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STORAGE RINGS FOR HEAVY-ION ATOMIC AND NUCLEAR PHYSICS

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ABSTRACT

A brief review is given of the physics goals and a few of the accelerator physics issues relevant to the new generation of small storage rings being built for atomic and nuclear physics use.

The last few years have seen a rapid growth in the number of projects to build storage rings designed for use in atomic and nuclear physics. All these projects involve some type of beam cooling. A table listing several of the projects and their status as of May 1986 is given below.

Table I

Type	Location	Bending Limit (T·m)	Status (May 1986)
"Granddaddy"	Indiana	3.6	Constr/Operating
"Small"	MPI, Heidelberg (TSR)	1.6	Constr
	Aarhus (ASTRID)	1.6	Constr
	Stockholm (CRYRING)	1.5	Constr
	ORNL (HISTRAP)	2.0	FY 1988 - DOE
	INS, Tokyo (TARN I)	2.0	Operating
"Medium"	GSI (ESR)	10	Constr
	Uppsala (CELSIUS)	7	Constr
	INS, Tokyo (TARN II)	7	Constr
	ORNL	10	Study
	LBL	9	Study
"Large"	BNL (RHIC)	835	FY 1988 - DOE

In 1985 there was one operating small- or medium-sized ring. In 1992 there will be nine to ten of these devices. In the following we attempt to give some reasons for the rapid growth in interest, physics to be pursued with these devices, and the accelerator physics issues and constraints which arise.

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The principal areas of physics of interest for the atomic physics rings (the "small" rings) can be broken into four broad areas. One area is basic studies of interest in atomic physics. This includes studies of "Lamb-shifts" in hydrogenlike ions of heavy atoms, which provide tests of perturbative and strong field QED, and of single and dielectronic recombination rates in multiply-charged ions, which provide sensitive tests of atomic structure calculations. A second area is the study of atomic exotica, such as very high- n Rydberg states, so-called "giant atoms," and multiphoton ionization. A third area is the study of electronic transitions in highly ionized heavy ions, which is of interest to the plasma physics program. This yields useful information helpful in identifying impurities in magnetically confined plasmas and for studying ways in which these impurities affect the plasma by absorbing energy from it. A fourth area is the (somewhat speculative) search for new devices. An interesting example is the proposal to optically pump a stored, highly charged ion beam. This could result in a "tuneable" (possibly lasing) light source in the ultraviolet or shorter wavelength region, depending on the bending limit of the storage ring.

Atomic physicists are led to the use of storage rings, not by center-of-mass energy considerations as are high-energy physicists, but because of the desire for improved beam currents, useful beam lifetime, and improved beam phase-space density. Heavy atoms are most easily put into high charge states by first accelerating them to energies of a few MeV/nucleon and then passing them through a thin ($10 \mu\text{g}/\text{cm}^2 \approx 1000 \text{ \AA}$) carbon foil to strip off outer shell electrons. The higher the energy, the more inner shell electrons are removed; a good estimate of the charge state obtained can be had from the Bohr velocity-matching criterion. Unfortunately, such a group of ions forms a beam which then passes only once through a target and/or apparatus. Storing the ions in a ring alleviates this problem and then allows the possibility of beam phase-space cooling. Cooling, especially electron cooling, can alleviate several of the problems of phase-space dilution resulting from accelerating and stripping very heavy nuclei. Once the atoms are stored in a ring, several advantages occur for the atomic physics program. Obviously, the magnetic elements can be adjusted to accommodate a wide variety of ions and/or different charge states for different experiments, and the magnets can be ramped to decelerate the ions to low energies ($<1 \text{ MeV/nucleon}$) of interest in atomic collision physics. By storing the beam in a ring, the effective currents for, e.g., merged photon-ion or electron-ion or crossed electron-ion experiments can be increased by four to five orders of magnitude over those obtainable in fixed-target experiments. In addition, storing the ions in a ring means time can be allocated to allow the metastable states created by stripping to decay before beginning a measurement. Finally, if one is interested in using laser beams to probe a stored beam, and if the lifetime of the excited state of interest exceeds the beam revolution time in the ring, an exposure occurring over only part of a ring circumference appears to the ion to be effectively continuous. This permits pumping a stored beam into an excited state, for example.

A graph of peak kinetic energy per nucleon vs. atomic mass number for the Oak Ridge HISTRAP project, a 2.0-Tm ring, is shown in Fig. 1.

Fig. 1

Kinetic energy per nucleon is shown for three possible injectors: the existing ORNL 25-MV tandem, which could produce beams from $^{12}\text{C}^{6+}$ to $^{197}\text{Au}^{40+}$; an electron cyclotron resonance ion source (ECRIS) coupled to an RFQ running high charge states at low current ("RFQ 1 nA") from $^{12}\text{C}^{6+}$ to $^{197}\text{Au}^{33+}$; and an ECRIS-RFQ running lower charge states at high current, representative ions being $^{12}\text{C}^{5+}$ to $^{197}\text{Au}^{20+}$ in this case. The ordinate is computed from

$$E/A \text{ (MeV/nucleon)} = [(299.79 \cdot B_p \cdot Q/A)^2 + 931.5^2]^{1/2} - 931.5 ,$$

where B_p is in tesla meters, Q is the charge state, and A is the mass number in amu.

For the nuclear physics rings ("middle" in the table), the physics issues include a broad range of topics of interest in heavy-ion nuclear physics. (The "large" project at BNL has, of course, as its goal the discovery of a quark-gluon plasma, which is discussed by Tom Ludlam in these proceedings.) One area needing cooled beams is the study of inelastic scattering, giant resonance and delta resonance excitation. These studies can be pursued cleanly using high resolution heavy-ion beams with kinetic energies in the range of 300-1000 MeV/nucleon (energies that are high enough that single-step

excitation works); these beams need energy resolutions in the range of $\Delta E/E = 10^{-4}$ to 10^{-5} , clearly requiring phase-space cooling. A second area needing considerable beam energy for heavy nuclei is the study of the equation of state for nuclear matter via the production of kaons at energies well below the free nucleon-nucleon threshold for strangeness production. Differing equations of state for nuclear matter give predictions for kaon yields that differ sharply, making the measurement a good discriminator among theories. A third area of study, which requires a sophisticated production target plus charge and mass separators, is the production, storage, and cooling of exotic nuclei far from the valley of β stability. This also requires an accelerator ring for primary beam production and a second, storage ring to act as the catcher, cooler and (possibly) decelerator. Being able to produce energetic heavy nuclei also leads to the possibility of studying "kinematically reversed" reactions, wherein a high-mass projectile bombards a low-mass target, resulting in a quite large dynamic solid angle for particle correlation experiments. Finally, a large enough accelerator ring allows producing the heaviest elements with enough energy that all or nearly all electrons can be removed by a post-stripping, meaning that the QED tests and optical pumping studies suggested above could be carried out for any element. Table II lists possible experiments, typical "heaviest beams" that might be employed, kinetic energies of interest, and finally the resulting B_p for the associated accelerator ring. Figure 2 summarizes the peak energy per nucleon performance of several proposed and existing machines; the top four curves are for synchrotrons, while the lower three curves are for cyclotrons and the "GSI" line is for the heavy-ion linac (UNILAC) there.

Table II

Topic	Beam	MeV/Nucleon	B_p (T·m)
"Subthreshold" kaon, hyperon production	$^{100}\text{Mo}^{32+}$	500-1000	11.3-17.6
Δ resonance excitation via transfer	$^{12}\text{C}^{6+}$, $^{40}\text{Ca}^{20+}$	1000-1500	11.3-15.0
Bremsstrahlung photons	$^{238}\text{U}^{43+}$	50-500	5.7-20.0
Elastic, inelastic scattering, GMR excitation	$^{40}\text{Ca}^{20+}$	300-1500	5.4-15.0
Exotic nuclei	$^{238}\text{U}^{43+}$	500-800	20.0-26.9
	$^{40}\text{Ca}^{20+}$	500-800	7.3-9.7
"Atomic physics"	$^{238}\text{U}^{43+}$	200-900	11.9-29.0
	$^{238}\text{U}^{75+}$	200-900	6.8-16.6

Table II continued

Topic	Beam	MeV/Nucleon	B_p (T·m)
Inverse kinematics experiments	$^{238}\text{U}^{43+}$	5-200	1.8-11.9
Pion interferometry	$^{20}\text{Ca}^{20+}$	700-1800	8.9-17.1
	$^{150}\text{Nd}^{50+}$	700-1800	13.4-25.7
Inverse (d,p) reactions for astrophysics	$^{238}\text{U}^{43+}$	20-200	3.6-11.9
$\gamma\gamma$ Hanbury-Brown/Twiss	$^{238}\text{U}^{43+}$	20-200	3.6-11.9
Subthreshold π^0 production	$^{238}\text{U}^{43+}$	20-200	3.6-11.9

Fig. 2

Considerations on beam brightness also motivate the construction of the medium-sized facilities. The only available facility in this range at present is the Bevalac, which is a relatively slow-cycling weak-focussing machine. Figure 3 shows desired vs. existing beam brightness as a function of mass number, with the proposed GSI, LBL, and ORNL machines' projected performance lying near the solid line shown.

Fig. 3

A number of issues confront the lattice designer for these small storage rings. Since they are designed for hadrons at moderate energies ($\gamma < 3$), no synchrotron radiation damping occurs as for the small synchrotron light sources. Thus, the maximum beam emittances (before cooling) tend to be large, of the order of $40\text{--}100 \pi \text{ mm mrad}$ for various projects. Injection into the small rings has to be by multiturn injection, charge-exchange injection being ruled out because of repeated charge state fractionation and multiple scattering in the stripping foils.

Many of the designs provide dispersion-free straights in which to locate electron-beam type coolers; whereas, others locate these in straight sections with dispersion from $1\text{--}3 \text{ m}$. There is an ongoing discussion as to which solution provides the best cooling rates. However, some of the atomic physicists wish to use the electron beams also as

electron sources for electronic recombination studies. Since changing the charge state of an ion in a straight with nonzero dispersion would result in inducing a large amplitude betatron motion, via $\chi_{eq} \Delta q/q$, a lattice to be used for such studies must have a dispersion-free straight for the cooling section. Usually 3-5 meters of free space is needed for the cooling apparatus. Beta functions of usually 2-10 m are chosen, there being the usual tradeoff between cooling rate (favoring large β) and ultimate lower limit for the emittance (favoring small β). The nuclear physics projects are also complicated by the need to allow for stochastic cooling to be able to handle the "hot" secondary beams produced by fragmentation of the heavy-ion beams from the primary accelerator.

The desire to accommodate multiple charge states also means that the ring needs a stable acceptance extending over $\Delta(p/q)/(p/q)$ of $\pm 2-6\%$. Orbit stability calculations and tracking must also include effects of magnet ends and the $1/\rho^2$ terms for these small rings. These same calculations are complicated, when sextupoles are introduced, due to the rather "lumpy" nature of the β functions and the desire to keep χ_{eq} small, leading to relatively large normalized strengths. All these rings operate below γ_{tr} , meaning sextupoles are not needed for the negative mass instabilities. However, the chromaticities ξ_x/ξ_y tend to be much larger than the tunes Q_x/Q_y , exacerbating the sextupole strength problem. Most groups are looking at lattices which use as a basic building block a doublet or triplet achromatic bend. The triplet achromat proposed for the ORNL HISTRAP project is shown in Fig. 4a. The lattice functions (focussing structure OBFDFBO) are as shown in Fig. 4b.

ORNL-DWG 86-12977

Fig. 4a

Fig. 4b

Many of the atomic physics proponents talk about quite low numbers of ions, from 10^6 – 10^{10} , in the ring for many experiments, whereas the nuclear physics projects emphasize the highest attainable currents, for example, needing 10^{11} ions/second hitting a production target to produce a useful number of radioactive secondary nuclei, 10^5 – 10^7 /s, for subsequent storage, cooling, and measurement. The atomic physics projects usually also involve deceleration of the ions to energies as low as tens of keV/nucleon. At this point, the Keil-Schnell limit strongly determines the number of ions which can be handled, given its scaling as $(\Delta p/p)^2 \beta^2 \gamma^3 (A/Q^2)$. How effective cooling is at low energies will also be strongly affected by intrabeam scattering, which is severe for very highly charged ions due to the Q^4/A^2 dependence of the Rutherford cross section. Otherwise, the number of particles which can be injected is usually governed by the incoherent space-charge limit, $\beta^2 \gamma^3 A/Q^2$, and/or the injector + ion source performance. The proposed injectors are a bewildering array of ECRIS + RFQ's, tandem electrostatic generators, heavy-ion linacs, and isotope separators injecting at energies from 100 keV to 20 MeV per nucleon, depending specifically upon the project considered.

Although the magnet and rf systems are straightforward for these projects (except for the 10:1 frequency swing often needed for the

rf system), the vacuum requirements tend to be severe. To avoid charge-changing collisions with residual gas molecules requires pressures in the range of 10^{-10} to 10^{-12} torr (nitrogen equivalent) to attain storage times of even a few seconds in the worst cases (e.g., 1-MeV/nucleon $^{238}\text{U}^{43+}$ has a single electron capture cross section of $\sim 10^{-16}$ cm², or 100 megabarns, on atomic hydrogen). The vacuum systems proposed include high temperature bakes (up to 350°C), generous use of titanium sublimation and sputter ion pumping in the magnet chambers, and NEG pumping near serious gas loads such as the anode and collector for the electron beam. Pump spacings of 3-4 meters appear to be necessary, as well as extensive chamber wall preparation, in order to preserve the possibility of an ultimate pressure of 10^{-12} torr. Due to the high bakeout temperatures, thermally insulating jackets, such as the ceramic wool type used at LEAR and the $\bar{p}$ sources, are necessary to prevent damage to magnet yokes and coils. Thin copper cooling sheets will probably have to be inserted between the thermal jackets and the yokes to keep the yoke temperatures low enough during bakeout. To allow fast (~ 2 T/s) pulsing of the dipoles, these will have to be slotted in the magnet gaps to minimize eddy current distortions of the magnet field. The whole process is made somewhat easier for the dipoles, as they often must have C-shaped yokes to allow experimenters access to the ring vacuum.

The next five years promises to be a busy period in this area of accelerator construction. The potential experiments for such rings are still being invented by the atomic and nuclear physicists awaiting the completion of the rings. Let us hope many fruits await the labors of the hundreds of people involved.