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WITH SYNCHROTRON LIGHT SOURCE ATTACHMENT

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ABSTRACT

The combination of a heavy-ion storage ring with the intense photon beams from a synchrotron light source present new opportunities for research in atomic physics. At Brookhaven a design for such a facility has been proposed as the basis of a comprehensive National Atomic Physics Facility. Vacuum considerations are an important factor in its performance since the storage time of the heavy ions in the ring is vacuum-dependent. A vacuum system design for attainment of pressures of order 10^{-11} Torr in the heavy-ion ion storage ring is discussed. The photon source will be the x-ray ring of the National Synchrotron Light Source, and the heavy-ion source will be the BNL Tandem Van de Graaff Accelerators. Differential pumping between components of the facility will allow for different pressures in the ion source, accelerators, transfer lines, and storage rings. For some experiments it may be useful to have gas jet or vapor targets in experimental sections viewed by detector systems that are not suitable for use in ultrahigh vacuum systems. Possible solutions to a wide range of vacuum problems are discussed.

INTRODUCTION

The three basic components of a proposed National Atomic Physics Facility (NAPF) are (1) a photon source, (2) a heavy-ion source and accelerator, and (3) a heavy-ion storage ring. The first two already exist at Brookhaven. They are the x-ray ring of the NSLS and the Tandem Accel-Decel Laboratory (TADL). The third component, a new heavy-ion storage ring, is being designed, and a feasibility study is now in progress.¹ The Cooled-Heavy Ion Storage Ring (CHISR) will be a unique new instrument for atomic physics studies of high-luminosity interactions between energetic photons and highly-charged heavy ions. A schematic diagram of the concept is shown in Figure 1. The vacuum conditions which must be met in CHISR are stringent since heavy-ion storage times are a critical function of pressure. A discussion of the vacuum considerations for each of the major components and the transfer line for heavy ions and photons is presented.

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Fig. 1. Schematic diagram of the Atomic Physics Facility showing the relationship of the several components. The vacuum needs for each section are summarized in Table I.

SYSTEM COMPONENTS AND PRESSURE SPECIFICATIONS

The overall APF contains a number of different components, each of which have specific vacuum needs. The subsystems are: ion source, tandem accelerator, heavy-ion transfer line, heavy-ion storage ring, photon beam line, and ring-experimental interaction region. The vacuum requirements for each component and the type of vacuum pump used are summarized in Table I. Some of the special design needs are discussed below.

Table I Components of the Combined Heavy-Ion-Storage-Ring
Synchrotron-Light-Source Facility

Component	Operating Pressure (Torr)	Type of Pumping System Used
1. Ion Source	10^{-8}	Cryopump
2. Beam Analysis and Transport	10^{-8}	Ion pump
3. Tandem Acceleration Tubes and Transport to Analysis Magnet	10^{-7}	Turbo/cryopumps
4. Ion Transfer Line (440 m)	10^{-9}	NEG strips
5. Electron Storage Ring	10^{-9}	Ion/sublimation pumps
6. Photon Beam Line	10^{-9}	Turbo/cryo/NEG
7. Ion Storage Ring	10^{-11}	NEG strips
8. Electron Cooler Region	10^{-11} to 10^{-9}	Ion/NEG
9. Experimental Section	10^{-11} to 10^{-7}	Turbo/ion/NEG
10. RF Section	10^{-11}	Ion/NEG

ELECTRON CAPTURE AND LOSS FOR MULTIPLY-CHARGE ATOMS

The lifetime of the beam in CHISR is mainly determined by electron capture and loss processes that occur in distant collisions between the beam and residual gases in the vacuum chamber. For satisfactory operation, the ion storage times must be long compared to the fill time.

The cross sections that determine these processes are a function of the atomic number of the beam, the composition of the residual gases, and the beam velocity. Approximate capture² and loss³ cross sections are:

$$\sigma_C \approx 4\pi a_0^2 q^3 \left(\frac{v_0}{v}\right)^6 Z_T^{1/3} \quad \text{capture.}$$

$$\sigma_L \approx \pi a_0^2 q^{-3} \left(\frac{v_0}{v}\right)^2 Z_P^{4/3} Z_T^{2/3} \quad \text{loss.}$$

where a_0 = Bohr radius

v_0 = Bohr velocity

q = charge state

Z_P, Z_T = atomic number of projectile and target

The capture and loss lifetimes are

$$\frac{1}{\tau_{C,L}} = \sigma_{C,L} \rho v$$

where ρ is gas density and v the ion velocity.

When the constants are evaluated, then:

$$\frac{1}{r_C} \approx [2.7 \cdot 10^5 q^3 Z_T^{1/3} E_{(\text{MeV/u})}^{-5/2} P(\text{Torr})] \text{ sec}^{-1}$$

$$\frac{1}{r_L} \approx [1.1 \cdot 10^8 q^{-3} Z_P^{4/3} Z_T^{2/3} E_{(\text{MeV/u})}^{-1/2} P(\text{Torr})] \text{ sec}^{-1}$$

and the total lifetime is given by:

$$r = \left(\frac{1}{r_C} + \frac{1}{r_L} \right)^{-1}$$

Results of evaluating these expressions are shown in Table II for several different elements and beam energies. Even for the heaviest beams, the ion storage times are greater than 1 second, while the injection times are of the order of 0.1 s.

COMPOSITION OF RESIDUAL GAS

The results in Table II were obtained assuming a ring pressure of 10^{-11} Torr and remnant gas composition of 95% H_2 and 5% CO_2 . Any admixture of heavier elements in the residual gas will reduce the ion storage times. Measurements⁴ at the NSLS and at an existing heavy-ion transport line⁵ show that residual gases are 99% hydrogen. The assumed composition of residual gas is therefore conservative.

HEAVY-ION TRANSFER LINE

The heavy ions produced by TADL are multiply-ionized atoms with energies of a few MeV/u. They must traverse the transfer line with negligible losses from charge-changing interactions with residual gas molecules. Consider transport of Au^{13+} or with Au^{33+} at an energy of 0.84 and 1.1 MeV/u, respectively, as typical cases. The attenuation of the two ions caused by their $\approx 30\text{-}\mu\text{s}$ long passage through the transfer line is given as a function of pressure in Figure 2. It can be seen that losses will be less than 1% for pressures less than 10^{-8} Torr. This result then sets the design criteria for the maximum pressure in the transport line.

The actual solution to this problem has been considered during the design of a transfer line linking TADL and the Alternating Gradient Synchrotron (AGS).^{5,6}

Non-evaporable getter (NEG) strips are used as the UHV pumps in this system. The beam line is fabricated using conventional UHV components. It has been demonstrated that working pressures in the 10^{-9} to 10^{-10} Torr range are reached in this system, thus guaranteeing that the use of the same solution in the new transfer line to the NSLS will result in a negligible loss of ions.

Table II Charge exchange lifetimes in a ring at injection and top energies (assuming pressure of 10^{-11} Torr, with 95% H_2 and 5% CO_2)

Projectile	q	E(MeV/u)	$\frac{1}{r_C} \text{ (sec}^{-1}\text{)}$	$\frac{1}{r_L} \text{ (sec}^{-1}\text{)}$	$\tau \text{ (sec)}$
Carbon (a)	5	7.5	4.8 (-6)	8.3 (-5)	1.4 (4)
(b)	5	32.9	1.2 (-7)	4.0 (-5)	2.5 (4)
(c)	6	7.5	8.3 (-6)	*	1.2 (5)
(d)	6	47.1	8.4 (-8)	*	1.2 (7)
Sulfur (a)	9	4.7	9.0 (-5)	6.6 (-5)	6.4 (3)
(b)	9	15.2	4.8 (-6)	3.7 (-5)	2.4 (4)
(c)	14	4.7	3.4 (-4)	1.8 (-5)	2.8 (3)
(d)	14	36.3	2.0 (-6)	6.3 (-6)	1.2 (5)
Copper (a)	11	2.9	5.5 (-4)	1.0 (-4)	1.5 (3)
(b)	11	5.9	9.3 (-5)	7.2 (-5)	6.1 (3)
(c)	21	2.9	3.8 (-3)	1.5 (-5)	2.6 (2)
(d)	21	21.2	2.6 (-5)	5.4 (-6)	3.1 (4)
Iodine (a)	13	1.7	3.4 (-3)	1.8 (-4)	2.8 (2)
(b)	13	2.0	2.3 (-3)	1.7 (-4)	4.1 (2)
(c)	29	1.7	3.8 (-2)	1.6 (-5)	2.6 (1)
(d)	29	10.0	4.6 (-4)	6.7 (-6)	2.2 (3)
Gold (a)	13	0.84	2.0 (-2)	4.4 (-4)	4.9 (1)*
(b)	13	0.84	2.0 (-2)	4.4 (-4)	4.9 (1)*
(c)	33	1.1	1.7 (-1)	2.3 (-5)	6.0 (0)
(d)	33	5.4	3.1 (-3)	1.1 (-5)	3.2 (2)

(a) injection, single stripping

(b) top energy, single stripping

(c) injection, double stripping

(d) top energy, double stripping

*Below tandem energy, cannot be ramped, magnetic rigidity limit.

Fig. 2. The loss of 0.84 MeV/u ^{13+}Au and 1.1 MeV/u ^{33+}Au in the transfer line from TADL to storage ring is shown as a function of pressure.

HEAVY-ION STORAGE RING

The lifetimes of the ions stored in CHISR must be as long as possible so that experiments can be performed in a stable way and so that injection and ramping times in the ring need not be excessively fast. Lifetimes for typical ions are given in Table II for a ring pressure of 10^{-11} Torr. An average ring pressure of 10^{-11} to 10^{-10} Torr average over the ion orbit will be sufficient to give excellent performance in almost all cases.

Methods for achieving these pressures are now comparatively well known. In particular, much theoretical and experimental effort has gone into designing and constructing test systems that show how ultrahigh vacuum can be attained at proposed BNL high-energy accelerator facilities.⁷ The results of the work on prototype systems demonstrate that pressures less than 10^{-11} Torr are reached using first sorption and turbo pumps and then a combination of UHV ion and sublimation pumps. Appropriate methods for producing the needed UHV conditions for CHISR have therefore been demonstrated and known for many years at BNL and at other laboratories.⁸ NEG strips may also be employed.

PHOTON TRANSFER LINE

The vacuum requirements in the photon transfer line are too diverse to discuss in detail. Much of the proposed experimental program uses photon beam energies greater than 4 keV. In these cases beryllium windows will be used as barriers to isolate regions with different vacuum needs and ensure zero impact on the heavy-ion ring operation. Windowless operation will also be provided for use of the white synchrotron beam and focussed monoenergetic beams at energies below 5 keV. Problems in this case arise from heat loads produced by the high-power synchrotron beams. Vacuum needs can be met by the same type of pumping used in the ion transfer line.

DIFFERENTIAL PUMPING CONSIDERATIONS

The various sections of the APF operate under rather distinct vacuum conditions. The most stringent conditions occur in the heavy-ion storage ring. It will be necessary to provide efficient differential pumping sections to isolate the ring vacuum chamber from the ion and photon beam transfer lines.

There are also several regions within the ring where differential pumping will be necessary. In the experimental straight section and the following ion detection chamber, it will be necessary to use and interchange various types of experimental apparatus, detectors, and spectrometers. A degradation of the vacuum conditions should be anticipated even when care is taken in the design of individual components. Differential pumping must be provided for isolation from the rest of the ring.

The most difficult conditions will occur when a gas target must be used. Two possible cases can be identified--one is when a gas jet is used to provide a well-localized target and the other when the entire straight section can be filled for charge transfer studies. The gas jet target will require additional differential pumping, but the pressures needed when the entire straight section is used are low because of the long path length, and no additional pumping is required.

CONCLUSIONS

The proposed Atomic Physics Facility makes complex demands on many aspects of vacuum technology. The technical means for meeting these demands are well in hand. TADL and the NSLS have been operating for years and much experience has been gained in pumping heavy-ion transfer lines and in dealing with problems from heating caused by synchrotron radiation. Previously performed design and testing work at BNL have conclusively demonstrated that it is possible to reliably and relatively easily produce vacuums of 10^{-11} Torr in large vacuum chambers. Thus, based on experiment, we can be confident that the heavy-ion storage ring can be constructed and operated without difficulty. These conclusions are in accord with results from other laboratories.

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