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Design Considerations for a Combined Synchrotron-Light Source and
Heavy-Ion Storage Ring Atomic Physics Facility

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Design Considerations for a Combined Synchrotron-Light Source and
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ABSTRACT

An Atomic Physics Facility (APF) based on the combination of photons produced by a synchrotron light source with heavy ions in a storage ring will open the way to the study of ionic states of almost all elements. The design considerations for such a facility are discussed in terms of the use of synchrotron radiation for photoexcitation and ionization experiments. Design considerations for an APF are given in terms of the accelerator facilities presently available at BNL which include the National Synchrotron Light Source and Tandem Van de Graaff Laboratory. The results show that the concept is valid and therefore that implementation would result in entirely new capabilities for the study of multiply-ionized atoms.

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1. Introduction

Investigations of the physics of multiply-charged ions is important in atomic physics and other fields of science [1]. Experiments have been traditionally difficult or impossible to perform because the production of the ions has been limited by the types of ion sources available and by the low yield inherent in crossed or merged beam experiments. Methods for ion production have advanced greatly with the comparatively recent widespread use of high-energy heavy-ion accelerators to produce ions by stripping or recoil and by improvements in the technology used in electron-cyclotron resonance sources (ECRIS) or electron-beam ion sources (EBIS) [2]. Only within the past few years have there been proposals made which would dramatically improve the luminosity (reaction rate per unit cross section) for ion-electron or photon collisions. The method proposed uses a synchrotron accelerator to accelerate the ions from a source to a high energy where they can then be stored in the synchrotron ring for extended periods of time for experimental use. The effective current of the ions is then given by the number of ions stored in the ring times their revolution frequency. For typical rings this frequency will be about $1-2 \times 10^6 \text{ s}^{-1}$ and the number of ions around 10^9-10^{10} . An effective current of approximately 1 particle milliampere (pA) can then be obtained, an increase of $\sim 10^6$ compared to the typical values in the pA range for very highly ionized atoms. More precise and detailed experiments of an entirely new scope should become feasible when these rings are implemented in the course of the next few years.

While these first generation rings will provide higher luminosities for several types of experiments, they are not the complete answer to the needs of the field. It has been pointed out [3] that it is also equally important to be able to probe the ions with photon beams of tunable energies. This can

only be done efficiently over an extended energy range by using the photons produced by a synchrotron light source.

The ion rings that have been discussed to date can be considered as FIRST GENERATION rings with limited capability that does not include the use of high-energy photons as an ionic probe. Here, some of the design parameters for a SECOND GENERATION ring facility, one that can be used with either electron or photon probes, are presented. The second generation ring will be associated with an electron storage ring that is used as a synchrotron light source (SLS) to produce high-brilliance beams of photons over a wide energy range. The brilliance achievable by an SLS [4] has now reached the point where such a conjunction of advanced accelerators is conceivable. The combination of capabilities that such a complex would present would be the basis for a unique type of new atomic physics facility (APF) that would make entirely new types of detailed investigations of atomic structure and collisions feasible. Some of the scientific possibilities for an APF have recently been outlined both informally [5] and formally [6].

2. Elements of the Atomic Physics Facility

The Atomic Physics Facility (APF) is intended to provide the means for measurements of the interactions of highly-ionized atoms with photons, electrons, ions, and atoms. The APF must then comprise sources that provide photons, ions, and electrons that can be employed for these measurements. The concept can be illustrated in concrete terms by making use of the facilities now in existence at Brookhaven.

The proposed source of photons is taken to be a superconducting wiggler on the X-13 port at the x-ray ring of the National Synchrotron Light Source (NSLS). Multiply-ionized atoms will be provided by the BNL Tandem Van de

Graaff Facility and stored in a storage ring located close to the NSLS. In addition to the larger components, conventional electron sources and ion sources will be used. A site diagram showing the arrangement of facilities is given in fig. 1. A view of the location of the proposed APF on the NSLS x-ray ring is shown in fig. 2. An expanded view showing the actual APF experimental arrangement is given in fig. 3.

The APF is a complex facility that requires the juxtaposition of state-of-the-art storage rings for electrons and photons. There are only a few locations where suitable physical facilities now exist for the APF. The NSLS and BNL tandem facilities are excellent examples of the levels of achievement in their categories. The use of BNL as an illustrative example is thereby justified since almost no other location contains these two starting ingredients.

3. Production of heavy ions

The production of multiply-charged heavy ions can be achieved in several different ways. The most direct way is to use a stand alone source of highly-charged ions such as ECRIS or EBIS [2]. Another effective method is to use beams from a Tandem Van de Graaff Accelerator that have been stripped at high energy to a high degree of ionization by a post-acceleration interaction with a foil or gas.

At the present time the charge states and beam production with the ECRIS and EBIS sources are more limited than with a tandem. The relative virtues for the various approaches were evaluated during preparation of plans for a Relativistic Heavy Ion Collider (RHIC) [7]. The results of this evaluation favored the use of the tandems for injection into the AGS. Hence, in this discussion, the source of ions was also considered to be the BNL Tandem

Facility. For simplicity, it is further assumed that only a single accelerator is used and that it has a terminal potential of 15 MV. This is a realistic assumption based on present operating conditions for production of heavy ions for injection into the BNL Alternating Gradient Synchrotron (AGS).

The performance of a 15-MV tandem for ion production is shown in fig. 3. The charge states, velocity, and final energy of the beams are given in table 1 for two cases: (1) for stripping only at the terminal in the accelerator (Q_T) and (2) for terminal plus post-acceleration stripping (Q_F). S_T and S_F are the corresponding stripping efficiencies.

The beams which are produced by the tandem are well suited for injection into a synchrotron storage ring. It is possible to operate the machine in a pulsed mode with ten 300- μ s long pulses per s. The pulsed operation makes it possible to efficiently fill the storage ring with the maximum number of ions that are permitted by space charge and phase space considerations. The beam quality is excellent with a transverse emittance that is less than 1π .mm.mrad with an energy stability which is better than 1 part in 10^4 . If post-acceleration stripping is needed, there will be an increase in the emittance by about 1π .mm.mrad so that the final value will be $\sim 2\pi$.mrad. The use of the stripper will also introduce a larger energy spread in the beam because of energy straggling in the stripping foil. For a heavy element, such as gold, the rms momentum spread will be about $\Delta p/p = \pm 0.05\%$.

4. Storage of heavy ions

Oxygen ions have recently been accelerated and stored at 14.6 GeV/u in the Alternating Gradient Synchrotron (AGS) at Brookhaven and at 200 GeV/u in the Super Proton Collider (SPC) at the European Center for Particle Physics (CERN)

[8]. The SPS is limited at present to no heavier than oxygen ions, while the AGS with injectors from the BNL tandems is limited to no heavier than sulphur ions. The extension of the method to heavier atoms at lower energies is of great importance to atomic physics because it represents a way in which the effective ion currents can be dramatically increased over conventional methods. If electron cooling can be used, it will also be a way in which very monoenergetic ions can be produced. As a result, storage rings have been designed at a number of laboratories; among them are: Heidelberg, Stockholm, GSI, Aarhus, and Oak Ridge [9].

The designs differ in details, but the various lattices that have been put forward produce beams of comparable quality. Fig. 4 shows a possible ring that could be used at the NSLS. The resulting beam parameters from a preliminary look at the ring optics are shown in fig. 5. These lattice parameters are based on the experience gained in working on the design of the heavy-ion booster synchrotron proposed for use in the BNL relativistic heavy ion collider (RHIC) project. The results are similar to the values for the designs put forward by the other groups. The important point is that existing accelerator design technology is capable of producing ion beams that have a spatial extent of several mm in diameter thus making them suitable for use with intersecting beams of electrons or photons.

Much attention has been given to estimating the lifetimes of the stored ions. The lifetime is very sensitive to the value of the vacuum in the ring since ions are lost after collisions where they gain or lose an electron. Calculations indicate that vacuums in the range of at least 10^{-11} Torr will be needed. This appears to be feasible, but will clearly be a major challenge in the actual construction of the accelerator. Note that the results of the calculations are extremely sensitive to values for electron capture and loss

cross sections assumed and that it is essential to have accurate experimental data for a range of ions, charge states, and energies.

The energy of the ions that can be stored in the ring assuming the equilibrium charge-state distributions shown in table 1 are displayed in fig. 6. Values are given for operation of the ring at 2 T-m and 0.07 T-m. Operation of the ring for storing ions of different charge states and energies to match different experimental needs is thus possible.

Fig. 7 shows the number of post-stripped and unstripped ions that can be stored in the ring as a function of mass number. The values were calculated assuming the space charge limit at tandem energies for a tune shift of 0.3. This tune shift is larger than the one that might be taken from theory, but is based on operational experience at the AGS.

The number of ions that can be stored as a function of energy is of crucial importance since it will in the end be a factor in the achieved reaction rates in intersecting beam experiments. Fig. 8 shows the number of Cu^{21+} and Au^{33+} ions that can be contained in the ring as a function of energy per nucleon. Values are given for the space charge limit with a tune shift of 0.3, as above a value based on operation experience with the 30-GeV AGS; for the Keil-Schnell stability limit for $\Delta p/p = 10^{-4}$ and impedance caused by space charge which is important to the electron cooling of the beam; and for an uncooled beam. Operation of the ring at as high an energy as is consistent with the needs of a given experiment will then give the maximum ion current.

A unique need for the APF is to correlate the operation of the ring with the time structure of the photon bunches produced by the NSLS. The NSLS x-ray ring can be operated with 1 to 30 bunches in the ring. The transit time around the ring for a single bunch is 567 ns. If the x-rays are produced in the single bunch mode and the heavy ions in the other ring are also stored in

a single bunch, then the revolution times for the two rings should be the same in order to overlap the two bunches. The values of ion energies required to fulfill this condition for different ion ring sizes is shown in table 2. The minimum size for the ring is set by needs to provide room for injection and for experiments and is felt to be around 20-30 m in circumference. It can be seen that the ion energy required is around 15 MeV/u which can be achieved with a ring operating with magnetic rigidities in the 2-3 T-m range. Energies that can be obtained directly from the tandem are of the order of a few MeV/u so that acceleration in the ring will be necessary in most cases. Matching of the bunch width in the NSLS of about 1.9 ns should also be feasible.

The combination of the tandem Van de Graaff ion source system with the heavy-ion ring described here gives performance figures which are close to those of other projects. In all of the proposals, the performance of the ring is limited by the ion source. In all cases, however, the ion source could be replaced, if methods for producing the ions improve in the future.

In picking parameters for the ion ring, it is first necessary to settle on the circumference. A circumference of 30 m is a conservative choice in terms of the space demands. This then determines a value for the energy of the stored ions of 14.8 MeV/u if the revolution times for the ions and electrons in the two are the same. More generally, the two rings can be operated on harmonics of the fundamental frequency of (1/567 ns) 1.76 MHz. This statement can be expressed as:

$$M f_{\text{NSLS}} = \frac{\beta_{\text{ion}} \cdot c}{L} N$$

where M and N are the integers defining subharmonics or harmonics of the fundamental NSLS frequency and the ion frequency. β_{ion} is given by v_{ion}/c , and L is the ion ring circumference. At the NSLS values of $M = 1, 2, 3, 5, 6, 10, 15$, or 30 are used. That is, there are between 1 and 30 electron bunches in the ring. The ion ring can be operated either with $N = 1, 1/2, 1/3, 1/4, \dots$ or $N = 2, 3, 4, \dots$ for energies smaller or larger than 14.8 MeV/u , respectively. Choice of operating conditions can also reduce the luminosity for the ion-photon interactions since a complete overlap between the ion and photon bunches is not necessarily preserved.

5. Cooling of stored heavy-ion beams

The momentum distribution in the heavy-ion beams can be reduced by the use of electron-cooling methods [10]. The cooling will reduce the momentum spread in the ion beam so that the ions are in temperature equilibrium with the electrons. In this way it should be possible to carry out merged beam experiments with very high energy resolution. A second advantage is that Doppler broadening of fluorescent radiation from the ion is very strongly reduced. As Deslattes has pointed out [11], very high resolution x-ray energy measurements can be considered for new experiments that can be used to check the predictions of quantum electrodynamics with greater precision than is now feasible. The drawback to these experiments is that in order to cool the beam, it is necessary to accept a reduction in the number of stored ions by many orders of magnitude.

The use of cooling is not, however, essential for many types of experiments. For example, the ions circulating in the ring can be excited or ionized and the electrons and photons emitted in the decay studied using several different types of detection methods. In these cases the energy

spread of the circulating beam will have minor effects on the measurements. It should thus be possible to investigate in great detail the atomic structure and lifetimes of particular states in the ion of interest.

6. Photon beams from a synchrotron light source

Photon beams to be used with the APF are a crucial part of the facility. For purposes of illustration we will assume that the APF is based on an existing SLS: The National Synchrotron Light Source (NSLS) at Brookhaven. We will further assume that it is operating at the energy and stored current specified in the original design, that is, at an energy of 2.5 GeV and a current of 500 mA.

The APF should be designed using an insertion device, be it undulator or wiggler, rather than a bending magnet radiation source. In the present paper the use of a wiggler is assumed since it gives increased radiation intensity and a shift of the spectrum to higher energies. It promises to make it possible to photoionize all elements in the periodic table with high probabilities. The spectrum from the undulator is more restricted, but may have special properties compared to the wiggler that would make it preferable for some applications. The use of the undulator will be considered elsewhere.

As a specific example, we will assume that a superconducting wiggler with 6 poles is used. This wiggler has been designed for use on the NSLS x-ray ring on the X-17 beam port and will be installed for use there during 1987 [12]. The parameters for it can therefore be considered as conservative and not as stretching the state of the art in any way. It should not be thought of as necessarily an optimum design for the SLS. This design could be reproduced on the NSLS X-13 beam port which is presently unassigned, or of

course, any other SLS and wiggler combination with similar parameters could be considered.

The properties of the NSLS 6-pole superconducting wiggler are given in table 3. The wiggler source flux and brilliance calculated by Shenoy and Viccaro [13] are shown in fig. 9. These quantities are the ones that determine how many photons can be delivered to a target under the different operating conditions called for with the APF. As one reference value to consider, if the ion beam has a size of the order of 1-2 mm, then the photon beam size should be approximately the same in the vertical direction, but can be used over a horizontal opening angle of several mrad. The size of the ion ring involved probably will preclude an arrangement with close proximity of the two beam orbits because of interferences with experiments on neighboring x-ray ports. Hence, a typical distance from the electron ring to the ion ring seems to be about 60 m. The vertical size of the beam for an opening angle of 1 mrad would then be 6 cm and focussing should be used for maximum intensity. The brilliance figures are therefore important. The vertical profile of the photon intensity is shown as a function of vertical opening angle for several different photon energies in fig. 10. For each energy, the curve is normalized to its value on the photon beam axis.

7. Photon beam line design

The APF will consist of a number of different experimental stations. Provision should be made for experiments using either white or monoenergetic radiation, and for experiments that use neutral targets or beams from low-energy ion sources. The white beams will also be useful for production of multiply-charged ions at very low energies. Use of traps and repetitive ionization (PHOBIS) [14] will make it possible to attain charge states

substantially greater than those that have already been observed [15,16]. The very low energies of the ions will make it possible to open up a whole new field of hot ion-atom chemistry and spectroscopy. The use of side ports on the wiggler should make it feasible to use several of the stations at the same time as the photons are used for experiments with the ions in the storage rings.

The equipment used for the beams that are intended for interaction with the ions will need to be diverse to reflect the differences in properties of various energy photons. Methods for handling photon beams up to 20 keV are now reasonably well advanced. A mirror which is capable of focussing radiation from about 3-20 keV with an acceptance angle of a few mrad should be easily attainable. The technological question of how to handle the peak white beam power (3.8 kW/mrad^2) incident on a mirror or monochromator is only now starting to be addressed. A magnification of about 1 should produce a focussed photon beam of a mm in size so that the photon beam size would match the size of the circulating ion beam without trouble. The actual type of mirror would be chosen to fit the experiment. If the maximum number of photons are wanted, then the focussing need be done only in the vertical direction. If a well-defined horizontal spot is needed for lifetime measurements, this could be obtained using slits or with a double focussing mirror. Use of photons in this energy range would permit ionization of the L-shell of elements to around uranium.

Production of beams at higher energies will be more difficult. The use of mirrors will be impossible because of the small grazing angles required and stringent figure and surface finish which are necessary. The focussing requirement is diminished, however, because the vertical opening angle is smaller (see fig. 10) at the higher energies. It should be possible to

effectively use perhaps 10% of the beam at the higher energies without recourse to focussing at all. Hence, use of the white beam to ionize the K-shell will be feasible. It can, therefore, be concluded that the ionization of K-shell electrons with the wiggler radiation will be possible to the range of 100-keV photon energy. Studies of the atomic structure of all shells of elements to the region of about lead or above will therefore also be possible.

It will be desirable to measure some variables as a function of photon energy. The production of monochromators in the low energy range is standard. Use of crystals or multilayers will make feasible beams with variable energy resolution from a few eV to a bandwidth of a few per cent. The efficiency of the system should be very high, and the resolutions for silicon, for example, should be of the order of a few eV. The resolution of the photon beams will be worse than those that can be achieved for the electron beams, but will be perfectly adequate for many applications. Studies of an atomic process and its inverse with good energy resolution for all channels will be possible. The presence of photons of all energies from the ultraviolet to hard x rays enables measurements from the K-shell to the outer shells in most elements.

8. Photon flux at ion ring

The crucial question that is involved in the design of the intersecting ion-photon beam facility is the photon flux at the point of intersection of the two beams. The actual numbers can be estimated from the information given above.

For the low energy region it is assumed that 5 mrad can be employed in the horizontal plane and that it will be possible to focus the beam to an

image size of 1 mm $\times$ 1 mm. Inspection of fig. 9 shows that it will be possible to deliver 10^{15} photons/s/0.1% BW from 1 to 20 keV under those conditions. This corresponds to a photon flux of 10^{17} photons/s/cm⁻² in a .1% bandwidth over that energy region. The number will decrease at higher energies mainly from increasing problems in the x-ray optics and not from a decrease in the production rate at the source. The value that can be achieved at 100 keV should therefore be down by 1-2 orders of magnitude when compared to the values below 20 keV. It should be possible to partially compensate for this by using a wider acceptance angle in the horizontal plane.

9. Luminosities for ion-photon interactions

Values that have been given for the ion ring performance and for expected photon fluxes at the ion orbit now make it possible to give an estimate of the luminosities that can be expected for this arrangement of accelerators. Luminosity is defined in the standard way as the interaction rate per unit cross section and is thus the product of the areal density of one beam with the total number of particles in the other.

As an example, we can consider the case of a merged beam experiment where a total photon current of 10^{15} photons (.1% BW) is merged with the total number of ions in the ring. This corresponds to the single bunch mode of operation for both ions and photons. The maximum value for the luminosity is obtained for a merged beam experiment and is just the product of the photon current and total number of ions. The luminosity under these conditions is then 10^{23} interactions/s/cm². Typical cross sections for photoionization of the K-shell for elements with atomic masses up to 100 are approximately 10^{-20} cm² which gives an interaction rate of 10^3 s⁻¹. For heavier elements the cross sections for L-shell excitation are larger by about a factor of 10,

and for M-shell excitation are larger by a factor of 100, compared to the K-shell case. The interaction rates would be increased by corresponding factors.

For cases where it is necessary to produce only the maximum number of interactions, the restriction on the bandwidth of the photon beam can be relaxed with a resulting increase in the interaction rate. This can be easily seen by inspection of the photon flux distribution for the superconducting wiggler shown in fig. 9.

The luminosity is reduced if intersecting and not merged beam geometries are used. The intersecting geometry is attractive since it gives a well-defined interaction region and since it makes possible the use of two straight sections in the ion ring for experimental purposes. The luminosity in a case where the common length of the intersecting beams is 1 cm is around 10^{21} to $10^{22}/\text{s}/\text{cm}^2$ depending on the momentum resolution assumed for the ion beam. These calculations took Ar^{17+} as an illustrative case with 8×10^8 to 10^{10} stored ions. Either assumption gives rates which are high enough to make experimentation relatively straightforward.

10. Scientific program

The scientific program than can be undertaken at the APF is vast, and a description is beyond the scope of the present work. Some particular thoughts on the possible uses of the photon probe are contained in the work cited in refs. [5] and [6]. The possible applications of the storage ring with electron beams are presented in the workshop proceedings listed in ref. [10].

11. Summary and conclusions

The possibility of using synchrotron radiation up to 100 keV for studies of the interaction of photons with multiply-ionized atoms has been examined. In order to emphasize that this type of work can be carried out using existing synchrotron light sources, a particular facility based on the use of the BNL MP Tandem Van de Graaff Facility for injection of a heavy-ion storage ring located at the BNL National Synchrotron Light Source is considered. Some of the design considerations most important for the problem are considered, and an estimate is given of the luminosities that can be achieved for intersecting photon-ion beam experiments. The design parameters for the ion storage rings have been examined by a number of design teams and appear to be within the range of current accelerator technology.

The results of this examination show that the luminosities that can be achieved are high and that a great variety of experiments will be feasible. As a result, it can be concluded that the construction of the APF could be of great importance in opening the way to many new scientific opportunities in the field of atomic physics. Since there are many first-generation ion storage rings proposed and being constructed which provide electron probe facilities, it appears, in the light of the present assessment, desirable to proceed to the formulation of detailed plans for a second-generation ring which adds the use of synchrotron-produced photons as a delicate atomic probe.

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Table 1. Tandem operation parameters.¹

	Q _T	S _T %	Kinetic Energy MeV/amu	β _F	Q _F	S _F %	Current ² particle-μA
Carbon	+5	39	7.5	0.1262	+6	90	82
Sulfur	+9	36	4.7	0.1002	+14	40	20
Copper	+11	27	2.9	0.0782	+21	27	11
Iodine	+13	20	1.65	0.0595	+29	20	6
Gold	+13	19	1.0	0.0463	+33	17	5

¹Ref. 7.

²75% transmission efficiency, 200-μA source current.

Table 2. Energy for 567 ns period as a function of ring circumference

Circumference m	Energy MeV/u
1	.016
2	.065
5	.41
10	1.64
20	6.56
30	14.76
50	41.01

Table 3. NSLS superconducting wiggler magnet and storage ring parameters.

Ring Operating Parameters

Energy (GeV)	2.5
Electron Current (mA)	500
Electron Beam Characteristics	
Source Size $\sigma_x \times \sigma_y$ (mm ²)	0.3 × 0.02
Angular Divergence $\sigma'_x \times \sigma'_y$ (mrad ²)	0.24 × 0.04

Magnet Parameters

Maximum Field (T)	6
Number of Poles	6
Period (cm)	17.4
Magnetic Strength Parameter K	97.5
Length (m)	1.4

Photon Beam Characteristics

Critical Energy (keV)	24.9
Total Radiated Power (kW)	37.9
Power per Horizontal mrad (kW)	1.2
Peak Radiated Power (kW/mrad ²)	3.8

Figure Captions

- Figure 1. Site diagram of Brookhaven National Laboratory showing the locations of the Tandem Accelerator Laboratory, the National Synchrotron Light Source, and a possible heavy-ion storage ring. Facilities of this type could form the basis of a versatile Atomic Physics Facility.
- Figure 2. Schematic diagram showing a possible arrangement for atomic physics facilities at the National Synchrotron Light Source.
- Figure 3. Expanded scale view of the Atomic Physics Facility as it could be installed at the National Synchrotron Light Source.
- Figure 4. Stored ion energy as a function of mass number for an ion storage ring operating at .07 and 2.0 T-m. The injected ions are produced by a 15-MV Tandem Van de Graaff Accelerator as shown in table 1. Curves are given for ions stripped or not stripped after acceleration through the tandem.
- Figure 5. Diagram of the lattice of a possible heavy-ion storage ring. The circumference of the ring is about 26 m. The injection section and rf acceleration cavity are placed opposite to each other. The remaining straight sections will be available for experimental apparatus. The magnets denoted QD and QF are defocussing and focussing quadrupole singlet magnets, respectively.

Figure 6. Calculated values of the Courant-Snyder parameter, β_x , β_y , and the dispersion function, x_p , are shown as a function of distance along the heavy-ion ring lattice. The dispersion function is defined as the ratio of the change in radial beam position, Δx , to the fractional change in momentum, $\Delta p/p$; that is, $x_p = \Delta x/(\Delta p/p)$. The results show that the ring can produce a beam suitable for the experiments discussed here. Values for β_x are given by the solid line, β_y by the dashed line, and x_p by the dotted line.

Figure 7. The number of ions stored in the ring are shown as a function of mass number. The stripped and not-stripped curves refer to ions which have or have not undergone post-acceleration stripping. The number of stored ions is assumed to be limited by space charge at tandem energies used for injection.

Figure 8. The number of ions stored in the ring are shown as a function of the ion energy in MeV per atomic mass unit for Cu^{+21} and Au^{+33} . The assumptions made for the calculations are shown in the figure.

Figure 9. Values for the photon flux and brilliance are shown as a function of the photon energy for a 6-pole superconducting wiggler. The results of Shenoy and Viccaro were used (ref. 13).

Figure 10. Vertical profile of the photon intensity produced by the 6-pole superconducting wiggler is shown as a function of vertical opening angle for several different photon energies.

Figure 1

Figure 2

Figure 3

Figure

Figure

Figure 7

Figure 9