PHYSICS WITH STORAGE RINGS

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ABSTRACT

In the past few years, new storage rings with cooled beams have appeared in several cyclotron laboratories and also in other locations. A few examples of the physics emerging from such storage rings are presented, in the context of future prospects for this technology.

1. INTRODUCTION

Beam storage was first a technology for attaining a maximum collision energy. Now storage rings are being constructed for a wider variety of purposes. The ring may be thought of as a processing device interposed between the traditional accelerator and the beam user. With the ring, beam properties can be altered to increase their usefulness.

Several of the new rings which have begun operation within the past four years incorporate beam cooling systems. Cooling was originally developed to improve beam accumulation to obtain stored beams of higher intensity. Beam cooling however endows the beam stored in a ring with a number of attractive properties. As the cooled metastable equilibrium state of the beam evolves, memory of initial conditions is lost. The beam user is thus isolated from fluctuations in the beam properties of the injecting accelerator. The phase space volume of the equilibrium state may be reduced by several orders of magnitude from conditions on injection. This bright intense beam with its reduced energy spread and emittance can make possible more precise experiments.

A particle beam is one of the ubiquitous tools of twentieth-century physics. The composition of atoms, nuclei and "elementary" particles has been probed through the interaction of particle beams with an appropriate target. A stored cooled beam may be used in this manner, but the nature both of the cooling process and of the beam-target interaction processes places constraints on the amount of target material which can be tolerated. Thus the event rate in an experiment is not as high as expected from the high stored current.

The event rate in a typical fixed-target experiment is the dimensionless product of four factors:

beam intensity - beam particles/second;

target thickness - target particles (eg. atoms)/unit area;

detector coverage - solid angle & efficiency;

interaction probability - cross sectional area/unit solid angle.

The product of the first two factors is commonly referred to as the luminosity L. The goals of the experiment determine an acceptable range for the magnitude of L. For an experiment in atomic physics, for example, where the cross section might be on the order of a megabarn, an L of 10^{24} cm^{-2} s^{-1} might be ample. For nuclear physics with a strongly-interacting primary beam and total cross sections of order of a barn, $L = 10^{30}$ cm^{-2} s^{-1} might suffice. For an electromagnetic probe, add about two orders of magnitude for the fine structure constant. To create a secondary beam of useful intensity, the primary luminosity would have to be much higher. Factories may be designed for $L = 10^{36}$ cm^{-2} s^{-1} or more.

The luminosity attainable with an internal target in a cooled storage ring depends on beam and target species, on beam energy, and to some extent on the ring design. For light targets and light beams of intermediate energy, $L = 10^{31}$ cm^{-2} s^{-1} has been demonstrated, and the ultimate limit is probably at least an order of magnitude higher. In broad terms, the luminosity attainable in rings is ample for atomic physics, acceptable for many strong interaction studies, but too low to consider their use in secondary beam production.

If beam is extracted after processing, a much thicker target may be used, but the average beam current is limited to the number of particles stored divided by the beam processing time. In general this will lead to a lower luminosity than for the direct beam from the injector, although the external target mode can still be useful as the processing may include acceleration to a much higher energy.

A more detailed discussion of the processes limiting performance of cooling rings is outside the scope of this paper. Further information on these facilities and their properties may be obtained from a recent review 1).

Abbreviated names, institutes and locations of cooling rings which are referred to in the following sections:

LEAR - CERN Geneva
Cooler - IUCF Bloomington
TSR - MPI für Kernphysik, Heidelberg
TARN II - INS Tokyo
CELSIUS - TSL, Uppsala
ASTRID - Århus University
ESR - GSI Darmstadt
CRYRING - MSI Stockholm
CoSy - FZ(KFA) Jülich

2. STRONG INTERACTION PHYSICS

2.1 Thresholds and Resonances

The creation of a meson in a nucleon-nucleon collision is a fundamental inelastic process. Studies of this process with accelerator beams began about forty years ago, and a considerable body of data has resulted. Near the threshold, the restricted phase space makes the cross section small and strongly energy-dependent. Target impurities can give a large background. For these reasons measurements near threshold have been more difficult and the information obtained has been of poorer quality.

A storage ring with cooling offers almost the ideal environment for threshold studies. The windowless internal targets are free of impurities, the cooled beam is nearly monoenergetic and the energy is readily varied in small or large steps. The luminosity attainable is sufficient for detailed measurements of sub-microbarn cross sections with detector arrays of good angular coverage. It is therefore not surprising that several of the new cooling rings have meson threshold measurements as a part of their planned research programs.

Experiments in the first years of operation of the IUCF Cooler have verified that the combination of cooled beam with a pure thin target can result in vastly improved measurements of pion threshold channels. The $pp \rightarrow pp\pi^0$ channel was observed by reconstruction of the event from the four-momenta of the two outgoing protons. The missing mass spectrum contained a useful sample of pp bremsstrahlung events as well. The results have been published 2). Data of comparable quality which has been obtained in the past year for the $pp \rightarrow pn\pi^+$ and $pd \rightarrow pd\pi^0$ processes will appear shortly.

An experiment of comparable luminosity has been carried out with antiprotons near the charm threshold with an internal target in the Fermilab stochasticly-cooled accumulator ring. An experimental resolution of 0.5 MeV is obtained for the narrow peak at the 3 GeV J/ψ resonance, and widths of other peaks with cross section as small as 1 nb have been measured [3]. Internal target experiments with the JETSET detector in LEAR are in progress. Internal and external target experiments at the Λ-$\bar{\Lambda}$ threshold at that facility exploit the good beam quality of the variable beam energy antiproton beam.

A comparably elaborate detector at the CELSIUS ring is being readied for studies of decay modes of the η^0 and π^0 mesons [4]. The CoSy ring now under construction has measurements planned in the energy region of strange particle thresholds and nucleon resonances. Electron cooling technology does not at present extend to the energy range above 0.6 GeV, so the beam for these measurements will be precooled prior to acceleration.

2.2 Polarized Beams and Targets

Experiments can be performed in storage rings with polarized beam or polarized targets or both. A scattering experiment on scattering asymmetry in the Coulomb-nuclear interference region, performed with 185 MeV polarized protons and an unpolarized proton target in the IUCF Cooler has been reported [5, 6]. A byproduct of this measurement was the observation that cooling does not reduce the polarization of the stored beam (a lower bound of polarization lifetime of several hours).

A new ^{3}He polarized target is operational at IUCF and has been used within the past month for the first "triple-scattering" measurements with an accelerated and cooled polarized proton beam. Within the ^{3}He nucleus, proton spins are antiparallel so polarization effects at some level of approximation reflect largely the spin of the unpaired neutron.

A polarized hydrogen target has been installed this past spring in the TSR where it will be used to demonstrate that an initially unpolarized beam may acquire a polarization by selective depopulation in interaction with a polarized target. A polarized hydrogen target is also in preparation for scattering and reaction measurements in the IUCF Cooler.

2.3 Heavy Ion Nuclear Reactions

At GSI, a measurement of half-life and mass of an unstable beam has been reported [7]. In this measurement, an external target bombarded by the SIS synchrotron beam created the radioactive isotope. After filtering by a fragment separator, the particles of interest were injected into ESR for storage and cooling. In this mode the ring functions as a precise measuring instrument following the production process. All stored species are cooled to the same velocity by electron cooling, but exhibit slightly different orbit frequencies even at the same nominal charge/mass ratio because of small differences in nuclear binding energies. The mass of the unstable species can then be directly compared to that of nearby reference ion peaks. A mass determination accuracy of 80 keV was reported.

Stored and cooled heavy ions can also be used in a mode with internal target interactions. At low beam energies, charge-changing processes have such large cross sections that nuclear reactions are difficult to observe. Experiments with internal targets are practical however at intermediate energies with fully-stripped beams. In this regime the cross section for a charge-changing event in the target is not too large.

The ESR at Darmstadt has demonstrated that the spallation products from the interaction of a stored beam with an Argon cluster jet target can be observed as accumulated and cooled secondary beams [8]. Satellite peaks are observed in the Schottky frequency spectrum.

Reactions of stored radioactive beams with light targets are planned, offering the study of conventional reactions with inverse kinematics.

The CELSIUS ring has recently stored a beam of ^{16}O at 100/Mev/amu. Heavy ion reaction studies are planned both there and at CoSy.

3. ATOMIC PHYSICS

The cooling electron beam may be employed as a target. Observations of radiative dissociation of H_2^+ at TARN II [9] and D_2^+ at CELSIUS[10] have been reported.

Radiative electron capture (REC) in the cooling region has been used as a monitor of the cooling process for light ions. The loss of beam through this process is normally less important than through interactions with residual gas in the ring. The cross section for REC increases with beam atomic number Z approximately as Z^2, so the electron density must be reduced for heavy ion beams to maintain a long beam lifetime. The capture may be stimulated by a pulsed laser [11] Rate enhancement factors of about 60 have been reached [12].

If the ring design accepts a substantial enough band of magnetic rigidities, charge-changing processes may not lead to beam loss. The preparation of a Bi^{80+} beam for dielectronic recombination (DR) studies by injecting Bi^{82+} into the ESR ring and then collecting the products of one and two electron pickup have been reported [7]. The injected beam serves as a reservoir, feeding the charge state of interest to maintain its population during the measurement. DR observations with a cooled ^{12}C beam at TSR [13] and with an uncooled ^{4}He beam at IUCF have been made.

TSR, ASTRID and the newly-completed CRYRING (which has accelerated and electron-cooled beams in recent months [14]) are examples of smaller storage rings with significant programs of atomic physics research.

4. ACCELERATOR PHYSICS

4.1 Spin Manipulation Studies

While polarized beams have been accelerated in strong-focussing synchrotrons for some time, there are problems with depolarizing resonances that can become severe at high energies or slow ramp rates. The use of spin rotators to ease the passage through resonances was proposed in 1977 but few rings have been constructed with the long open space required for a spin inverter. The rings designed for internal target experiments tend to have long straight sections to house targets and detectors. This fact has led to a sequence of measurements on spin rotators mounted in the IUCF Cooler [15] which establish the usefulness of such "Siberian Snakes", especially for the passage through imperfection resonances. In the course of these studies it has also been established that a partial snake may be employed to produce a stable in-plane polarization component at an internal target, and that the solenoids, toroids and correcting dipoles in the cooling section may conspire to produce a significant shift in the energy of depolarizing resonances[16, 17]. More recently an rf solenoid has been used to demonstrate that the spin direction of a stored beam can be reversed in an "nmr" process. Reversals during a measurement are important for control of systematic errors.

4.2 Laser Cooling

Fast cooling of selected stored ion species has been obtained with lasers. Experiments at TSR with Be^+ and with metastable Li^+ ions have demonstrated very low longitudinal temperatures of below 0.02 Kelvin [12]. Electron precooling to reduce the transverse emittance, and careful mechanical stabilization of photon transport structures to reduce vibration were needed to reach this temperature.

4.3 Collective Phenomena

At ASTRID a very cold Li^+ beam injected for laser cooling studies was observed to heat itself up rapidly through intrabeam scattering. Short length beam pulses showed an additional growth of kinetic energy through a Coulomb explosion. As the pulses lengthened, the stored potential energy was converted to kinetic form. The same system showed a curious implosion phenomenon for long pulses. The inflector could be used to fill most of the ring circumference, leaving a short gap in the beam azimuthal density distribution. Instead of the gap simply closing, it was found to split into two short gaps which maintained a constant width while moving away from each other [19].

The electron-cooled beam at LEAR shows collective instabilities for stored particle number N above about $N = 5\ 10^9$. Application of fast feedback damping circuits for coherent betatron motion in both transverse planes has raised this limit about one order of magnitude [20]. The control system of LEAR allows the dampers to distinguish between incipient unstable betatron motion and the closed orbit changes encountered during energy changes so the dampers can be employed in antiproton deceleration. Other cooling rings show similar thresholds for coherent instabilities.

4.4 Orbit Dynamics Studies

A cooled beam has suppressed Landau damping, which means that coherent motion persists for a rather long time before smearing into emittance growth. Beam phase space phenomena may be explored by kicking the cooled beam and tracking the coherent motion with position detectors. The technique generates, for example, almost textbook examples of phase space motion around islands of stability near non-linear resonances [21].

4.5 Injection Studies

It is clear that almost any kind of accelerator can serve as a cooling ring injector. Cyclotrons are used as injectors at several laboratories, although the continuous output of such machines is not an ideal match to the intermittent filling requirements of a storage ring. Other facilities employ synchrotrons, linacs, or electrostatic injectors.

Each of the cooling rings seems to contribute one or two new methods of cooled injection to a growing inventory of such techniques. Cooling eliminates phase space volume constraints on the filling process, replacing these by a rate limit set by the strength of the cooling force. If enough time is available, the ring can be filled to the limit of cooled beam stability.

When filling is rate-limited, the optimum luminosity is in general not obtained with the thickest target. If small angle scattering causes beam loss, choose a target thin enough that the emittance remains small compared to the ring acceptance.

5. PROSPECTS FOR FUTURE FACILITIES

The glimpses of very useful output which have emerged from the early years of operation of cooled beam storage rings indicate that an interesting decade or more of their exploitation lies ahead. It is perhaps no longer premature to ask whether the concept might be extended in other new directions.

One field of significant current interest is the use of radioactive beams. The ESR is in a unique position to process beams of all masses up to some hundreds of MeV per nucleon. A proposal for a new two-ring facility at JINR Dubna is under review. This facility has a goal of collecting products of reactions between a cooled beam of about 150 MeV/amu and a rare isotope target.

The extension of the cold storage concept to lighter beams and lower energies eventually runs into the charge-changing problem. An electron pickup in an internal target leads to a lost beam particle if the changed magnetic rigidity lies outside the ring acceptance. Possibly a ring of greater topological complexity should be designed, one in which discrete paths are provided for distinctly different rigidities. This concept has been advanced as a method for improving the efficiency of strippers [22], but also may be used to increase the efficiency of beam use with internal targets and heavy ion beams, lowering the threshold energy for which this mode is useful.

A natural limit to cooling of radioactive species is set by the relation between decay lifetime and cooling time. Very short-lived species are not amenable to cooled beam storage. However when the production rate is very low, it is conceivable to apply particle-by-particle feedforward methods to reduce the phase space density in flight. The idea has been advanced for slow muons [23] but may have applicability also to more exotic species.

A second direction for possible future extension is toward higher beam energies. Electron cooling in the present machine generation is limited to about 0.3 MeV, which can cool beams to about 0.6 GeV/amu. Pressurized electrostatic terminals may extend this limit in future by about one order of magnitude, provided that non-trivial problems of efficient electron collection and beam confinement can be solved for this energy range. Stochastic cooling has no such energy bounds. The internal target experiments near the charm threshold [3] show the promise of this physics. A proposal for a "superLEAR" facility has been under discussion [24].

The possibility of a cooled light facility for higher energy cooled polarized beams has been suggested at IUCF. This would be a slow-cycling device, filled from the present Cooler, with ample space for internal targets, spin manipulation elements, and cooling systems. Injection at about 400 MeV after acceleration in the IUCF Cooler should raise the beam current limit by an order of magnitude.

The target heating-beam cooling equilibrium which determines the thickest useful target requires further careful study before a luminosity limit for this unexplored energy region with cooled beams can be predicted with confidence. One thing that is clear is that the small angle Rutherford scattering that provides the dominant loss process for light ion beams of lower energy is negligible above a few GeV. The stored beam may therefore be used to create nuclear reactions with great efficiency.

6. ACKNOWLEDGMENTS

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