with the following results:

1. The mechanical system is suitable for higher repetition rates.
2. Off-line source point diagnostics shot-by-shot intensity reading and calibration is not feasible.
3. A rotating aperture debris filter system was developed and electronically tested, which can be used up to 100-200 Hz maximum.

The adjacent figure shows the laser plasma source tested for the use at higher repetition rates. The OFHC cylinder barrel is built from identical segments for fast and convenient refurbishing of the target. The main performance values are still limited by the commercially available laser systems, which have a max. repetition rate of 200 Hz. The first 1kHz systems with sufficient pulse energy and beam focusability are expected to be commercially available at the end of 2012.

The monochromator beamline consists of five elements: the toroidal focussing mirror M1, the plane grating G, two plane mirrors M2A and M2B, the exit slit ES and the toroidal refocusing mirror M3. M1 creates a virtual 1:1 image of the source in the dispersive direction illuminating the Grating convergently. The virtual source of the grating is imaged onto the exit slit de-magnifying it approximately 3:1. The exit slit is imaged onto the interaction center magnifying it by a factor 1:10, which results in a focus size around 100 µm at an exit arm length of ~1500 mm. The resolving power for this design will be in the range 1000 – 3000 using a grating with only 600l/mm at an overall beamline length of ~4m. In the non-dispersive direction the source is imaged directly onto the interaction center magnifying the source approximately by a factor of 3, which will result in a focus size in that direction of ~100 µm.

SPECS (summary)

In this period, SPECS has finished a complete system concept for a multi-diagnostic end-user station combining the EUV source from BESTEC with its own developed analysis tools.

In this period, a multi-diagnostics end station attached to the beam line/EUV source designed by the project partner BESTEC has been designed. After refocusing the project on the EUV source from BESTEC and integration of sources from SPECS, the number of techniques in the analysis spot have been reduced to X-ray induced photoelectron spectroscopy (XPS), UV induced photoelectron spectroscopy (UPS), Scanning electron microscopy (SEM) and Scanning Auger Electron Microscopy (SAM). Furthermore the sample stage can be equipped with an in-situ

SPM, so that also structural analysis with parallel Scanning Tunneling Microscopy (STM) and Non-Contact Atomic Force Microscopy (nc-AFM) is possible in the same sample spot as the spectroscopic techniques mentioned above. The SEM can in this case be used as a navigation tool for the microscopy probe used. A transfer line brings the samples into a preparation chamber and the Load Lock chamber for sample introduction. In the adjacent figure the EUV system from BESTEC is shown on the right side of the system.

For the electron spectroscopic part of the system a hemispherical electron analyser design has been made with the capability of running at 7-15keV kinetic energies with parallel angle detection over a large angle segment of 60°, called PHOIBOS 225 WAL HV. With slight modifications, this analyser can also run under elevated pressure environments (up to 25mbar) as a PHOIBOS 225 NAP HV.

Because the photon sources used in the endstation are entirely capable of running at maximum photon energies of 1500eV, SPECS has developed a new X-ray monochromator source design utilizing the Cr K? emission line at 5414.805eV.

UNIFE (summary)

The activities of UNIFE in the third period were focussed around the characterization of the liquid metal jet anode x-ray tube system using both simulations and experimental measurements.

In this period, the objective was to study the x-ray properties of a novel source based on a liquid-metal-jet anode by means of Monte Carlo simulation and experimental measurements. Such novel source has been developed by a swedish company (http://www.excillum.com/) and a prototype is available at the Bruker factory in Karlsruhe (Germany). Bruker, a well known company in materials research and quality control instrumentation for elemental and crystalline structure investigations (http://www.bruker-axs.com/), has recently set up an exclusive collaboration with Excillum to develop and market the unique new metal-jet x-ray source for x-ray diffraction applications.

Simulation study - A thorough simulation study has been performed to calculate x-ray spectra for different liquid metal alloys and to investigate the main properties of the novel x-ray source. Technical characteristics of the experimental x-ray source available at Bruker (Germany) have been used to carry out the simulation and pertinent physical parameters were varied to compare different configurations. For this task, the well known MCNPX code has been be used.

The photon-uence spectra were calculated by Monte Carlo simulations and are normalized to be per starting electron and are specifed at 100 cm, in vacuum. Results are shown below for a 70 keV electron beam. Simulated radiographs of the test object described above were calculated using simulated spectra. By comparing the data of the table it is apparent that the physical image quality is lower than that of a conventional x-ray source for mammography. Nevertheless, when simulating a liquid-jet-anode source using the Indalloy® no.51 alloy, a K-edge added filter (100 µm Sn) and a lower incident-electron energy (50 keV), then the resulting x-ray spectrum more closely resembles spectra generated by conventional x-ray tubes for mammography.

An appreciable improvement in the monochromaticity of the beam can be observed. A higher physical image quality than that of conventional x-ray tubes for mammography could also be achieved

Experimental study - X-ray performance of the novel x-ray tube has been evaluated at Bruker facilities in Germany where the prototype of liquid-metal-jet anode source is installed. To fully characterize the novel source we have measured the x-ray spectrum, the focal spot shape and size and spatial distribution of the irradiation field. X-ray imaging capabilities have been also assessed by means of various test objects. As a medical application we are interested in x-ray mammography so specific phantoms were imaged and evaluated. We made use of the x-ray detector available at the Physics Department of Ferrara University (RadEye2) so as to compare the results with the previous MIRRORCLE source.

Potential Impact:

The LabSync project was a design study around a facility with novel light sources. The impact of the project can thus be divided in the following categories: i) scientific impact, ii) designs made and iii) novel instruments and setups developed and tested.

D1. Scientific impact

The Mirrorcle compact sources are of a very interesting concept unfamiliar to most researchers in Europe. Hence the interactions of the different scientists in the LabSync project, has offered a lot of opportunities to learn new concepts and to bring their expertise into a new field. This is also well documented by the long list of publications that have come out of the project.

The main scientific impacts are listed below:

- A better understanding of the working principles of the Mirrorcle systems whereby systems with a smaller radius lead to a higher produced photon flux.
- Study of the beam dynamics in the Mirrocle systems with a thermograph to determine the life time and the damping time.
- Improved methods to characterize the photon flux and brilliance that comes out of the Mirrorcle systems.
- Evaluation of medical imaging applications with the Mirrorcle systems though the appropriate choice of target material and size.
- Detailed simulations of electron beam interactions with matter for Bremsstrahlung and parametric x-ray rays.
- Detailed simulations of photon beam interaction with matter for the calculation of emitted photo-electrons and Auger electrons.
- Electric field simulations to calculate the trajectories and the life time of electrons in the Mirrorcle systems.
- Measurement of the focal spot length of the different Mirrorcle x-ray source.
- Explanation of the edge enhancement effect in medical imaging with the Mirrorcle 6X systems.
- Simulations of magnetic field distribution around high magnetic field coils and their impact on x-ray sources.

- Detailed x-ray tracing simulations for the design of beamline elements such as collimators, mirrors and monochromators both for the x-ray range as well as the EUV range.
- Detailed electron trajectory simulations for the wide-angle (60 degrees) electron lens design of the XPS analyser.
- Develop experience with different nanoparticle preparation techniques including wet chemistry and sol-gel methods
- Detailed simulation of the photon spectra emitted by different liquid metal jet sources including gallium and Indalloy
- Experimental measurements of photon spectra emitted by liquid metal jet sources and evaluation of their usefulness for medical imaging applications

D2. Designs made

As a design study project under the Infrastructure part of FP7, one of the main goals in the project has been to make designs. In some cases these designs were made by a single partner will in other cases, several partners collaborated to make a final design. In many cases, the designs made, have opened the door to novel experimentation and instrumentation. Some of these designs have already been build into actual instruments that will come onto the market in the near future. In other cases, they may never reach that stage. In some other cases, existing designs were vastly improved during the course of the LabSync project.

The main designs made during the LabSync project are listed below:

- Optimization of the different Mirrorcle system design by improving on several important parameters such as the microtron, the klystron, the injection frequencies etc.
- Design of a beamline for protein structure analysis at 12.7 KeV radiation based on the Mirrocle CV4
- Novel 4 MeV Mirrorcle system design called CV4
- Novel 10 MeV Mirrorcle system design called CV10
- Laboratory layout based on a Mirrorcle system whereby several beam lines can be installed around a single storage ring with different targets for soft and hard x-rays.

- Improved layout of the concrete enclosure around the different elements of the Mirrorcle system including the microtron and the storage ring in order to reduce the background scattering effects.
- Beamline design for the soft x-rays generated by the Mirrorcle source
- Beamline design for the soft x-rays generated by the laser plasma source
- Laser plasma source design for the BESTEC EUV source
- Monochromator design for the BESTEC EUV source
- Debris filter design for the BESTEC EUV source.
- Collimator, mirror and a noel monochromator design for the EXAFS beamline around the Mirrorcle
- Wide-angle electron lens design for the Phoibos XPS analyser.
- Multi-diagnostic end-user station design combining the laser plasma source from BESTEC with the x-ray source and analyser from SPECS
- Design of a Cr K? x-ray source and monochromator for Cr K? based XPS measurements
- Design of a high magnetic field laboratory compatible with x-ray based measurements capabilities.

The above figure shows a design of a laboratory with different beamlines around one Mirrorcle system. It also shows an improved concrete enclosure around the different elements of the system.

The above figure shows ray tracing of the wide-angle lens showing the acceptance cone of 60 degrees and the angular resolving capability.

The adjacent figure shows the design of a beamline for protein structure analysis operating at the energy of 12.7 KeV. The radiation emerging from the Mirrorcle CV4 is reflected from the FOX2D MO mirror and then is additionally monochromatized and finally directed towards the protein sample.

D3. Novel instruments developed or further refined

While a lot of questions regarding the photon output, resolution and spot size of the Mirrorcle systems were not clear in the beginning of the project, several options were considered for the instruments to be developed. Some of the questions were clarified during the course of the project but a number of mysteries remained. Many options considered initially did not mature beyond the stage of simple sketches. Nevertheless several instruments and systems were actually developed and will end up in commercial products. In the section C of this report, there are already several images and pictures of the systems developed here. For the two European SME’s participating in this project, namely BESTEC and SPECS this project will certainly have a major impact in terms of future product sales. Also the good interaction between these two SME’s has led to a common design for a instrument that combines an EUV source with a analytical system.

The main novel instruments developed by the SME’s involved during the project or further refined during the project are listed below. Although not specifically detailed here for each of these instruments also a considerable effort was devoted to prepare the appropriate electronics driving hardware as well as the control and analysis software.

- Mirrorcle CV4 instrument by PPL
- Laser plasma source by BESTEC
- EUV monochromator by BESTEC
- EUV debris filter by BESTEC
- Wide-angle lens for XPS analyser by SPECS
- High energy analyser (7 KeV – 15 KeV) for XPS applications by SPECS

The adjacent figure shows a picture of the CV4 Mirrorcle system made by PPL. For most of the other systems mentioned in the list above, pictures are already included in this report in the previous section C.

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