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6. **ABSTRACT**: A soft x-ray undulator is to be based at the vacuum ultra-violet storage ring at the National Synchrotron Light Source. The undulator will be used as a radiation source by a multi-institutional research team to perform the first spin-polarized photoemission experiments in the United States to study novel ultra-thin magnetic films and surfaces.
Annual Report:

December 1986 - December 1987

SOFT-X-RAY UNDULATOR

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FEL Applications Program

Strategic Defense Initiative Program Funding
This is the first annual report for a two-year program to base a soft x-ray undulator at the vacuum ultra-violet (VUV) storage ring at the National Synchrotron Light Source (NSLS). The undulator will be used as a radiation source by multi-institutional research teams to perform the first spin-polarized photoemission experiments in the United States. The undulator source will permit major advances to take place in materials research in the forefront area of novel, ultra-thin magnetic films and surfaces.

The activities are summarized on the attached bulletized "Chronology of Activities". Contractual arrangements with ONR were successfully completed and the undulator procurement process was initiated. Technical specifications and evaluation criteria were finalized. A synopsis to invite bidders appeared in the Commerce Business Daily (see attached). Bids were received and recommendations were made by a Technical Evaluation Team to the Argonne Source Selection Board. A purchase order will be placed in a timely fashion as internal and DOE reviews are completed.

Two auxiliary equipment issues are being pursued simultaneously. One invokes the vacuum chamber assembly that the undulator envelopes. A bid has been received for a ribbed chamber that accommodates the pole corrugations of the undulator. The other involves photon beam monitoring and feedback control for beam positional stability. Various strategies for ensuring stability have been evaluated and the task has been divided into two parts. First data will be collected with a passive monitoring system to evaluate (i) the magnitude and (ii) the frequency spectrum of the instability, and (iii) the passive measures that can be taken to minimize instabilities. Then an appropriate feedback system will be instituted as needed. These auxiliary issues involve open and continuing dialogue with NSLS staff personnel.
Related programmatic activities included: a) invited talks at major national/international meetings on "Magnetic Properties of Novel Epitaxial Films", and b) numerous publications on the subject, including invited papers and letters. Synchrotron-radiation-related activities included: a) a tour of the Photon Factory in Tsukuba, Japan, b) participation in the SRI Conference, Madison, Wisconsin, c) participation in magnetic x-ray scattering experiments at the Cornell High-Energy Synchrotron Source (CHESS), and d) appointment to the Program Committee of the upcoming conference (sponsored by NSLS and the American Vacuum Society) entitled "Vacuum Design of Advanced and Compact Synchrotron Light Sources".

Enclosed also is an invited summary for the forthcoming meeting on "FEL Applications in the Ultraviolet" sponsored by the Optical Society of America. It is entitled "Novel Magnetic Materials Research Using Free Electron Lasers". It contains a comparison of the estimated source flux from the soft-x-ray undulator of the present proposal to that anticipated from the conceptual design for futuristic FEL sources.
Chronology of Activities

December 15, 1986  • Start date of Contract.

February 1987  • Contract Reviewed at ONR for Fiscal Data.
  • Department of Energy accepts $1,017,583 incremental funding.

March 1987  • Argonne Account BC437-00 set up.
  • Iterate specifications with NSLS Machine physicists.

April 1987  • Undulator procurement process starts at ANL.
  • Tour Photon Factory, Tsukuba, Japan.*

May 1987  • ONR Contractors Meeting for SDIO/FEL Programs.
  • Commerce Business Daily Synopsis Appears.

June 1987  • Synchrotron Radiation Instrumentation Conference, Madison, Wisconsin.*

July 1987  • DOE accepts $366,417 incremental funding.

August-September 1987  • Proposals received from bidders.
  • Appointment to Program Committee: "Vacuum Design of Advanced and Compact-Synchrotron Light Sources", NSLS/AVS.*

October 1987  • Technical Evaluation Team forwards Recommendations to ANL Procurement.
  • Summary prepared for Optical Society of America Topical Meeting on FEL Applications in the Ultraviolet".*

November 1987  • DOE accepts $198,000 final funding increment.

December 1987  • Magnetic X-ray Scattering Experiments at CHESS, Cornell University.*

*Related (not supported).
May 15, 1987

TO: DonCarlos James PRO/201
FROM: S. D. Bader MSD/223
RE: CBD Synopsis

Specification for a Hybrid Undulator for the U5 Beamline at NSLS

This specification is for the design and fabrication of the basic magnetic and mechanical structure of a permanent-magnet hybrid undulator to be used on the U5 beamline on the vacuum ultraviolet VUV ring at National Synchrotron Light Source (NSLS). The device shall have a variable gap with provisions for remote adjustments incorporated into the design. The first choice for the permanent magnet materials shall be the Nd-Fe-B alloy and for the ferromagnetic pole, vanadium permendur. The specifications are such that the undulator will provide the recommended field strength and the smallest bandwidth on the first and third harmonic radiation within the emittance of VUV ring. Both the magnetic and mechanical properties are to be compatible with the vacuum chamber housing of the storage ring. The stand and mechanical structure shall also comply with the space requirements of the storage ring. End correctors, end-field clamps, and residual steering errors shall comply with the NSLS requirements for the VUV ring.

The permanent magnet materials shall have a minimum coercive force of 10.6 kOe. The recommended period is 7.5 cm and the maximum length is 2.25 m. The gap adjustment should be rugged and dependable for constant daily operation from a minimum of 2.4 cm to a maximum such that the on-axis magnetic field is less than 500 Gauss. The gap setting shall be reproducible to within 0.001 inch. The maximum deviation of the midplane field variation from a pure sinusoidal one shall be less than 2% at any gap setting to within 2 period on each end of the device. The device shall be delivered to NSLS within fifteen months from the acceptance of the order.

SDB/b
NOVEL MAGNETIC MATERIALS RESEARCH USING FREE ELECTRON LASERS

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October 1987


Novel Magnetic Materials Research Using Free Electron Lasers

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Synchrotron-radiation sources have dramatically increased the research capabilities of materials scientists. This increase has motivated advances in source development, from the

(i) early, "parasitic" stage, to the
(ii) present-day, dedicated bending-magnet stage, to the
(iii) proposed, all-insertion-device stage.

This latter development will permit spin-polarized photoelectron spectroscopy to become a convenient probe of magnetic materials. This form of spectroscopy warrants undulator radiation sources because electron spin detectors are inefficient by a factor of \(10^{-4}\) compared to conventional photoelectron detection. Thus, it becomes very exciting to consider the future scientific possibilities offered in the ultimate stage in the source progression: the realization of soft x-ray free electron lasers (FEL). In the following, broad examples of magnetic materials research opportunities are considered. Order-of-magnitude estimates are then given of source flux and spin-polarized signal level for an undulator and an FEL source. The comparison illustrates the impact expected of FEL sources on magnetic materials research in the future.

The classes of physical phenomena that can benefit from spin-polarized photoemission studies are diverse and include

(i) the characterization of ground-state magnetic properties, and the challenge of testing local-density-theory predictions,
(ii) the area of surface magnetic critical phenomena,
(iii) the photo-excitation process itself, by adding the spin dimension to screening and resonant mechanistic studies.

The area of surface-modified magnetic order includes the characterization of

(i) magnetic dead layers,
(ii) enhanced magnetic moments at the surface, and even
(iii) new types of magnetic order.

Model systems involve

(i) surfaces of bulk materials,
(ii) epitaxial ferromagnetic mono-, bi- and tri-layers, etc., and even
(iii) one-dimensional magnetic chains, such as might be realized by lithographic techniques or by selectively adsorbing magnetic adatoms at ordered step sites of non-magnetic substrates.

The theoretical description of finite-temperature magnetism, and the role of short-range order and spin fluctuations presents an open challenge. The interplay of magnetism and

(i) chemisorption,
(ii) surface segregation,
(iii) surface order-disorder phenomena,
(iv) epitaxy and film growth, etc.

provide numerous problems requiring additional experimental elucidation. The method of epitaxial growth enables one to "atomically engineer" magnetic properties of interest by altering natural lattice constants, and by stabilizing unstable and new phases of bulk materials.

The area of f-electron magnetism provides localized magnetic order in rare-earth metals, in contrast to the itinerant magnetism of transition metals, and the challenges of "heavy-fermion" behavior in certain cerium-, uranium-, and transuranic-based materials. Rare-earth materials often exhibit helical magnetic structures. Creating these materials in ultrathin form via epitaxy necessarily should induce new properties because the film thickness can be engineered to be less than the pitch of the helix. In the heavy-fermion systems the measurement of the width of the electronic structural features in the vicinity of the Fermi level is believed to be resolution limited at present.

The question of the nature of the amorphous state has benefitted recently from a deeper understanding of the structure of disordered materials. Magnetic-glass research poses the interesting possibility of assessing the role of magnetism in helping to stabilize the amorphous state. This is an area that is also at the interface of basic and applied research because of the technological applications of magnetic glasses. Other technological materials include magnetic recording media and magnetic catalysts. It is known, for example, that chemical reaction rates can differ in character above and below the magnetic ordering temperature of the catalyst.

Magneto-optical materials are important in the future development of magnetic information technologies. Magneto-optical properties in the soft x-ray range have not been explored. Transition-metal-rare-earth systems should show interesting reversals of the magneto-optic coupling strength as the photon energy is increased. There is also great interest here in increasing the photon energy to core-level threshold energies. Non-linear magneto-optic effects and second-harmonic generation further contribute to the richness of opportunities. These studies can be pursued simultaneously with photoemission experiments.
Spin-polarized photoemission of dilute magnetic alloys potentially could provide a clear illustration of the fundamental interactions that lead to magnetic order. Even exotic host materials could be utilized, such as superconducting materials. Ternary superconductors and the new high-T<sub>C</sub> oxide superconductors can tolerate a magnetic atom in each unit cell of the material. There is very little understanding of the influence of superconductivity on magnetic ordering. Usually the approach is applied in reverse, and the influence of magnetism in suppressing superconductivity is studied. Dilute magnetic systems could be created artificially, as well, via optical pumping techniques. This presumably could be done in much the same way as the molecular photophysicists and semiconductor researchers envision pump-probe experiments.

Having enumerated a variety of interesting topics in magnetic materials research, it is of interest to evaluate technical considerations to determine the appropriate source for a given experiment. For the undulator source the estimate presented below is based on a device on the VUV storage ring at the National Synchrotron Light Source (NSLS). This undulator is chosen because it is planned for installation at a beamline dedicated to spin-polarized photoemission. It is a hybrid, over 2 m long, with a period of 7.5 cm. It will be constructed of neodymium-iron-based permanent magnets and vanadium permendur poles. The FEL source used in the comparison is that conceptually designed at Los Alamos National Laboratory for operation on an rf linac. The comparison is made at 50 eV, which is a high photon energy for angle-resolved experiments. The rf-linac FEL flux drops approximately as the square of photon energy as photon energy increases in this range, so it is a conservative estimate of FEL performance when extended to lower energies. The undulator has a usable source flux of $4 \times 10^{14}$ photons/sec/0.1% bandwidth. This is for an on-axis pinhole collection angle (0.2 mrad x 0.2 mrad) that includes the natural opening angle of the radiation. The rf-linac FEL provides a factor of $10^3$ increase in flux over that of the undulator, with the bandwidth measured in cm<sup>-1</sup> units! The count rate at the spin detector from an iron sample is expected to be in the kHz and MHz range, respectively, for the undulator and FEL source. This takes into account the photoemission cross section and the spin detector efficiency. An additional consideration is that the undulator source requires a monochromator, while the FEL would not. Transmission loses in the monochromator are difficult to factor in, but they will be present. The comparison illustrates striking advantages of the FEL source. The flux is orders of magnitude improved over that of the undulator. The FEL source collimation and spectral and polarization purity are all improved over that of the undulator as well.

For spin-polarized photoemission studies the advance from the undulator to the FEL source is a development that parallels that which is occurring in conventional photoemission studies in going from bending-magnet sources to undulators. This latter advance has captured the imagination of the scientific community and motivated major advanced-source projects world-wide. The scientific case in support of such projects documents the need for undulator
radiation. The following materials research areas have, thus, been identified:

(i) pump and probe experiments,
(ii) dilute impurity studies,
(iii) relaxation phenomenon, and
(iv) photoelectron microscopy.

It is important to note that the spin-polarized analogue of each of these generic areas would require FEL sources to be comparably successful. Another critical point is that the areas of magnetic materials research that are already accessible with undulator radiation would be significantly improved by the availability of FEL sources. The improvements could qualitatively change the importance of the experiment. For instance, it would be interesting if the enhanced monochromaticity of the FEL source would reveal magnon sidebands on the photoelectron spectra.

While many of the areas considered above take advantage of photon-energy tunability and enhanced flux, the photoelectron microscope would directly benefit as well from the superior brilliance of the FEL source. The ability to focus the radiation within a magnetic domain eliminates the technical problem of magnetizing the sample. This is a non-trivial issue, since stray magnetic fields can deflect photoelectron trajectories in undesirable ways.

In addition, FEL sources provide the potential for opening up new scientific frontiers based on ideas that have yet to be conceived. Given the intellectual challenges these sources provide, such frontiers are expected to be encountered, and their exploration will undoubtedly be richly rewarding.

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