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Atomic Physics with High-Brightness Synchrotron X-Ray Sources*

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ABSTRACT

A description of atomic physics experiments that we intend to carry out at the National Synchrotron Light Source is given. Emphasis is given to work that investigates the properties of multiply charged ions. The use of a synchrotron storage ring for highly charged heavy ions is proposed as a way to produce high current beams which will make possible experiments to study the photoexcitation and ionization of multiply charged ions for the first time. Experiments along the same lines which are feasible at the proposed Advanced Light Source are considered briefly.

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I. INTRODUCTION

Atomic physics experiments commonly use very dilute targets so that atoms or ions can be studied under single-collision conditions. This requirement sets stringent conditions on the intensity of ion or photon beams used to excite or ionize the target atoms if the experiment is to be done in a finite time.

With ion beams it is easily possible to obtain particle fluxes of about 10^{13} to 10^{15} particles/cm^2/s. Such fluxes correspond to DC beam currents of a few nanoamperes to a few microamperes. A further improvement of 2-3 orders of magnitude can be achieved for work that requires pulsed beams since then beam bunching techniques can be applied. These statements hold for conventional ion sources used to produce beams of negative or singly ionized elements.

It can be seen that if we want to use synchrotron produced photon beams to excite or ionize dilute gas targets in a way strictly analogous to the work done with ion beams, then it will be necessary to use photon beams of very high brightness. We estimate that it will be possible to obtain monoenergetic photon beams that will give fluences of around 10^{15} photons/cm^2/s from the National Synchrotron Light Source (NSLS) bending magnets. Thus it is now beginning to be possible to do experiments on atom-photon interactions in a way that is comparable to ion-atom studies.

It is a different story, however, if we consider the case of ion-photon experiments. In this case we deal with ion beams where the particle density is much less than can be utilized with gas targets and the use of high-brightness photons sources produced by use of undulators or wigglers becomes mandatory. The availability of such facilities at the NSLS, the proposed Advanced Light Source (ALS), or any other synchrotron is therefore an exciting prospect for atomic physics research.

In this paper we present briefly some of our plans for initial atomic physics experiments at the NSLS. The discussion is not meant to be comprehensive and is directed at our particular interest alone. Other workers in the field will have different ideas, although we believe that there will be a concern for intensity of photon beams that is common to all the discussions. Our intent is to define the range of photon intensities that are needed for ion-photon experiments and present our ideas on how to approach the problem of low interaction rates. This represents, in effect, a description of our atomic physics program at the NSLS.

The energy spectrum of photons produced by the ALS extends over a smaller range than the NSLS spectrum. Traditionally, the atomic and molecular physics experiments with synchrotron radiation have concentrated on a detailed examination of the outer shells. For such experiments a source of high brilliance at an energy up to 1 keV is very necessary. There are, however, crucial reasons why there is need to examine inner shells as well. The ALS can be used effectively for studies in atoms with K-shell ionization energies up to ~ 5 keV, that is, into the first-row transition elements, and even higher for the L-shell. Therefore, in addition to the examination of outer atomic shells, the ALS can be used for experiments that are similar to the ones discussed here--experiments which will relate to other fields of physics and chemistry and should occupy a basic position in the overall research program.

II. FLUORESCENCE EXPERIMENTS WITH GAS OR VAPOR TARGETS

In our first experiment at the NSLS we plan to look at fluorescent radiation emitted by gas targets irradiated with the white beam from the x-ray ring. Gas target pressures will be about 10^{-4} Torr. A VUV spectrometer will be used to measure radiation emitted at wavelengths greater than 25 nm. Measurements of Auger electrons may also be undertaken. These measurements will combine the use of white and monoenergetic photons with energies high enough to create K-shell vacancies. It is known that the mean charge state of a typical residual atom could be +5 or more. The results of the experiments can thus be compared with spectra obtained from beam foil spectroscopy (BFS) both for particular states which are excited and for measuring lifetimes in the ns region. It will be particularly interesting to look for forbidden transitions which are too long in lifetime to be seen in BFS. These states will not be excited by allowed transitions so that if they can be observed it should be possible to estimate the purity of the wave functions describing the initial and final states with some accuracy. Conceptually these are simple experiments, but improved photon fluxes mean that higher resolution photon spectrometers and detection apparatus can be used to enhance data quality.

III. THE USE OF ION TRAPS

The next step in developing an experimental program is to look at the possibility of doing experiments with trapped ions. Jones et. al. have pointed out [1] that it should be possible to use ion traps to store photoionized ions and that the use of high intensity beams makes it possible to use repetitive ionization events to produce ions of high charge states. The use of vapor sources should make it possible to look at almost any element in the periodic table. This type of source is called PHOBIS for PHOton Beam Ion Source in analogy with EBIS for Electron Beam Ion Source.

Figure 1 shows results from Ref. 1 that give the time evolution of ionization of Ar atoms in a Kingdon trap exposed to a focused beam from a 25-pole wiggler on the NSLS. It can be seen that totally stripped ions could be produced in a time span of only a few seconds. Our estimates of ion densities in the trap indicate that it will be possible to obtain about 10^8 ions/cm length of trap. These ions can be studied in-situ in the trap or, alternatively, extracted for external experiments on ion-atom interactions at eV energies.

Another approach is to use a Penning trap to store the ions. This trap can be used to store ions at a fraction of an eV energy and is therefore particularly well suited to high precision experiments. The drawback is that it can not hold very many ions, about 10^4 for fully ionized Ar. The design of an experiment using a Penning trap is described by Church et. al. [2] D. A. Church and I. Sellin in collaboration with our BNL group will try initial tests on this type of trap also.

IV. USE OF ION BEAMS

In order to be able to experiment with ions of arbitrary charge state of any element, it will be necessary to merge or cross ion and photon beams. Unfortunately, there are no universal sources at this point which can produce high current beams of all elements in high charge states. Several different types of experiments can be identified.

1. Sputter type sources can produce negative ion beams of all elements with intensities around 1 µA and up. With chopping and bunching, peak intensities around 1 mA are possible.

2. Similar or better performance is possible with various sources for production of positive ions. For example, Brown et. al. [3] have recently reported a source that gives DC currents in the mA range. Bunching could then improve on this for peak currents, although, at some point it will be necessary to cope with space charge problems.

3. The production of multiply-charged ions is the province of the electron cyclotron resonance ion source (ECRIS) or the electron beam ion source (EBIS). Peak currents run over several orders of magnitude and probably it is safe to say will not exceed the 1 mA peak values obtained with the sources mentioned above. At this time the really high charge states for heavy atoms are not produced by the ECRIS, and peak currents from the EBIS cannot be expected to be better than the µA range.

We consider the rates which can be achieved in crossed beam experiments for these sources in Section VI.

V. USE OF TRAPPED ION BEAMS

One of the most interesting recent developments in instrumentation for the study of ion-atom collisions and other types of experiments with highly charged ions has been the introduction of the storage ring and electron cooling concept. This originated in the nuclear and particle physics fields, but has recently been proposed by various atomic physics groups as well. Groups in Germany and Sweden are proceeding with construction of rings which are fed from EBIS sources or from associated heavy ion accelerators. The Oak Ridge group has also been interested in a similar facility in the United States.

The use of a storage ring associated with a synchrotron light source has been discussed by the BNL group in collaboration with V. Kostroun for several years [4,5] and appears to be a truly viable concept that has now been looked at in detail by the many groups cited above. It appears that it will be possible to inject a synchrotron storage ring with ions from an external source such as the ECRIS, EBIS, or PHOBIS. After injection the energy of the stored ions is raised to about 10 MeV/nucleon which gives transit times in the ring which will match the repetition rate of the electron storage ring. The high velocity of the ions gives a basic frequency around 2 MHz which multiplies the number of stored ions by the same factor. The basic accelerator physics puts limits of around 10^8 total ions in the ring and therefore we can estimate that the total currents available are similar to those obtainable directly from the high intensity sources for lightly ionized atoms.

The size of the storage ring is relatively large because of the need to confine high momentum ions and because of the need to provide long straight sections for the RF accelerating cavity, interaction section, and ion injection. The circumference will be about 20-30 m. Figure 2 show a schematic layout of the device on a typical port of the NSLS. It can be seen that the size can be accommodated, but that there is some impingement on the space of adjacent beam lines. This intrusion can be minimized or eliminated by building the heavy-ion ring in a vertical plane. Other types of storage rings should also be considered which would fit in a smaller space.

It will also be possible to do experiments with the ring using beams other than photons. Provision for electron beam sources to permit electron impact ionization and excitation experiments will be possible and will give a complementary approach to the photon interactions since the selection rules are different. Particle ion sources or gas targets will also make it possible to look at ion-ion or ion-atom interactions.

We have called this new concept for study of photon-ion interactions APIPIS to stand for Atomic Physics Ion-Photon Interaction System. We believe that a facility of this type is urgently called for if we are to fully develop the potential that high-brightness photon sources present for new experiments in atomic physics.

VI. INTERACTION RATES

We pointed out already that the use of high brightness synchrotron light sources possibly combined with the use of insertion devices will make possible extensive atomic physics experiments with gas, gas jets, or vapor sources. It is thus sufficient to give estimated rates for the use of other types of ion targets to decide if their use appears to be feasible. This can be done by giving the interaction rate in terms of the luminosity. The luminosity is defined as the interaction rate per unit cross section. A discussion of the concept and sample calculations are given by T. H. Kruse [6] and V. Kostroun [7].

We estimated the luminosities for several different types of experiments that are relevant to the research described in this paper. The values that were obtained are summarized in Tables I-IV. It can be seen that the values for ion-photon interactions are high enough to make possible precision experiments on highly ionized atoms of almost any charge state and element.

VII. RELATIONSHIP TO EXPERIMENTS AT THE ALS

The experiments and methodology that we are working on at the NSLS are ones that are feasible and useful at high brilliance synchrotron storage rings, such as the ALS, which have the ability to produce photons at energies of several keV. The experiments which can be done will differ in degree, but not in essence from those possible at the NSLS or at the proposed 6-GeV synchrotron storage ring. At the ALS the work can cover fully-stripped ions up to about Ca, while at the NSLS coverage up to about Mo, and at the 6 GeV uranium can be considered.

The instrumentation required is not too much affected by the size of the ring, except in the case of heavy-ion storage ring where it would be reasonable to consider a smaller machine. Use of an ECRIS would be sufficient for the ALS since EBIS is more to be considered for production of more highly-ionized heavy atoms.

We have not tried to go into the science that can be addressed in this type of project in this brief summary. Suffice it to say that high intensity synchrotron radiation combined with the use of traps, ion sources, and storage rings should have a substantial scientific impact when used at the ALS, NSLS, and 6-GeV rings even though the range of photon energies produced is very different for these rings.

VIII. CONCLUSIONS

The use of high brightness synchrotron storage-ring photon sources promises to radically expand the scope of experiments that can be done to measure atomic photoexcitation or ionization processes. It will soon be possible for the first time to systematically investigate changes in spectra or cross sections as a function of charge state for a given Z or as a function of Z for a given charge state or isoelectronic sequence.

The equipment that is required to do this rests for the most part on ion sources and accelerator technology developed for use in high energy and nuclear physics laboratories. To successfully implement crossed or merged beam experiments will thus require adding new weapons to the arsenal of the atomic physicist. This requires the addition of physicists skilled in these techniques to groups interested in doing atomic physics experiments. It must also be recognized that the apparatus is relatively large and complex and that as a result the cost of building and operating such devices is much larger than the costs generally entailed in doing atomic physics experiments.

As an example the cost of purchasing or constructing an ECRIS or EBIS source will be of the order of $1,000,000. If a storage ring of the synchrotron type mentioned is considered for storing ions from the ion source, then an additional construction cost of perhaps $5,000,000-$7,000,000 could be anticipated. The operating costs will also be non-negligible since replacement parts and several technicians and scientists would be needed to develop the capabilities and to keep it in good operating condition.

Our group at BNL, as discussed above, is developing experiments that are aimed at studying ion-photon interactions in a very general way. Some of them should be running during the course of the next year. At the same time we are trying to make more detailed studies of the APIPIS storage ring and proposing that it be constructed on an insertion device beam line at the NSLS.

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TABLE I

LUMINOSITIES FOR DC HEAVY-ION BEAM EXPERIMENTS

	L (cm^{-2}-s^{-1})
Tandem beams + 10^{-3} Torr gas target, 1 pnA	2×10^{23}
Crossed electron-beam experiment Fe^{15+}; 2A electron beam	2×10^{20}
Merged electron-beam experiment Fe^{15+}; 2A electron beam	5×10^{19} per cm of of length, assuming 1 cm^2 beam area
DC ion-ion crossed beam experiment Fe^{15+} - 1 pnA @ 10 MeV Ar^{+} - 10 μA @ 20 keV	10^{17} 1 mm^2 beam area

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TABLE II

LUMINOSITIES FOR EXPERIMENTS WITH PULSED HEAVY IONS IN CRYRING

	L (cm^{-2}-s^{-1})
Crossed ion-ion beam experiment	10^{20}
Merged proton beam experiment	5×10^{16}
Merged electron-beam experiment	1.5×10^{24}

FROM: CRYRING REPORT
RESEARCH INSTITUTE OF PHYSICS
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TABLE III

LUMINOSITIES FOR COLLISION EXPERIMENTS WITH

LOW-VELOCITY MULTIPLY-CHARGED IONS

	L (cm^{-2}-s^{-1})
Assume GAS TARGET:	
1-cm long - 10^{-3} Torr	
n_τ = 3.5×10^{13}	
Hammer beams	$\approx 10^{21}$
PHOBIS at NSLS	
25-pole wiggler - 10^8 atoms/sec	3×10^{21}
EBIS @ 100 Hz for 100 pnA	$\approx 2 \times 10^{25}$
(Ions have higher energies are less monoenergetic)	

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TABLE IV

LUMINOSITIES FOR PHOTON - HEAVY-ION EXPERIMENTS WITH NSLS SYNCHROTRON RADIATION

Monoenergetic photons = 10^{15} cm^{-2} - ARC Source

	L (cm^{-2}-s^{-1})
Gas target	3.51×10^{28}
PHOBIS target	10^{22}/cm length
Singly-charged ion source - 10 keV, 10 μA	3×10^{22} 1 mm height
ECR for crossed beam experiment 100 pnA; 10 keV/amu	$\approx 4 \times 10^{19}$ 1 mm height
EBIS crossed beam experiment 100 pnA; 10 keV/amu	$\approx 4 \times 10^{19}$ 1 mm height in cross over

APIPIS = Storage Ring + NSLS, ion energy=10 MeV/nucleon:

Total of 4×10^{8} ions in ring; 30 bunches total include duty cycle	1.5×10^{22}
Additional factor of ≈ 25 with use of insertion device - 25 used here	$\approx 4 \times 10^{23}$

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FIGURE CAPTIONS

Figure 1. Time evolution of charge states produced by irradiating a Kingdon trap with synchrotron radiation. See Ref. 1 for other details.

Figure 2. Possible arrangement for APIPIS on a NSLS beam line. The squares represent one meter intervals. The synchrotron storage ring shown is the CRYRING machine to be built at the Institute of Nuclear Physics in Stockholm. The size of the ring is largely dictated by the need for straight sections that contain apparatus needed for experiments and machine operation.

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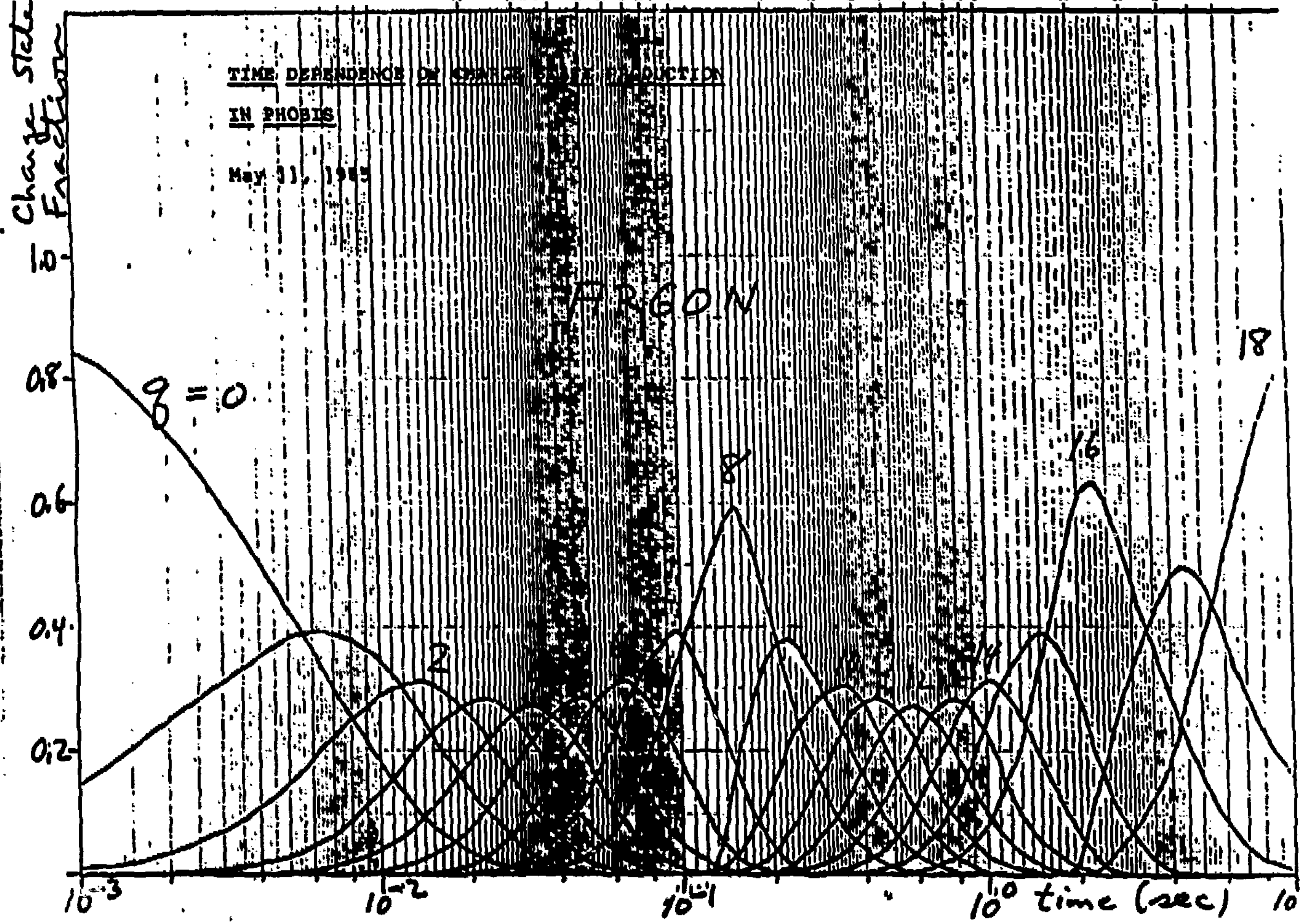

Figure 1

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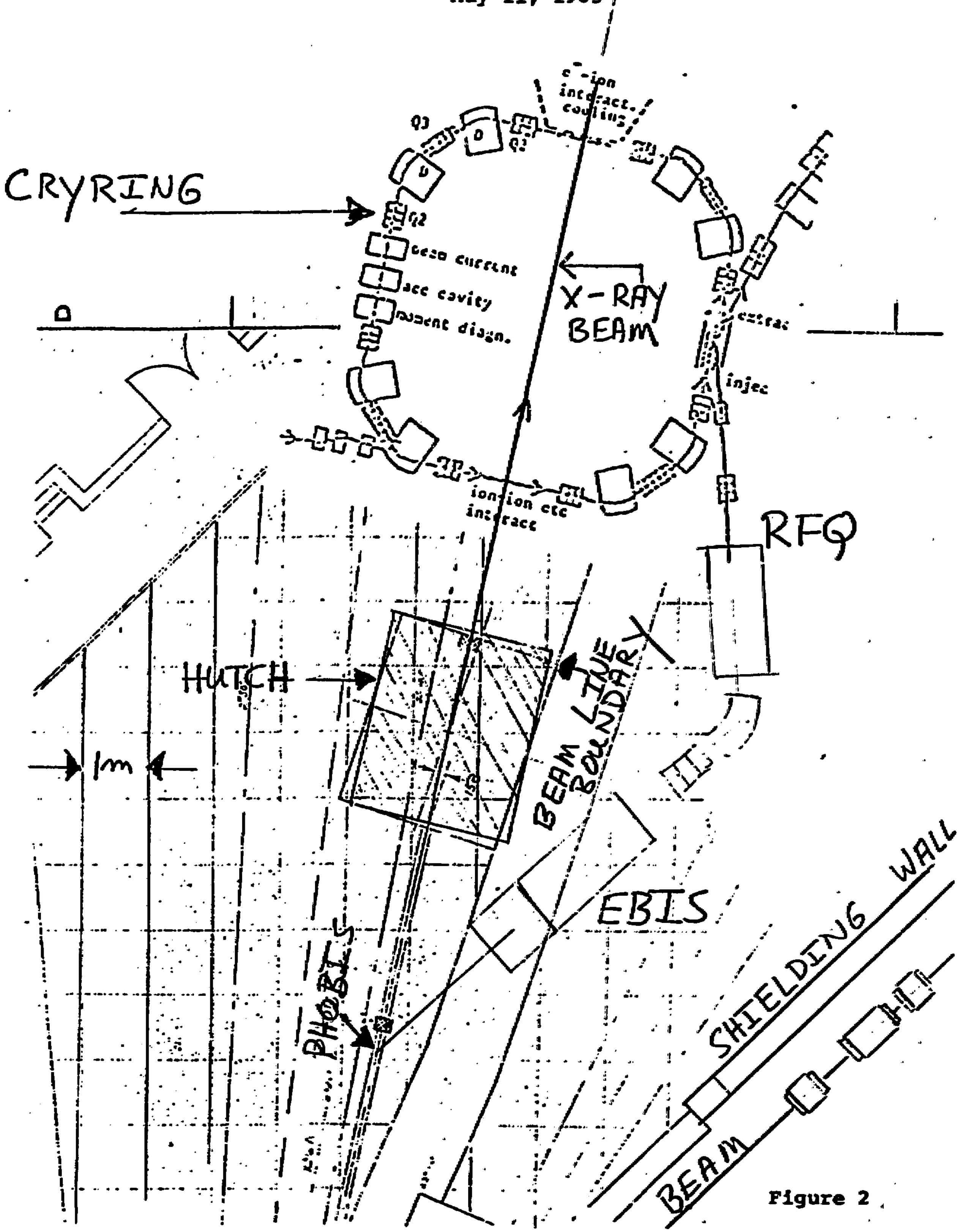

Figure 2