# ION SYNCHROTRONS AND STORAGE RINGS FOR NUCLEAR AND ATOMIC PHYSICS*

Robert E. Pollock
Indiana University Physics Department
Swain Hall West
Bloomington, Indiana 47405

## Abstract

Within the past decade, a number of laboratories have embarked upon construction projects having in common the application of synchrotron and/or storage ring technology to research in atomic and nuclear physics. The designs span a wide range of ion species and energies. Most of these projects plan to employ stochastic cooling and/or electron beam cooling techniques. The sudden burgeoning of interest in the application of technology originating in the high energy accelerator community has clearly been influenced by the success of cooling in test rings and in the LEAR project. Why have we so many new projects of this type? Are they likely to perform well enough to justify the current level of effort and the significant allocation of resources to the construction of these facilities? What can we say about the performance boundaries of these devices before they are in operation? The talk will attempt to summarize our present understanding of the likely behavior of these devices and will review pertinent design features. Some examples of the experimental applications which appear well-suited to the properties of these rings will be described.

## Introduction

Storage rings for electrons were a topic of great interest at the first conference in this series in 1965[1]. The high center-of-mass energy advantage over fixed targets for relativistic energies, combined with the intrinsic radiation damping mechanism to aid injection, and to control beam growth and some classes of instabilities, have allowed these lepton rings to play an important role in the history of particle physics. This role is still developing, and we now understand the strengths and limitations of the technique in considerable detail.

With the advent of stochastic and electron cooling techniques for hadron beams, the storage ring for antiproton accumulation has in its turn had a dominant influence on the recent history of this field.

In 1979, construction of the LEAR facility[2] marked a new direction, the exploitation of storage and cooling technology to manipulate antiproton beams for another purpose, to bring the energy down from the high value at production to a much lower regime where new phenomena are accessible. The excellent beam quality of the LEAR antiprotons makes possible great improvements in the data quality as well.

Within the past few years, several laboratories have made plans to construct storage rings for use with other ions which are far less rare and exotic. The characteristics and motivations for this class of new facilities are the subject of this note.

To restrict the topic to manageable proportions, little will be said about important classes of rings designed for a single purpose, including the stretcher-compressor rings used to manipulate duty factor, and the rings designed primarily as synchrotron radiation sources. Each of these classes is richly deserving of attention in its own right, and the increasing number of laboratories involved in development of such facilities adds even more cross-fertilization to the ring design field.

It is also my intention to say little about the conventional synchrotrons used primarily as beam sources for external target work. These continue to be the workhorses of the accelerator field for energies above a few hundred MeV, and are the source of much of our understanding, for example, of nuclear reactions with kaons.

I want to review the growing list of rings being planned, or now under construction, which have been influenced by the ideas of beam cooling and its application to nuclear and atomic physics research. The energy, mass, luminosity, and beam quality ranges made accessible by storage and cooling are to be considered as free parameters to be determined by an overlap of the interest of the user with the properties of the accelerator physics governing the application.

Since our practical experience is at the moment restricted to the operation of LEAR, of three earlier test rings (alas, none of which is still in operation), and of rings built primarily for accumulation purposes, the performance boundaries can at best be estimates guided by extrapolations from our present understanding of the limiting phenomena. In a few years we will have access to much more detailed results from operation of the rings in this new family.

## Classification by Loss Mechanism

The new world of these little rings may be divided naturally into two classes by the behaviour of two cross sections. Consider a beam of charge $Z_b$, mass A, & kinetic energy E striking a target of nuclear charge $Z_t$. Coulomb scattering, which varies essentially as $(Z_t \cdot Z_b/E)^2$, gives a mechanism for emittance growth and for the loss of stored beam particles by outscattering through interaction with residual gas in the ring or with internal target material.

There is a much more rapidly varying cross section for pickup of an electron by a fully stripped beam particle from residual gas or target material. This cross section[3] varies approximately as $(Z_t \cdot Z_b)^4/(E/A)^5$ and thus becomes the dominant loss mechanism for lower energies and heavier ions.

At lower energies where pickup losses predominate, the luminosity can become so low that nuclear studies, with a few interesting exceptions, are generally impractical. The reaction cross sections are too small, and life is short.

Using the energy at which losses by single Coulomb outscattering and by electron pickup are comparable as the dividing line, we identify a first class of rings which use low energies and heavy ions to explore atomic phenomena with atomic cross sections, and a second class of rings, using lighter beams and higher energies, where the reduced losses allow luminosities appropriate for studies of nuclear processes.

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The influence of loss cross section on luminosity arises from particle number conservation. The ring must be refilled on the average at the same rate that beam is lost, and the refilling rate is itself limited either by the intensity of the injector or by the ratio of maximum number of particles stored to cycle time.

## Classification by Cooling Process

There is a weaker practical subdivision of the higher energy rings into subclasses, depending on whether the beams of interest have energies low enough to allow electron cooling. Since there is active development work underway at at least three sites to raise the technological limit on the voltage of electron cooling devices, this boundary must, for the moment, be considered somewhat time-dependent.

Stochastic cooling has no energy boundary and the use of this technique may be considered in both classes of rings. However there is an important difference in the cooling rate between electron and stochastic cooling. To stay below the threshold for driving coherent instabilities, the gain of a stochastic cooling system must be reduced as the number of stored particles is increased[4]. So the stochastic cooling force will be weaker for high stored current. As far as we know, electron cooling is largely independent of the stored current, although the critical tests of electron cooling with more than a few times $10^9$ particles have yet to be carried out.

The strength of the cooling force determines the amount of material that may be placed in the beam path when internal targets are used, or the time needed to prepare a beam of given brightness if the the beam is to be extracted and used with an external target. With the assumption that the time needed for injection, and for acceleration if employed, can be made shorter than the cooling time, the properties of stochastic cooling give an upper bound to luminosity for a given beam quality. It does not help to increase the stored beam beyond some threshold, set by stochastic system noise levels, because the force must be weakened as explained above so that internal targets must be thinner or for external targets the cycle time made longer and there is therefore a well-defined upper bound on luminosity. For protons of a few hundred MeV, this bound appears to be in the neighborhood of $L \approx 10^{31}$ $cm^{-2}s^{-1}$ for stochastic cooling with present technology.

For electron cooling, there is an upper bound on internal target thickness set by the strength of the electron cooling force. The amount of beam stored is limited by one of a number of coherent or incoherent instabilities. The product of target thickness and stored current gives a luminosity limit which under comparable circumstances may be estimated to be of order $10^{33}/Z_t$ $cm^{-2}s^{-1}$, for lighter targets where the limit arises from energy loss to target electrons.

The subdivision by performance is thus that for energies low enough that electron cooling is now feasible ($v/c < 0.75$), the increase in available luminosity from the use of electron cooling is predicted to be sufficient to justify the considerable complexity of the electron cooling system in rings intended for use in measuring nuclear cross sections. One must always remember however that the stochastic limits are based on more extensive operating experience than the electron cooling limits. For the moment the latter involve a larger extrapolation. Both techniques also have room for further technological development.

## Example of Low Energy Rings

Each of the smaller ring projects must plan an extremely good vacuum in order to limit the beam loss rate by charge-changing interaction with the residual gas. Apart from this common feature, they exhibit a remarkable variety in other aspects. The wide range of projected applications can lead to considerable complexity in the facility design.

Just as the LEAR antiproton beam is purified by long storage times, it is increasingly recognized that ion beams may be contaminated by metastable electronic configurations, and that storage in a ring can give time for these states to decay to prepare a more unambiguous sample for atomic physics measurements.

Two of the low energy rings are being designed to contain simultaneously beams of the same momentum in different charge states. The history of this concept goes back at least as far as the suggestion by Cramer[5] for a ring serving as a highly efficient stripper. The vocabulary of dispersion, chromaticity and related concepts has to be used with care for ions of differing rigidity but identical momentum. The design criterion for this feature is equivalent to a broad momentum acceptance, with interaction restricted to regions of low p/Q dispersion so the beam remains within the emittance envelope following a charge-changing event.

### ASTRID at F.I. Aarhus

This ring[6] of 1.9 Tesla-meter maximum rigidity has a lattice reminiscent of LEAR. It can be filled either by a variety of beams from a 6 MV tandem electrostatic accelerator, or by ions from a 150 keV mass separator, or by electrons from a 10 MeV microtron, accelerated in the ring to 0.56 GeV so that the ring may serve part-time as a synchrotron light source.

There is provision for collinear and crossed beam geometries in one of the four straight sections, to be used for optical photon-ion, electron-ion, ion-ion, and ion-atom interaction studies.

The laboratory has a rich tradition of investigations in the overlapping region between atomic and nuclear physics. There are plans to investigate cooling by laser light interacting with a stored, not-fully-stripped beam. The 3 keV electron cooling system which is also planned would be useful for stored cooled ions to below 6 MeV/amu.

### TSR at M.P.I. Heidelberg

This 1.5 T-m ring[7] with four sides, is to be injected by beams such as 1 GeV $^{127}I^{47+}$ from an MP tandem with linac booster. The ring can accelerate the ions to its rigidity limit, and the 65 keV electron cooling system covers the full proton energy range, as well as the range of heavier ions.

Considerable attention has been given in this design to obtaining a very broad rigidity acceptance to permit operation with simultaneous storage of several neighboring charge states. This would allow studies of charge-changing processes with accumulation of the reaction products.

The TSR ring is conceived as a test device for investigation of electron cooling of heavy ions, and for a variety of investigations in accelerator physics and atomic and nuclear physics. It is to come into operation in 1988.

CRYRING at A.F.I. Stockholm

A ring of 1.4 T-m to be filled with highly charged ions from a CRYEBIS type of ion source, with a 0.3 MeV/amu RFQ booster[8]. The present lattice design has 12 sides with alternating straight sections free of quadrupole lenses. Rapid acceleration (8.4 T-m/s) is envisioned, and provision is made for slow extraction. Electron cooling is under consideration.

The project was conceived in 1983, is now funded and under construction, and is expected to begin operation in 1989. The ion source began operation in 1986 and has delivered, for example, $Ar^{16+}$.

The goals of the physics program include ion-electron and ion-laser photon studies. A second ion source is planned to facilitate crossed beam and merged beam studies and to permit stand-alone use of the CRYEBIS source for research unrelated to the ring.

HISTRAP at ORNL

A proposal for a 2 T-m ring has been prepared[9]. The ORNL tandem and an ECR-RFQ would be available to serve as injectors. The present lattice design has eight sides, alternately free of quadrupoles. As with the Heidelberg ring, the lattice is planned to permit storage of more than one charge state. Construction funding may be available in 1989, development work is underway.

## Higher Energy Rings

These rings are distinguished by a research program with a greater nuclear and particle physics orientation, and a lesser emphasis on atomic physics.

Cooler at IUCF

Conceived in 1979, funded for construction in 1983 and expected to begin operation later in 1987, this 3.6 T-m six-sided ring[10] will be filled with beams from the 200 MeV isochronous cyclotron in the IUCF laboratory at Indiana University. The ring will be used to extend the present intermediate energy nuclear physics program. Electron cooling up to 275 keV is being provided. The ring is planned to have polarized hydrogen beams and light ions with $1 \leqslant A \leqslant 7$.

The ring has three straight sections for internal target use with clear lengths up to 6 m. Slow acceleration of 1 T-m/s is provided and injection may be either by stripping of ions such as $H_2^+$ or $He^+$, or by stacking in the longitudinal phase space.

The IUCF cyclotron has good beam quality which has proven of considerable importance to the success of the research program. The electron-cooled beams should be of better emittance and energy spread by a factor ten.

CELSIUS at GWI Uppsala

The magnets from the ICE ring at CERN have been reassembled in an underground laboratory where they will function as a 6.3 T-m ring filled by the rebuilt 2 T-m cyclotron. Slow acceleration is planned as is electron cooling, initially to $T_e$ = 300keV.

The magnets are not laminated, but it is believed that the effect of eddy currents on the field purity can be controlled at the ramping rates which are planned. Magnet mapping has been underway for the past several months.

Among the interesting research plans[11] of the CELSIUS group is the use of a frozen deuterium pellet generator as an internal target with optical tracking to reconstruct the interaction point.

This first injection into the CELSIUS ring is planned for the end of 1987, with cooling available about one year later.

TARN II at INS Tokyo

Following successful operation of a smaller TARN I ring, with multi-turn injection from a cyclotron and stochastic cooling studies, this group is now building a 6.9 T-m ring with electron cooling[12]. There are provisions for acceleration, slow extraction, and for one internal target station.

One of the the principal emphases of the research program appears to be in accelerator physics.

The ring magnets were installed in an existing building in 1986, and startup in 1987 is planned.

CoSy at KFA Juelich

Approved for construction at the end of 1986, this 12 T-m racetrack configuration[13] will be filled by stripping $H_2^+$ ions from the Juelich 1.8 T-m cyclotron. The beam will be accelerated up to the 2.7 GeV kinetic energy limit set by ring rigidity, assuming the dipoles may operate at 1.7 T. Slow extraction will send beams back into the target areas now used for cyclotron research.

The present plan is to use electron cooling at the injection energy to increase the brightness to the stability limit, then to accelerate, with stochastic cooling available at energies where electron cooling is not yet feasible. In this configuration the gain in luminosity from the internal target mode applies to a smaller subset of experiments than is the case for example in the IUCF Cooler.

Research planned for CoSy will be in some respects similar to the light ion component of the Saturne program, an energy range which gives this ring a role in hadron physics complementary to that of LEAR.

ESR at GSI Darmstadt

The heavy ion linac will feed an 18 T-m "SIS-18" synchrotron which will in turn provide beam to a 10 T-m storage ring with electron cooling[14]. The main thrust of the research program will be to exploit the unique beams of fully-stripped Uranium and other heavy ions.

The ring has provision for internal target experiments. By using a stored heavy ion beam of, say, 300 MeV/amu and a hydrogen target, it is possible to duplicate the experiments of light ion labs such as IUCF but with very different kinematical conditions that make detector problems quite different and lead to technical advantages in a number of cases. For example a fast residual nucleus is much easier to detect than a very slow-moving recoil.

The ring can also be used as an accumulator of exotic reaction products, or as an injector into the synchrotron for further acceleration.

The ESR storage ring has provision for both electron and stochastic cooling. It is expected to begin operation about the end of this decade.

## Remarks

To the user of a traditional low energy accelerator, the rings of this new generation of facility superficially resemble a long beam line in which there has been fanatical attention to good vacuum practice. But to the accelerator physicist who has the opportunity, perhaps for the first time, to work with a ring, there are new concepts to assimilate, of which the most difficult may be the loss of cause and effect relationships among the ring components. In a beam line there is a clear distinction between upstream (causes) and downstream (effects). This distinction is not lost in a cyclotron because there is a spatial ordering, with the beam beginning at the center and moving to larger radii as momentum is added. Many diagnostic procedures depend on the identification of problems by the location where they first appear.

The closed orbit in the ring means that the beam is affected globally by a localized problem. The strategies for detecting and correcting problems with steering that distort the closed orbit, or problems with focussing that modulate the beam envelope in an undesirable manner, must be sorted out without the familiar guide to localization. To exacerbate the situation, pairs of misset dipoles for example can give rise to a local orbit distortion in the region between them and to a global distortion throughout the rest of the ring. These two distortions behave differently if an integer resonance is approached. Diagnostic and operational procedures have to deal with the total response of the ring, rather than with isolated portions.

The use of a ring with internal targets will give the experimenter some of the same conceptual difficulties. He will find for example that the properties of the beam incident on his target depend on the target. He may find that he has generated a background from a point upstream of his target arising from a beam halo produced in the target. In the thermal equilibrium established between electron cooling and target heating, the beam energy spread and emittance are controlled by the choice of target thickness. We may expect an interesting learning period as these rings come into use.

The nine projects briefly described above represent a sizeable commitment of resources to storage ring technology by atomic and nuclear research communities that in the past have been somewhat disconnected from their brethren in the particle physics accelerator game. It is interesting that the newly developing commonality of interests has increased the interaction strength between the communities in the same period that recognition of the nucleus as a laboratory of applied QCD has started nuclear and particle theorists working more closely together[15].

Whether these new little rings will fulfill the rosy expectations of their builders is a question for the future. Over the next few years we expect to see first results from operation of several of these facilities. We will have had a chance to explore the performance boundaries in some detail, and if past history repeats, may have discovered that the best reasons for building the rings were not part of the original justification, but will have emerged from the availability of beams under new conditions of cold storage.

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