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# The Indiana Cooler: A Retrospective

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## Key Words

storage ring, internal target, electron cooling, polarized beams,  
polarized targets

## Abstract

From 1983 to 2002, the Indiana Cooler was constructed and operated at the Indiana University Cyclotron Facility. During that period, a relatively small group of people built an accelerator complex, explored the new technology of electron cooling, and demonstrated its usefulness in nuclear and particle physics. This review recounts the history of the project, describes the facility, and summarizes the scientific results in atomic, nuclear, and particle physics, and in the physics of beams.

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## 1. INTRODUCTION

The Indiana Cooler was built in response to the emerging new technology of electron cooling. Electron cooling (Section 3.1.3) was first demonstrated in Novosibirsk in 1974. Five years later, a proposal for the Low-Energy Antiproton Ring at CERN, featuring a cooled beam in a storage ring, promised unprecedented experimental possibilities. By that time, the scientists at the Indiana University Cyclotron Facility (IUCF) began to consider the application of cooling methods to intermediate-energy nuclear physics. Finally, when electron cooling of 200-MeV protons was demonstrated at Fermilab, the scientists at the IUCF decided that they were on safe ground, submitting a proposal entitled “The IUCF Cooler-Tripler: Proposal for an Advanced Light-Ion Physics Facility” to the National Science Foundation in December 1980. The plan included a new cyclotron, the Tripler, which was dropped in a second version of the proposal (and later realized in Osaka, Japan). Start-up funds (\$1 million) were received in 1982, and funding for the Cooler construction (\$6.5 million) began in 1983. The state of Indiana paid for the necessary building addition (\$2.7 million).

The Cooler was leading the way, but was joined quickly by similar projects at a number of laboratories in Europe and Japan, which also began planning and building storage rings that employed either electron or stochastic cooling (1). This review describes the Cooler facility, recounts its history, and summarizes the scientific accomplishments that encompassed the fields of the physics of beams and of atomic,

nuclear, and particle physics. For a review of the role of storage rings in nuclear physics, see References 2–4.<sup>1</sup>

## 2. THE FACILITY

This section recounts briefly the construction of the Cooler from 1982 to 1988 and describes in some detail the accelerator complex and its components. Because the Cooler was a national-user facility, we also include information about the composition of the user community and its interaction with the facility.

### 2.1. Construction History

**2.1.1. Construction.** In 1982, a Cooler-working party consisting of 14 engineers, technicians, and physicists was formed and began holding weekly meetings. In 1983, the construction of a new building was initiated, and the first funds for major equipment purchases became available. By the end of the next year, most major components to complete the ring were procured and started to appear in the new building. The years 1985 to 1987 were marked by an intense assembly and installation effort. There were 28 full-time employees working on the project. Lamination stamping and stacking, coil winding, and fabrication and mapping of the magnetic elements were in full swing. The high-voltage platform for the electron cooler was erected and its 300-kV supply was tested. Concrete support blocks were cast, magnets were mounted and surveyed, and the beam pipe was installed and sections of it put under vacuum. By the end of July 1987, the first beam was injected and the beam path commissioned, section by section, until the orbit was completed. The functioning of the storage ring was demonstrated when a beam lifetime of more than 1 s was observed.

**2.1.2. Commissioning.** Early in 1988, the ring was operated as a synchrotron accelerator for the first time, and events from a nuclear reaction were observed by the ce01 detector (Section 4.2.1) in the G region. Finally, on April 16, 1988, electron cooling of a stored 45-MeV proton beam was achieved. The next day, the first interaction of a cooled beam with an internal hydrogen target was observed, and an equilibrium between cooling and target heating was established as expected, opening the way to experiments with internal targets. Shortly thereafter, deuterons and polarized protons were stored and cooled. The construction phase ended in May 1988. A detailed account of the progress of the Cooler construction is provided in Reference 5 and in a series of quarterly reports produced to inform the funding agency of the progress made.

This was the beginning of an exciting period, marked by many firsts and rapid progress in demonstrating the capabilities of the new technology. On June 2, 1988,

<sup>1</sup>The references cited throughout this review amount to a (it is hoped) complete list of all Cooler-related journal articles. Contributions to conference proceedings are included if they are the sole record on a given subject. For reasons of space, the reference list was limited to the scientific output of the Cooler. For links to supporting work, the reader is referred to the citations in these Cooler-related publications.

a formal dedication of the new facility took place. This event coincided with a celebration of 50 years of nuclear physics research at Indiana University.

**2.1.3. Later Additions.** For the first few years, beam for the Cooler was supplied by the existing cyclotron. In 1994, the source terminal of the cyclotron was equipped with a new polarized ion source (6) to improve the intensity of polarized beam.

To overcome the limitations inherent in the cyclotron as an injector, a new accelerator complex, dedicated to Cooler injection, was constructed between 1994 and 1997. It consisted of a new ion source, a pre-accelerator, and a small accumulator synchrotron (Section 2.2.2). Funding (\$3.5 million) was provided jointly by Indiana University and the National Science Foundation; beam delivery to the Cooler started in September 2000. With this addition, the Cooler facility reached the peak of its performance. The first Cooler experiment had been conducted with less than 25  $\mu\text{A}$  of stripping-injected unpolarized protons on a simple  $\text{H}_2$  gas jet target. By the time operations ended, 1.5 mA of polarized proton or deuteron beam could be stored, and polarized proton and deuteron targets were available (7).

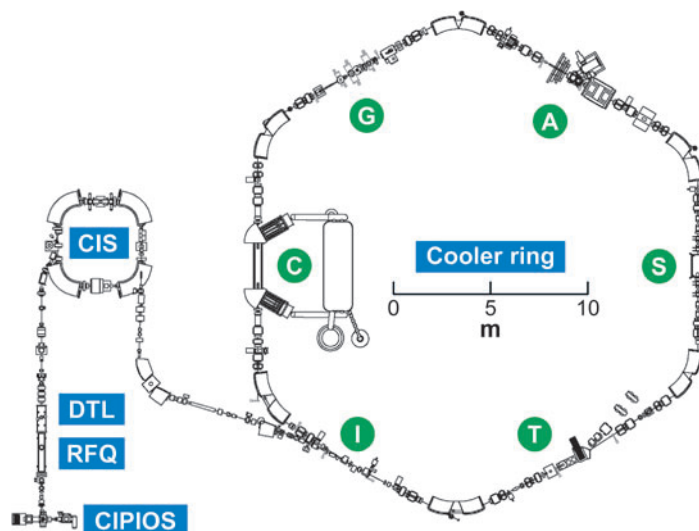
In 1999, the National Science Foundation announced that it would no longer support the operation of the Cooler. An exit strategy for a final research program was implemented, and the last beam was orbiting in the ring at the end of July 2002.

## 2.2. Facility Description

**2.2.1. Cooler ring.** At the time of decommissioning, the Cooler facility presented itself as shown in **Figure 1**. The lattice of the ring had the shape of a hexagon. Breaking with the conventional wisdom of ring design, which calls for perfect symmetry, compromises were made to enhance beam-parameter flexibility and to accommodate

**Figure 1**

Layout of the Cooler facility as it presented itself in 2001. Shown are the Cooler Injector Polarized Ion Source (CIPIOS), the radio-frequency quadrupole accelerator (RFQ), the drift-tube linac (DTL), the Cooler Injector Synchrotron (CIS), and the storage ring itself.



the requirements imposed by nuclear physics experiments. The six straight sections were labeled C, I, T, S, A, and G for cooling, injection, time-of-flight, spectroscopy, adjustment, and general purpose, respectively.

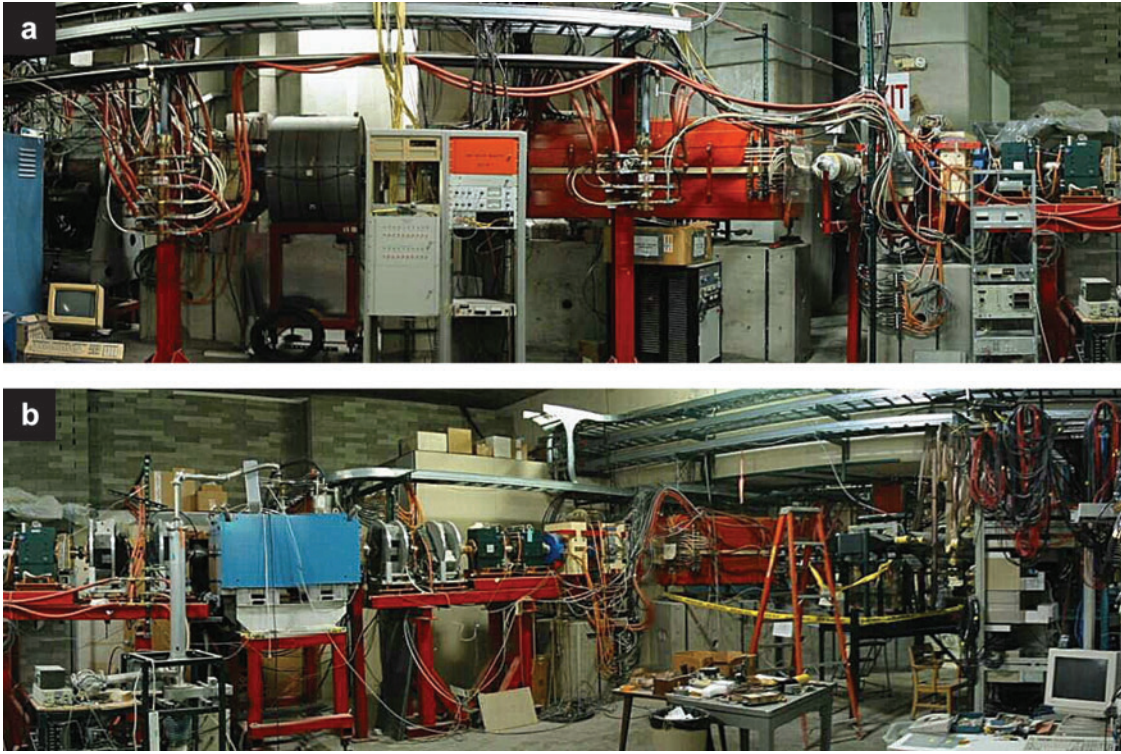
The main bends at the corners of the hexagon (four of  $60^\circ$  and two of  $54^\circ$ ) were accomplished by pairs of dipole magnets with a maximum field of 1.51 T. Additional horizontal bending magnets were located in the straight sections C, I, and T, as we discuss below. The beam position was controlled by 2 horizontal and 16 vertical steerers, together with extra windings in the corner dipoles and the additional bending magnets. The magnetic elements needed for focusing and chromatic control (36 quadrupoles and 12 sextupoles) were grouped near the corners to provide more space for experimental equipment (6.1 m in S, I, and G; 5.1 m in A and T; and 7.1 m in C). The optics design called for tight waists with dispersion (i.e., the orbit depends locally on beam momentum) in S, I, and G, whereas in the other straight sections the beam was not dispersed.

Beam from the injector entered the Cooler at the center of the dedicated I region between two  $3^\circ$  bending magnets. Initially, the ring was filled by stripping  $H_2^+$ ,  $D_2^+$ , or  $^3\text{He}^+$  ions on a  $20\text{ }\mu\text{g cm}^{-2}$  carbon foil with one unsupported edge. For beams for which no strippable ions were available, such as polarized beams, injection was achieved by a pair of full-aperture kickers, followed by rf stacking. For both injection modes, cooling was employed to increase the stored proton current (8). For polarized beams, spin-precession solenoids in the beam line between the injector and the Cooler were used to match the spin alignment of the incoming beam to the stable spin direction (Section 3.2.1) at the injection point.

The C region contained a 2.8-m-long solenoid with a maximum field of 15 T, which was needed to prevent the spread of the cooling electron beam due to its own space charge. Adjacent to the solenoid, two toroidal field coils served to inflect and extract the electron beam. The electron beam had a diameter of 2.5 cm, overlapping with the stored beam. Its largest energy was 275 keV, and currents of up to 2 A could be provided. After its extraction, the electron beam was decelerated and efficiently collected. To compensate for the steering of the stored beam by the toroids, the C region contained four strong steerer pairs. To offset spin precession in the cooling solenoid, two compensation solenoids with opposite fields were placed before the first toroid and after the second one, respectively.

The straight sections T, S, A, and G were all used for experiments. The T region contained a  $6^\circ$  bending magnet with a large gap, supplied by the University of Pittsburgh. This magnet served to separate low-rigidity reaction products from the beam for a number of experiments, and made possible the observation of neutrons at  $0^\circ$ . **Figure 2** shows a panoramic view of the S region, and part of the A and T regions.

The maximum rigidity of the stored beam was  $3.6\text{ T m}$  (corresponding to a proton energy of 490 MeV). An rf cavity in the A region (obtained from DESY, Hamburg, and built originally for the Princeton-Penn accelerator) was used to bunch and accelerate the beam. A second rf cavity was added to widen the choice of the beam time structure. During acceleration, the rigidity was ramped at a rate of up to  $1.0\text{ T m s}^{-1}$ . To suppress eddy currents, all magnetic elements were laminated. Electron cooling was employed



**Figure 2**

Panoramic view of approximately one-third of the Cooler circumference at the time of decommissioning. (a) The pd elastic scattering experiment in the A region is visible on the left. The orange corner dipole pair at the end of the S region is visible to the right of the center of the picture. The view continues in panel b. (b) The blue box houses the spin-precession solenoid of the Siberian snake. Another dipole pair is also visible, and the equipment that was used to measure the  $dd \rightarrow \alpha\pi^0$  cross section in the T region can be seen on the right. Photo courtesy of R.E. Pollock.

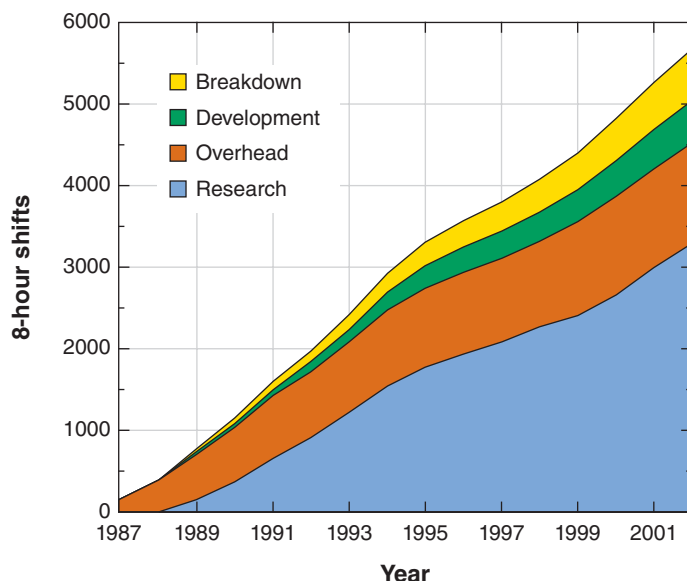
before and after the acceleration. The rf cavities were also used to decelerate the beam. The ramping protocol differed between acceleration and deceleration because of magnet hysteresis. The circumference of the ring was 86.77 m (9). The transverse design acceptance of the lattice was  $25\pi$  mm mrad, and the momentum acceptance was  $\Delta p/p = \pm 0.2\%$ . The betatron tunes in the horizontal and vertical directions were  $Q_x = 3.86$  and  $Q_y = 4.86$ , respectively.

The beam pipe was constructed of welded stainless steel, prebaked at  $900^\circ\text{C}$ , with a few nonconducting sections made from ceramic. After installation and pump down, the beam pipe was baked at approximately  $150^\circ\text{C}$ . In the corners of the ring, the vacuum was maintained at  $10^{-10}$  torr. The stringent vacuum constraints were often relaxed near tight waists in the interest of more flexibility in the use of internal targets.

**2.2.2. New injector and ion source.** After the completion of a new injector (10) in 2000, the beam was produced by the newly constructed Cooler Injector Polarized Ion Source (CIPIOS) (11). This negative ion source featured a pulsed hydrogen or deuterium gas jet emerging from a cooled nozzle. The appropriate magnetic substates were selected by a combination of permanent sextupole magnets and radio-frequency transitions, as necessary to produce polarized protons or vector- or tensor-polarized deuterons. The atomic beam was ionized by a plasma ( $H^-$ ,  $D^-$ ) charge-exchange ionizer. The source potential was  $-25$  kV, and the extracted peak current was up to 12 mA with an emittance of  $1.6\pi$  mm mrad.

For proton operation, the beam was first accelerated to 3 MeV by a radio-frequency quadrupole and then to 7 MeV by a commercial drift-tube linac. The beam was then accumulated in a small Cooler Injector Synchrotron (CIS) by stripping on a  $4.5 \mu\text{g cm}^{-2}$  carbon foil. After acceleration to 203 MeV, the entire CIS content (approximately  $5 \times 10^9$  protons) was transferred and kick injected into the Cooler ring as a single bunch. This process was repeated several times with a repetition rate of 0.8 Hz. For deuteron operation, the vane structure of the radio-frequency quadrupole was replaced with a different assembly, a process that took approximately five days (mainly to recover the vacuum). In this mode, the radio-frequency quadrupole accelerated deuterons to 4 MeV, while the drift-tube linac was inactive. The deuteron energy was ramped to 90 MeV in the CIS before transfer to the Cooler (12).

The beam usage for different tasks of the Cooler over its lifetime is illustrated in **Figure 3**. The category labeled overhead includes regular maintenance and the setups for new runs. The category labeled research is detailed further in the following section.



**Figure 3**

Accumulated beam production during the lifetime of the Indiana Cooler in units of eight-hour shifts. The total beam usage is subdivided into equipment breakdown, development of new capabilities, overhead for maintenance and changeover, and research time during which the experimenters had control of the beam.

### 2.3. The Cooler as a User Facility

Planning for the first Cooler experiments started in 1984 with weekly meetings among the Cooler experimenters. The group quickly realized that a measurement with an internal target is quite different from the traditional situation, where the beam passes through the target only once, because in a ring the presence of the internal target affects the beam properties and background generated after the target may show up in front of it.

While the Cooler was under construction, the experimenters were preparing for the challenge ahead. A Monte Carlo simulation of how an internal target affects the beam properties was carried out (13), and various methods to prepare sufficiently thin internal targets were explored (Section 3.4). In addition, a workshop on “Nuclear Physics with Stored Cooled Beams” was organized. It took place at McCormick’s State Park and was attended by 114 participants from 10 countries (14).

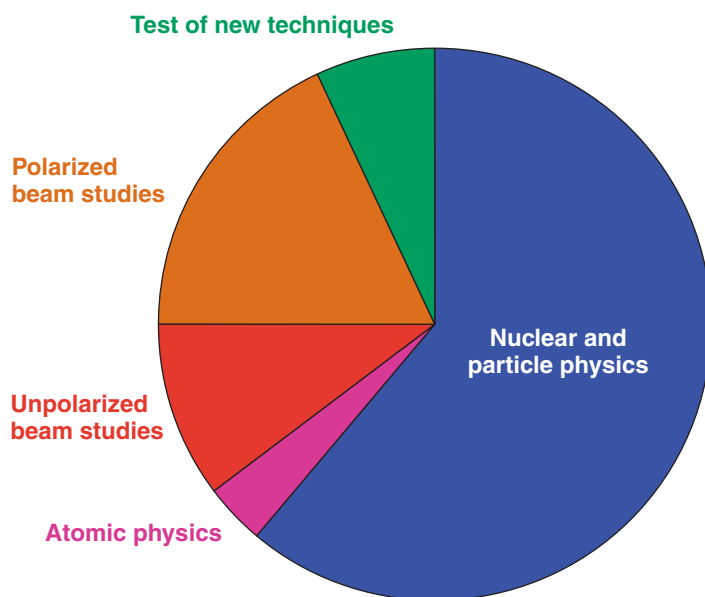
In the fall of 1984, the nineteenth regular biannual IUCF Program Advisory Committee for the first time considered two Cooler proposals. On the basis of its recommendation, procurement for a major detector system in the G region was initiated. The components of this detector were tested concurrently with Cooler commissioning activities. The detector system was operational by the time that cooled, and accelerated beams became available in the fall of 1989. Outside users from the Universities of Michigan, Pittsburgh, and Wisconsin and from Northwestern University contributed strongly to the initial experimental effort, which consisted of most of the first 10 proposed experiments.

The Cooler research effort soon became notable for its worldwide visibility. One example of this is the fact that in the first five years after commissioning, Cooler scientists received 55 invitations for talks at international conferences. The IUCF was also the host for the Fourth International Conference on Nuclear Physics at Storage Rings (STORI99) (15).

Several Cooler proposals appeared on the agenda of each of the thirty Program Advisory Committee sessions that followed the nineteenth Program Advisory Committee, resulting in a total of 75 new proposals and 9 updates of active experiments. The authors on these proposals were from 116 different institutions in 16 countries, and included 54 graduate students. Approximately half of the 38 spokespersons were from the IUCF. Most Cooler experiments represented relatively modest projects that could be completed within 40 to 60 eight-hour shifts of beam time. However, some more involved research efforts consumed up to 300 shifts, while 11 experiments did not go beyond the proposal stage. Approximately two-thirds of the 3200 shifts of beam time spent on research was devoted to nuclear and particle physics. The remainder was split between accelerator physics, atomic physics, and tests of new techniques (**Figure 4**).

## 3. ACCELERATOR PHYSICS

The exploratory nature of the Cooler project made the accelerator structure accessible to changes or additions. It thus provided an ideal laboratory for investigating accelerator physics topics related to storage rings.

**Figure 4**

Fractional expenditure of research beam time for different fields of study.

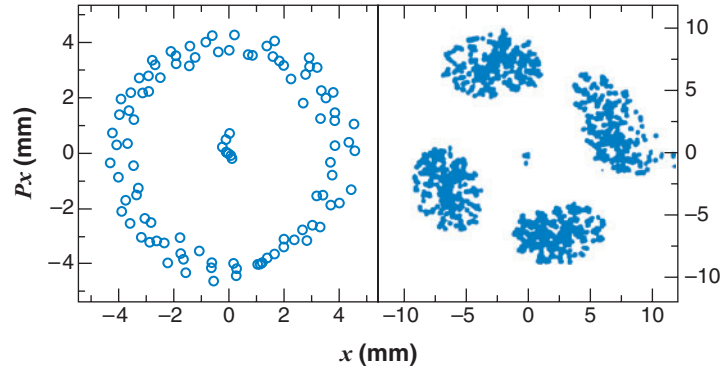
### 3.1. Unpolarized Beam Studies

**3.1.1. Phase space.** The coordinates of the four-dimensional transverse phase space include the position and angle (or transverse momentum) of the stored particles relative to the equilibrium orbit, in both the vertical and horizontal directions. To first order, the particles execute betatron oscillations about the equilibrium point (owing to the focusing elements in the ring). The number of such oscillations per turn is termed the betatron tune. The occupied phase volume is known as the emittance.

The coordinates of the two-dimensional longitudinal phase space include the phase and momentum relative to an orbiting fixed point. When an rf cavity is present, the beam is bunched and the fixed point is taken to be the center of the bunch phase space distribution. In the absence of drag forces (from an internal target or residual gas), an equilibrium particle at the fixed point encounters the cavity when the field is zero. All other particles execute synchrotron oscillations about that point. The number of oscillations per turn is termed the synchrotron tune.

**3.1.2. Nonlinear beam dynamics.** In rings with long storage times, the small, nonlinear part of the forces acting on the stored particles may play a significant role. For instance, during the design of the Superconducting Super Collider in the years after 1990, it became urgent to verify the nonlinear beam motion in accelerators and to model the long-term beam stability in the presence of nonlinear forces.

A beam bunch of small emittance marks the path of a single particle, and a turn-by-turn measurement of the bunch position at two locations a quarter of a betatron oscillation apart then yields the transverse phase space coordinates. The small-emittance beam of the Cooler thus offered the opportunity to investigate nonlinear dynamics



**Figure 5**

Measured Poincaré map at a fourth-order betatron resonance (*right panel*). The left panel shows the same, slightly off the resonance. The axes correspond to the horizontal phase space coordinates. Reprinted with permission from Lee SY, et al. *Phys. Rev. Lett.* 67:3768 (1991). Copyright 1991 by the American Physical Society (16).

experimentally. From a study of a Poincaré map (a plot of phase space coordinates for subsequent turns, as in **Figure 5**), the Hamiltonian was derived that described the complex particle motion at third- and fourth-order resonances (16, 17), linear coupling resonances (18), and nonlinear sextupolar coupling resonances (19). Knowledge of the Hamiltonian allows one to devise measures to compensate for the ring nonlinearity. The same technique also found use in measuring the betatron tune (20).

To manipulate the beam tune, a ferrite window-frame magnet was developed that could function as a dipole or as a quadrupole (21). Tune modulation was used to lock particles onto resonance islands to establish chaotic dynamics (22), and by employing the magnet as a quadrupole for rapid tune jumps, the beam dynamics near overlapping resonances was explored (21).

The longitudinal phase space coordinates for individual turns can be deduced from a measurement of the time of passage of a beam bunch at a given point and its position in a dispersed location. This has been used to construct longitudinal Poincaré maps of a beam driven by rf modulation (23–25), and to study the coupling between synchrotron and betatron motion and its effect on beam emittance (26–28). The latter is important because the synchrotron motion in large rings is of a low enough frequency that it can be excited by ground movements. Demonstrations of the use of nonlinear beam dynamics in manipulating beam distributions included bunch compression (29), bunch phase space dilution experiments (30, 31), and investigations of parametric resonances in quasi-isochronous systems (32).

**3.1.3. Electron cooling.** The use of a ring for beam storage gained practical interest with the invention of cooling, that is, when it became possible to control the phase space occupied by the beam particles. There are essentially two methods to achieve this. In electron cooling, the stored beam is immersed in a comoving electron beam for part of the ring circumference. The random motion of the beam particles in the

electron rest frame is then transferred to the cold electrons. The beam energy is limited by the energy range for which one can generate an intense electron beam. In the other method, stochastic cooling, the departure of the stored particles from some reference point in phase space is sensed at one location of the ring, and a corresponding corrective kick is applied at an appropriate second location. Because the kick affects all particles, the correction has to be decreased as the number of particles increases, which results in a weaker cooling force. This method, therefore, works best for low-intensity beams over a wide range of energies, and has mainly been applied in antiproton accumulation. However, electron cooling is largely independent of the number of stored particles and was thus the method of choice for the Cooler.

In a ring with an rf cavity, the velocity of an equilibrium particle may differ from the electron velocity. When this difference is large enough, the fixed point abruptly changes into a limit cycle and the beam distribution in longitudinal phase space becomes ring like. Mathematically, this corresponds to a Hopf bifurcation. This phenomenon was observed and investigated in the Cooler (33–35), and it was demonstrated that one could make use of it to measure the temperature of the electron beam.

Electron cooling at the IUCF Cooler provided beams with an emittance of less than  $1\pi$  mm mrad and a momentum spread  $\Delta p/p$  of less than a few times  $10^{-4}$ . Electron cooling also proved crucial in injecting beam into the ring (8) because it made it possible to overcome the limitation of a constant phase space distribution, required by Liouville's theorem.

**3.1.4. Intense beams.** With beam cooling working well, it was possible for the Cooler beam intensity to reach the space charge limit (36). This limit is of general importance in accelerator physics, and the Cooler provided a welcome opportunity to systematically study the dynamics of space-charge-dominated beams (37–39). Together with the earlier results from nonlinear beam dynamics studies, this activity contributed to a better fundamental understanding of beams near the space charge limit.

Intense beams may also be vulnerable to collective instabilities caused by the impedance in the accelerator. A common remedy is a double rf system that increases the tune spread of the beam and enhances Landau damping. A series of experiments was carried out to understand the dynamics of double rf systems (40–42).

Alternatively, the collective beam instability can be alleviated by modulating the rf amplitude at twice the synchrotron frequency. A detailed study of such a dynamical system showed the bifurcation of the nonlinear resonance and the suppression of noise in the beam spectrum, and established this technique as a method for providing active damping of collective beam instabilities (43, 44).

## 3.2. Polarized Beam Studies

**3.2.1. Depolarizing resonances.** The behavior of particles with spin in a storage ring is determined by the interaction of their magnetic moment with the magnetic fields along the orbit. In a synchrotron, vertical fields guide the particles around a closed orbit. With only these fields present, the vertical component of a spin vector

is stable, whereas any in-plane component precesses. The number of precessions per orbit is termed the spin tune  $\nu_s$ .

Sometimes magnetic field components in the plane of the ring are present that do not average to zero over one orbit. Such fields inflict a kick on the spin vector away from its stable direction, once per revolution. When the spin tune is an integer, these periodic kicks add up coherently and the beam can be depolarized. This condition is known as an imperfection resonance.

Particles in a ring carry out betatron oscillations (Section 3.1.1) owing to the focusing quadrupole fields. The horizontal fields encountered by a vertically oscillating particle also provide precession kicks. An intrinsic resonance occurs if the spin tune is an integer multiple of the vertical betatron tune.

Other depolarizing resonances arise from coupling between the vertical and horizontal betatron tunes (45), or between the transverse and the synchrotron motion of the stored particles. It is also possible to induce a depolarizing resonance on purpose by generating precession kicks at the proper frequency, using an rf solenoid or a dipole.

Depolarizing resonances can make it difficult to accelerate a stored beam to high energy. Tune-jumping techniques can be used to solve this problem when only a small number of resonances are encountered, but this method is no longer feasible with many partly overlapping resonances. To overcome this difficulty, a local spin rotator has been proposed (e.g., a longitudinal solenoid field) that precesses the spin by  $180^\circ$  (known as full snake) or by less than  $180^\circ$  (partial snake). With a full snake, the spin tune is exactly a half integer, independent of beam energy. The experimental proof that a full snake indeed removes intrinsic, as well as imperfection, resonances (**Figure 6**) was obtained soon after the Cooler was commissioned (46, 47), attracting worldwide attention.

Partial snakes, which have been studied extensively (48–51), also remove imperfection resonances, but in the case of intrinsic resonances, merely shift the beam energy at which these occur. These displaced resonances are then termed snake resonances (52). Overlapping resonances (53), which are obviously important in high-energy machines, were studied in the Cooler by introducing an induced resonance either on top of the imperfection resonance at 108.4 MeV (54) or in the form of synchrotron sidebands that occur with imperfection or induced resonances (55–57).

The polarization lifetime in the vicinity of a depolarizing resonance was investigated for an intrinsic (58) and for an induced resonance (59). The result showed that the polarization lifetime is usually much longer than the beam lifetime, unless one is quite close to a resonance.

**3.2.2. Polarized beam properties.** When the stored-beam parameters cross the condition for a depolarizing resonance at the appropriate rate, the spins are reversed in a process called adiabatic fast passage. The ability to flip the spin of the stored beam is clearly important to nuclear experiments, and thus extensive tests of this technique were carried out (60–66). In these studies, an induced resonance was moved by ramping its driving rf frequency. A spin flip efficiency of better than 99% was achieved, and several nuclear physics experiments made use of the method.

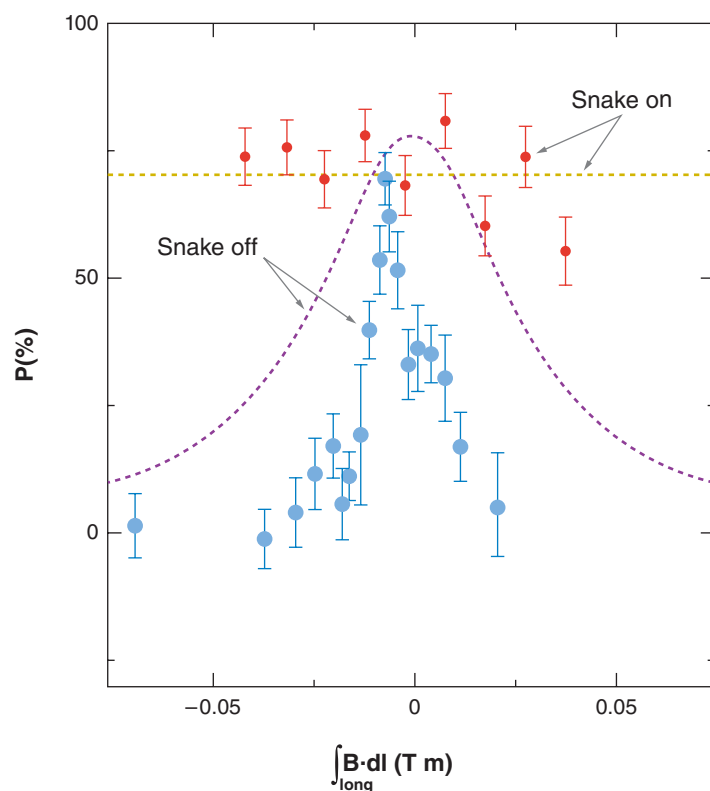


Figure 6

Proton polarization as a function of a longitudinal residual field integral. This imperfection field was varied by means of the cooling compensating solenoids. Without snake, the  $G\gamma = 2$  imperfection resonance destroys the polarization unless the residual field is exactly compensated. With a full snake (*small red circles*), the depolarizing resonance has vanished. Reprinted with permission from Krisch AD, et al. *Phys. Rev. Lett.* 63:1137 (1989). Copyright 1989 by the American Physical Society (46).

In a ring with only vertical fields, the spin tune is given by  $\nu_s = G\gamma$ , where  $G$  is the anomalous moment of the particles and  $\gamma$  is the relativistic Lorentz factor. The location of the imperfection resonance then depends only on the beam energy and can be used for energy calibration. This is not quite true in a ring that contains a series of vertical bends. Even if the net bending angle is zero, there is still net spin precession because the respective spin rotations do not commute. The horizontal fields of the toroids in the C region of the Cooler and of the related correction dipoles represent just such an arrangement. The existence of this type III snake has been proposed (67) and experimentally verified (68, 69) at the Cooler.

The stable spin direction is determined by the magnetic fields present along the orbit and does not depend on the polarization direction prior to injection. Snakes not only change the spin tune but also affect the stable spin direction. For example, at a point opposite from a full snake, the stable spin direction is along the beam. Several experiments in the A region required longitudinal beam polarization, which was produced by a superconducting solenoid in the T region and a solenoid field in the C region. The latter was obtained by simply reversing the current in the solenoids that normally are used to compensate the electron confinement field, resulting in a field integral of twice that of the confinement solenoid.

Spin-1 particles such as deuterons are more complicated because the description of their polarization requires a vector as well as a tensor, which arises from an imbalance of the  $m = \pm 1$  substates, relative to the  $m = 0$  substate. When operating the ring with a stored deuteron beam of mixed vector and tensor polarization close enough to an induced resonance (so that the polarization lifetime was short enough to be measured), the experiment showed that the vector polarization lifetime was twice that of tensor polarization (70). In addition, spin flipping of a vector beam was demonstrated, and it was shown that, in principle, tensor polarization could be manipulated as well (66).

Some researchers have suggested that a stored beam may be polarized by spatially separating stored particles of opposite spin by the Stern-Gerlach effect. There has never been any evidence of this, and an exploratory measurement with the Cooler (71) did not lead to more activity.

### 3.3. Beam-Target Interaction

Electron cooling makes the use of internal targets possible. As a prerequisite to experiments with internal targets, it was necessary to understand the interplay between such targets and the properties of the stored beam (lifetime, emittance, energy spread).

At low energy, multiple scattering in an internal target causes beam emittance growth, or heating, an effect counteracted by cooling. Beam loss occurs mostly by Rutherford scattering by an angle large enough for the particle to leave the ring acceptance. At higher energies, beam loss is dominated by nuclear scattering. For protons on a  $H_2$  target, the transition between the two regimes takes place at approximately 1 GeV, that is, well above the Cooler energy range. The lifetime of a stored cooled beam over a range of Cooler energies was systematically studied in the presence of targets of varying thickness and species, and models were developed to explain the results (72).

The target thickness is limited by the cooling power available to compensate for multiple scattering. For electron-cooled protons, this limit is approximately  $10^{16}/[Z(Z+1)]$  atoms per  $cm^2$ , where  $Z$  is the atomic number of the target material. Beam loss is caused by large-angle Rutherford scattering, and thus the beam lifetime scales roughly as  $(T/Z)^2$ , where  $T$  is the beam kinetic energy. The lifetime also depends on the machine acceptance. A short beam lifetime means that more unproductive time is spent refilling the ring. The target thickness and the timing of the experimental cycle, which consists of ring filling, beam manipulation, data taking, filling, and so on, can be chosen such that the average luminosity is optimized (72). Researchers concluded that the average luminosity is roughly proportional to  $1/Z^2$ , indicating that heavier targets come with a penalty of lower luminosity.

## 4. TECHNOLOGY

### 4.1. Internal Targets

The limit on the thickness of internal targets rules out self-supporting target foils or windows of gas cells. Various target schemes that avoided this restriction were

developed in preparation for Cooler experiments, including a pure electron beam target that was used as a diagnostic tool (73, 74). In the following, the development of targets for nuclear physics experiments will be recapitulated. Typical internal targets are windowless. Thus, the beam encounters only the nuclei of interest, and undesired background is minimized. The targets are thin (Section 3.3), and low-energy outgoing reaction products are detectable. The small target thickness is offset by a large stored current, and the resulting luminosity is comparable to that of a conventional one-pass experiment.

**4.1.1. Gas targets.** The ideal thin internal target is a localized volume occupied by a rarefied gas. For Cooler experiments, this was achieved by a gas jet emerging from a cooled glass nozzle, positioned a few millimeters from the stored beam (75). To maintain the ring vacuum, differential pumping was added on each side of the target region. This jet target, which served many experiments, was operated with  $\text{H}_2$ ,  $\text{D}_2$ , HD,  $\text{N}_2$ , argon gas, and water vapor (to produce an oxygen target). A target thickness of up to  $10^{16}$  atoms  $\text{cm}^{-2}$  was achieved, 85%–90% of which was in the jet itself, with the remainder distributed along 16 cm inside the first pumping stage (76).

**4.1.2. Solid targets.** Even though target foils are ruled out, solid targets are still acceptable if they intercept only a small fraction of the circulating beam, so that a given beam particle misses the target most of the time while being cooled all of the time. Early experiments with the Cooler demonstrated that, averaged over many beam revolutions, the effect on beam lifetime and energy spread is the same as that of a uniform target of equivalent thickness. Despite the effort to develop solid targets, there turned out to be little demand for them, mainly because of the severe luminosity penalty incurred by heavier targets.

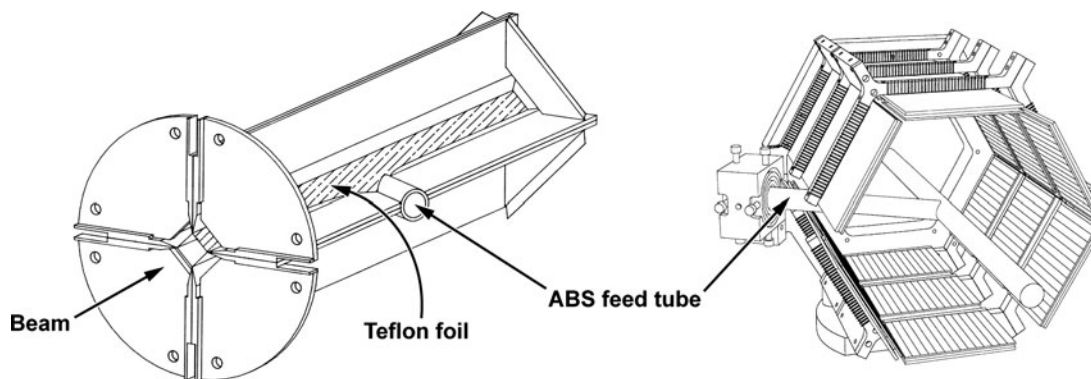
A solid internal target may take the form of a stream of micron-sized particles. Such a target is versatile because a wide range of materials is commercially available in particulate form. In the Cooler dust target, a laminar flow of a carrier gas in a capillary was seeded with the particles. This produced a narrow beam of particles exiting the capillary, where the carrier gas was removed by differential pumping. The dust beam then crossed the stored beam (77). A test with graphite particles and target thicknesses from  $3 \times 10^{13}$  to  $2 \times 10^{15}$  atoms  $\text{cm}^{-2}$  proved that such a target is feasible (78).

Thin fibers represent another choice of a nonuniform solid target. Extremely thin carbon fibers were produced by evaporating carbon through a wire grid onto a glass substrate and floating off the resulting microribbons onto a water surface, from where they could be picked up and mounted on a frame. The thinnest usable ribbons produced in this manner were  $7 \mu\text{g cm}^{-2}$  thick,  $12 \mu\text{m}$  wide, and 5 cm long (79). The time-averaged target thickness could be decreased further by periodically sweeping the fiber across the beam. The interaction of fiber targets with stored beams was investigated in detail (80). This study included the effect of fiber heating on the interaction energy spread, and of fiber charging (by secondary electron emission) on the stability of the beam. Thin fibers like these have found use in Coulomb-nuclear interference polarimeters in high-energy rings.

Skimmer targets consist of a thick slab of target material that intercepts just the fringe of the stored beam. Because the intercepted beam is lost, such a target acts as a form of slow extraction rather than a true internal target. The position of the skimmer edge has been adjusted remotely to keep the interaction rate constant. In most polarized beam studies (Section 3.2) a graphite skimmer was used to measure proton polarization.

**4.1.3. Polarized targets.** The thickness of polarized gas targets is limited by the production rate of polarized atoms. Despite impressive advances made over 40 years of development, polarized gas targets are usually too thin for conventional experiments. However, with the intense beam accumulated in a storage ring, the use of such targets became feasible (81). Polarized internal targets have unprecedented properties: They are pure, not susceptible to radiation damage, and offer rapid reversal of the sign of the polarization and free choice of its direction.

All polarized targets in the Cooler relied on a storage cell to enhance the target thickness. A storage cell is a narrow open-ended tube through which the stored-beam passes. Polarized atoms arrive at the center of the cell via a capillary or a feed tube. The cell confines the atoms to the vicinity of the beam while they drift toward the open ends of the tube. To minimize depolarization when the atoms collide with the cell wall, the cell must consist of (or be coated with) a suitable material (82, 83). Effects that influence the target polarization include the formation of molecules (Section 5.4.2), and spin-exchange collisions (Section 5.4.3). When choosing the diameter of the storage cell, one has to deal with a trade-off between target thickness and ring acceptance (which affects the beam lifetime). Experimental requirements such as minimization of background from cell walls and detectability of recoil nuclei must also be taken into account (84). Two typical storage cell targets are shown in **Figure 7**.



**Figure 7**

Two typical storage cells. (*Left*) The walls of this cell consist entirely of very thin Teflon foils (83), facilitating the observation of low-energy recoils. (*Right*) This arrangement offered full azimuthal coverage for recoil particles. The storage cell in the center is made from 25- $\mu\text{m}$ -thick aluminum; it is surrounded by 18 microstrip detectors. A polarized atomic deuteron beam from the atomic beam source (ABS) entered through the feed tubes indicated in the figure.

The orientation of the spin alignment axis is determined by a magnetic field present at the cell location. Usually, this holding field merely has to overcome the ambient Earth field, and is generated with coils outside the target chamber. For a typical cell of 1 cm diameter and 25 cm length, as used in conjunction with the atomic beam target, the target thickness was between  $10^{13}$  and  $10^{14}$  atoms  $\text{cm}^{-2}$  (85, 86).

The first polarized target installed in the Cooler used  $^3\text{He}$  atoms obtained by creating metastable atoms by optically pumping the  $^3\text{S}_1-^3\text{P}_0$  transition, and then transferring the nuclear polarization by metastability-exchange collisions to the ground state. A flow into the storage cell of  $10^{17}$  atoms  $\text{s}^{-1}$  with a polarization of  $P = 0.4$  was reported (87). The proof of principle for spin-correlation experiments in a ring was the measurement of  $\text{p}^3\text{He}$  scattering at 45 MeV and 197 MeV (88).

The second source of polarized atoms that was operated in the Cooler was an atomic beam source (ABS). In this source, polarized H and D atoms were produced by dissociating molecules, forming a beam, and then selecting a single hyperfine state (for H) or the appropriate combination of hyperfine states (for D). The selection was achieved by a combination of inhomogeneous magnetic fields and rf-induced transitions between magnetic substates. Typically, the ABS generated a beam of 1 cm diameter with a fluence of approximately  $3 \times 10^{16}$  polarized H atoms  $\text{s}^{-1}$  in a pure spin state (89). The proton polarization was approximately  $P = 0.75$ . This target was used by 13 experiments. The capability to produce polarized deuterons was added in 2002 (90).

An alternative method for producing polarized hydrogen by spin exchange with optically pumped potassium was also tested in the Cooler (91). The fluence from such a laser-driven source (approximately  $10^{18} \text{ s}^{-1}$ ) is larger than that from an ABS, but the nuclear polarization is low (approximately  $P = 0.15$ ), and there is a contamination of K atoms of a few percent.

A comprehensive review of the development of polarized gas targets for the Cooler in the context of similar work at other facilities can be found in Reference 92.

## 4.2. Detectors and Experimental Techniques

**4.2.1. Forward detectors.** In the many Cooler experiments dedicated to meson production near threshold (Section 5.1.1), it was sufficient to cover a relatively small forward cone with a detector with moderate energy and angle resolution. These requirements governed the design of the ce01 detector (93), which was in operation throughout the life of the Cooler and served numerous experiments. It consisted of two scintillator arrays, able to stop 200-MeV protons, and four wire chamber planes. The wire chambers were of a new design and featured a hole in the center (for the stored beam to pass through) bounded by a narrow ring that was supported solely by the wires and thin foils (94). The ce01 detector was capable of measuring the momenta of multiple charged particles, making it possible to reconstruct the kinematics of each recorded event. The cylindrical symmetry of the detector was essential in disentangling polarization observables.

**4.2.2. Recoil detection.** Because of the low beam halo of a stored beam, solid-state detectors could be placed just a few centimeters from the beam, traversing a

thin, windowless target to detect low-energy recoil particles (95). When operated in coincidence with a forward detector, position-sensitive recoil detectors of this type were used to localize the interaction point and to define the events of interest. Recoil detection was also used in the production of a tagged neutron beam (96, 97) (Section 5.2.2), and an array of microstrip detectors with associated electronics (98) was developed for a measurement of pion production from  $^{12}\text{C}$  via the detection of the recoil nuclei (99).

**4.2.3. Polarimetry.** All polarization measurements in the Cooler were related to the analyzing power of proton-proton (pp) elastic scattering at a fixed energy (183.1 MeV) and angle ( $8.64^\circ_{lab}$ ). This calibration point ( $A_y = 0.2122 \pm 0.0017$ ) was established by a careful measurement, relative to an absolute standard (100). This calibration could be exported to other energies by making use of energy ramping. To this aim, first the polarization of a beam stored at the calibration energy was established. The stored beam was then accelerated to the new energy, and the pp analyzing power was measured, becoming the new standard. The beam was then decelerated to the injection energy to verify that no beam depolarization was incurred while changing the beam energy (101). Thus, when used with a hydrogen target, the ce01 detector (Section 4.2.1) provided an absolute proton polarimeter for the energy range from 200 MeV to 500 MeV. For most of the polarized beam studies (Section 3.2), where absolute measurements were not essential, a carbon skimmer target (Section 4.1.2) was employed because it was more efficient and easier to use than a gas target.

The polarization of stored deuterons (12) was deduced from proton-deuteron (pd) elastic scattering, using analyzing powers from the literature. To measure the output polarization from the CIS (Section 2.2.2), a novel polarimeter had to be developed that could cope with a luminosity duty factor of  $10^{-8}$  (102).

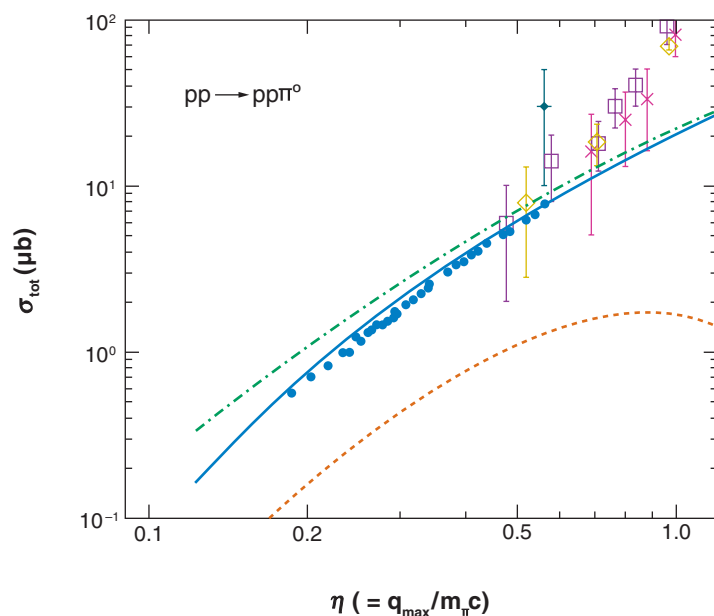
## 5. NUCLEAR AND ATOMIC PHYSICS

The intended purpose of the Cooler was to explore how a stored cooled beam interacting with an internal target might benefit nuclear physics experiments. It turned out that some of the attempted experiments were spectacularly successful, leading to data of unprecedented precision that could not have been measured in any other way.

### 5.1. Pion Production

**5.1.1. Heavy-meson exchange.** The first nuclear physics measurement with the newly commissioned Cooler was devoted to the  $pp \rightarrow pp\pi^0$  total cross section near threshold. Originally viewed as a warm-up experiment, it demonstrated dramatically how new technology often leads to surprising results and new physics.

Pion production benefits from the internal target environment in a number of ways. A pure and windowless target is crucial because it avoids heavier nuclei for which the pion-production threshold is much lower. Furthermore, with a thin target, the momenta of the emerging baryons can be measured, the mass of the produced particle can be reconstructed, and thus the events of interest can be cleanly selected.



**Figure 8**

Total cross section for  $pp \rightarrow pp\pi^0$  versus the maximum pion momentum in units of  $m_\pi$ . The solid blue dots are the Cooler data (9); all other symbols represent the data available prior to the Cooler experiment. A calculation with heavy-meson exchange is shown as a solid blue line. Also shown is the same calculation without the Coulomb interaction (*dash-dotted green line*) and without heavy-meson exchange (*dotted red line*) (105). Reprinted with permission from Horowitz CJ, Meyer HO, Griegel DK. *Phys. Rev. C* 49:1337 (1994). Copyright 1994 by the American Physical Society.

Despite the thin target, the luminosity is reasonable because intense orbiting beams can be obtained by accumulation. Emittance and energy spread of a cooled beam are small, and the absolute beam energy can be determined to a few hundred keV from measuring the orbit frequency. This is important because, near threshold, the cross section varies rapidly with bombarding energy.

The  $pp \rightarrow pp\pi^0$  total cross section data from the first Cooler experiment (103) are shown in **Figure 8**. The energy dependence of the cross section is well explained by phase space, the Coulomb repulsion between the final-state nucleons, and the final-state nucleon-nucleon (NN) interaction. [In a remeasurement in small energy steps (9), no evidence of the opening of the competing channels  $pp \rightarrow d\pi^+$  and  $pp \rightarrow pn\pi^+$  was found.] Surprisingly however, the magnitude of the cross section turned out to be five times larger than expected. At that time, the theoretical treatment included the impulse term (where the pion is emitted by one of the nucleons), with negligible contribution from rescattering (where the pion is emitted by one of the nucleons and then rescattered by the other). These findings were presented at a Workshop on Particle Production near Threshold that was hosted by the IUCF (104). It took a couple years for the theorists to realize that a process as fundamental

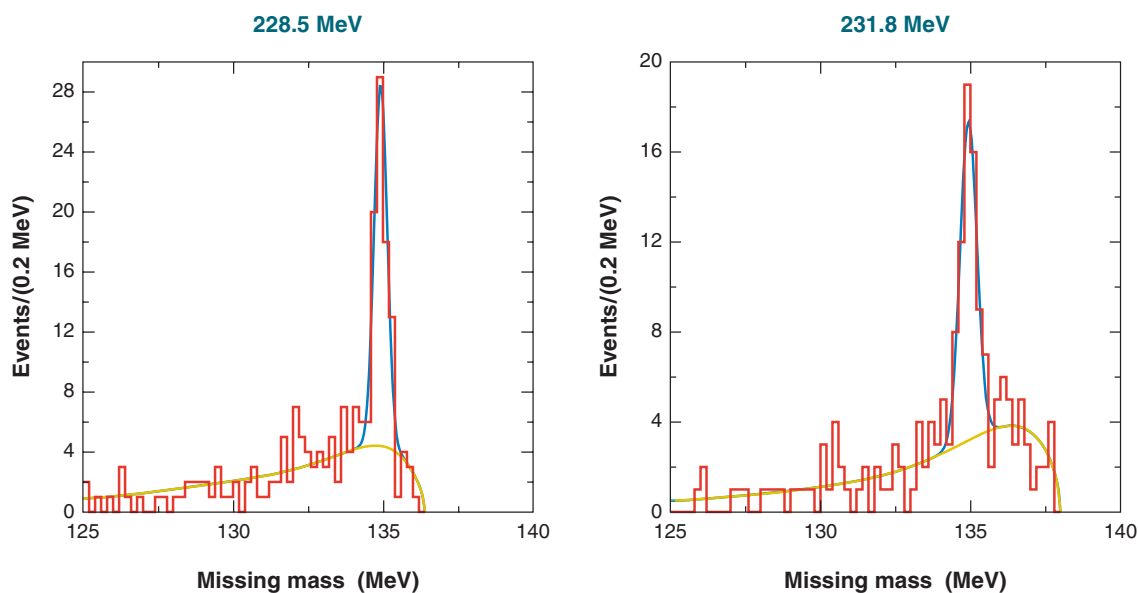
as this may not be understood. As is illustrated in **Figure 8**, the main missing ingredient turned out to be the exchange of  $\sigma$  and  $\omega$  mesons (in a Z-graph with an intermediate negative-energy state), but rescattering, driven by the off-shell isoscalar  $\pi N$  amplitude, may also be more important than originally thought. The ensuing theoretical activity included the work of local theorists (105), and is ongoing today.

The impact of the first pion-production experiment was ample justification for subsequent measurements of the  $pp \rightarrow pn\pi^+$  (106) and  $pp \rightarrow d\pi^+$  (107) cross section and analyzing-power angular distributions, and of the total  $pd \rightarrow pd\pi^0$  cross section (108, 109). Near threshold, the angular momenta in the final state are either 0 or 1. Together with the Pauli principle, and the conservation of angular momentum, parity, and isospin, this greatly limits the number of partial waves that can contribute. With polarized proton beam and target, spin-dependent total cross sections and spin-correlation coefficients could be measured, and it became possible to isolate individual partial waves. This was demonstrated for  $pp \rightarrow pp\pi^0$  (110, 111), for  $pp \rightarrow pn\pi^+$  (112, 113), and for  $pp \rightarrow d\pi^+$  (114). The culmination of this program was a complete map of all  $pp \rightarrow pp\pi^0$  observables that can be measured with both initial-state protons polarized, as a function of two angles needed to describe the three-body final state (115). This data set is in principle sufficient to determine all contributing partial-wave amplitudes, providing a stringent test of models as they are being refined. This measurement also showed that the longitudinal analyzing  $pp \rightarrow pp\pi^0$  (with three particles in the final state) can be quite large (116), even though this observable vanishes by parity conservation in reactions with a two-body final state.

**5.1.2. Chiral symmetry.** Double-pion production,  $pd \rightarrow {}^3\text{He}\pi^+\pi^-$ , has a threshold just within the energy range of the Cooler. It was studied with the expectation that some of the pion pairs in the final state would form a bound state (pionium). Measuring the branching ratio for pionium decay into two photons or two pions, respectively, would then determine the  $\pi^+\pi^-$  scattering length, which in turn is related to the breaking of chiral symmetry. The experiment was carried out just 1 MeV above threshold, where the recoil  ${}^3\text{He}$  nuclei as well as pions from unbound pairs fall into a narrow cone in the forward direction and can be detected with near 100% efficiency. A 67-pb cross section for the production of free pions was observed, but unfortunately no evidence for pionium was found (117).

**5.1.3. Charge symmetry.** The goal of the very last Cooler experiment was to measure the total cross section for the reaction  $dd \rightarrow \alpha\pi^0$ . This reaction is forbidden, unless charge symmetry is broken. The measurement was carried out at two energies close to threshold using a deuterium gas jet as a target. **Figure 9** shows missing-mass spectra with a distinct peak from the  $dd \rightarrow \alpha\pi^0$  reaction. At the lower energy, the measured cross section was  $12.7 \pm 2.2$  pb (118). This result has the potential to constrain the contributions to charge symmetry breaking by the up-down quark mass difference and by meson mixing mechanisms.

Previous attempts to measure this cross section had failed, and it is remarkable that this experiment was successful in establishing a nonzero value while facing a hard



**Figure 9**

Missing-mass spectra from the reaction  $dd \rightarrow \alpha + X$  at two bombarding energies. The peak corresponds to the charge-symmetry-violating  $dd \rightarrow \alpha\pi^0$  reaction (118). The background is due to the reaction  $dd \rightarrow \alpha\gamma\gamma$ . Reprinted with permission from Stephenson EJ, et al. *Phys. Rev. Lett.* 91:142302 (2003). Copyright 2003 by the American Physical Society.

deadline owing to the looming permanent shutdown. Thus, the last Cooler experiment, like the first one, provided another surprise, attracting worldwide attention.

## 5.2. Nucleon Scattering

**5.2.1. Proton-proton partial waves.** Much of our understanding of the NN force has been gained from the study of free NN scattering. The observables are parameterized in terms of empirical partial-wave phase shifts, which serve as the basis for tests of NN interaction models. Below 1 GeV, the main features of the pp scattering phase shifts are known quite well, and it is clear that new data can have an impact only if they have a large weight (small experimental uncertainties) and if they comprise observables that are not yet well represented in the database. These conditions were met by a new generation of analyzing-power and spin-correlation measurements in pp scattering that became possible with the Cooler.

Scattering experiments in a storage ring use a pure target, yield background-free data, and offer the possibility to measure cleanly at small angles, where the nuclear and the Coulomb amplitudes interfere. This was demonstrated by a measurement of the pp analyzing power from  $5^\circ$  to  $20^\circ$  at 183 MeV with a hydrogen jet target (119). The data proved sensitive to the small higher-order terms of the Coulomb potential (120). The start-up experiment with the polarized internal ABS target in the A region

(Section 4.1.3) was a measurement at 198-MeV bombarding energy of three of the four possible spin-correlation coefficients ( $A_{xx}$ ,  $A_{yy}$ ,  $A_{xz}$ ) from  $4^\circ$  to  $17^\circ$  (lab angle) (121). After some detector improvements that allowed the measurement to cover nearly the full angle range, this study was extended to a number of energies between 200 MeV and 450 MeV (122, 123), where previous measurements of spin-correlation data were quite sparse. The data were collected in less than one week of running time. Using a snake (Section 3.2) to make the polarization at the A-region target longitudinal, the fourth correlation coefficient,  $A_{zz}$ , was also measured at 198 MeV (124). The achieved statistical uncertainty was approximately  $\pm 0.01$ , while systematic errors were less than that, and the error of the absolute overall normalization was 2.4%. These uncertainties were considerably smaller than some of the differences between different phase shift analyses, and thus the new data improved our knowledge of the free pp interaction, in particular the higher pp partial waves and the tensor splitting parameters.

At a given polar angle, 16 yields were measured (four azimuths, with positive or negative polarization for both, the beam, and the target). A new method was developed to reduce these yields to observables, making use of a mathematical method known as diagonal scaling (125). Diagonal scaling represents a generalization of the cross-ratio method used traditionally in analyzing-power measurements.

**5.2.2. Pion-nucleon coupling constant.** The ease with which low-energy reaction products could be detected was utilized to produce a secondary, tagged neutron beam by observing the two protons from the  $pd \rightarrow ppn$  breakup reaction. An internal deuterium jet target was used with position-sensitive solid-state detectors in close proximity of the target, to provide precise reconstruction of the neutron four momentum for each event. This secondary neutron beam was used for a careful, absolute measurement of the neutron-proton (np) elastic scattering cross section near  $180^\circ$  (126, 127). From an extrapolation of the large-angle np cross section to the pion pole, the  $\pi NN$  coupling constant could be deduced. The result of the Cooler measurement was consistent with the Nijmegen 1993 partial-wave analysis, and disagreed with a previous np scattering experiment from CELSIUS in Uppsala.

**5.2.3. Off-shell interaction.** An important aspect of the force between nucleons in nuclei is its off-shell component. Models of the NN force predict different off-shell behavior. Since the early days of nuclear physics, it has been hoped that the bremsstrahlung process  $pp \rightarrow pp\gamma$  would provide empirical constraints of the off-shell NN interaction. In the 1980s, a number of new calculations became available, creating a demand for more data. The Cooler inadvertently made a contribution to this effort when it was realized that missing-mass spectra, obtained during  $pp \rightarrow pp\pi^0$  measurements, also featured a peak at zero mass, corresponding to  $pp \rightarrow pp\gamma$ . With a 310-MeV cooled proton beam on a hydrogen jet target, some 70,000  $pp\gamma$  events were collected (128). Because both outgoing protons were inside a  $20^\circ$  cone, the collected data were far off the kinematics for elastic scattering. Comparison with theory, however, was hampered by the difficulty of providing calculations that reflected the actual coverage of the three-body final-state phase space.

### 5.3. Three-Nucleon System

**5.3.1. Spin-structure function of  $^3\text{He}$ .** The  $^3\text{He}$  nucleus is of interest because it is a nuclear system with properties that can be calculated and precisely compared with data. It is also thought that polarized  $^3\text{He}$  can be used as an effective polarized neutron target in nuclear and particle physics experiments. Quasi-elastic knockout of the constituent nucleons of polarized  $^3\text{He}$  by polarized protons offers a direct method to constrain the spin dependence of the single-particle wave functions of  $^3\text{He}$ . Such a measurement was carried out with 197-MeV protons and an optically pumped polarized  $^3\text{He}$  target (87). This was the first Cooler experiment that made use of a polarized target. The measured spin-correlation coefficients for  $^3\text{He}(p,2p)$  and  $^3\text{He}(p,np)$  are described in Reference 129, while the results in terms of spin-dependent momentum distributions are discussed in Reference 130. The experiment revealed that with increasing nucleon momentum, the polarization of the neutron in polarized  $^3\text{He}$  decreases, and that the two protons have nonzero net polarization (Figure 10). These findings are in agreement with the theoretical expectation for a nucleon momentum of up to approximately 300 MeV/c.

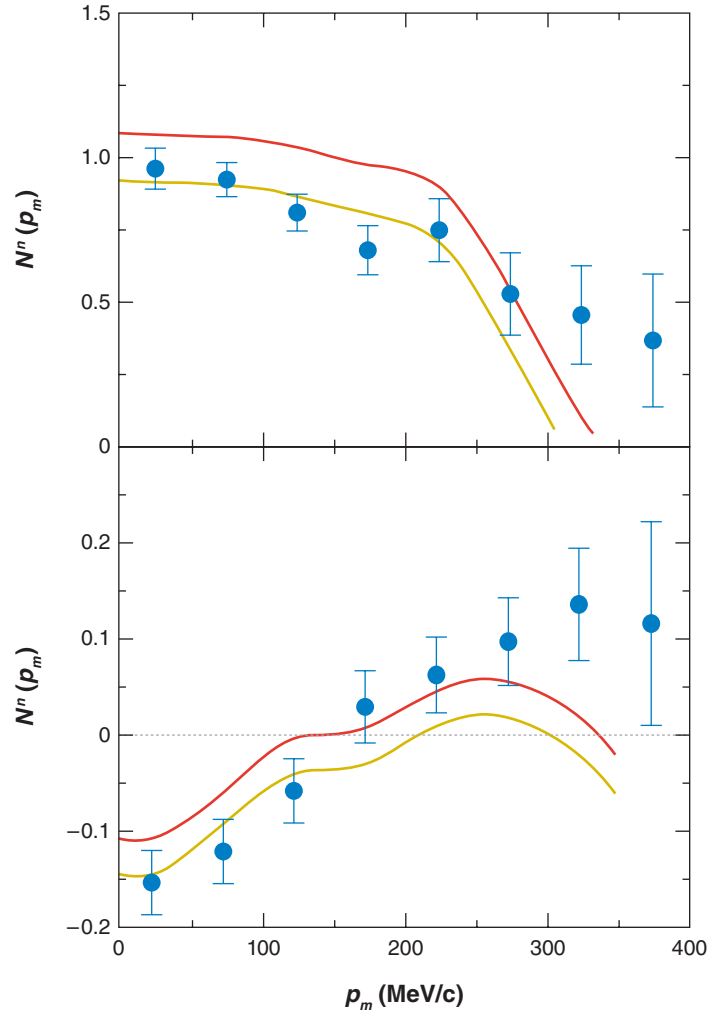
**5.3.2. Three-nucleon force.** In March 2000, the polarized ABS in the A region was upgraded to supply a vector- or tensor-polarized deuterium target, and in early 2001, the CIPPOS (Section 2.2.2) started to deliver a polarized deuteron beam to the Cooler. Having the choice of either polarized protons or polarized deuterons for either the beam or the target provided a unique opportunity to measure an almost complete set of polarization observables in the three-nucleon system. Subsequently, angular distributions for the proton analyzing power, four target analyzing powers, five vector correlation coefficients, and seven tensor correlation coefficients in pd elastic scattering were measured at 135- and 200-MeV proton bombarding energy (131).

The data were compared with Faddeev calculations that predict three-nucleon observables on the basis of a given NN potential. It is usually assumed that these calculations accurately describe how nature would behave without a three-nucleon force (3NF). Thus, discrepancies with the data are attributed to the effect of a 3NF. However, including various versions of a 3NF in the calculation did not significantly improve the overall agreement with the Cooler data. This leads to the conclusion that either the theoretically constructed 3N potentials are not realistic, or that the difference between the data and the 2N calculation is not really dominated by 3NF effects. In either case, there is no empirical evidence for a 3NF. Thus, the long-standing quest to understand the 3NF is still open, and new theoretical input is required.

A measurement of the breakup reaction  $dp \rightarrow ppn$ , carried out with a polarized 270-MeV deuteron beam on a polarized proton target, focused on the axial polarization observables  $A_y$  (longitudinal analyzing power),  $C_{y,x} - C_{x,y}$  (vector correlation coefficient), and  $C_{zz,z}$  (tensor correlation coefficient) (132). In reactions with a two-body final state, these observables are zero by parity conservation, but in the three-body breakup, they may be sizeable. A theoretical argument suggested that axial observables might be particularly sensitive to 3NF effects. To compare the data to theory, a novel method was developed to carry out Faddeev calculations in a way that

**Figure 10**

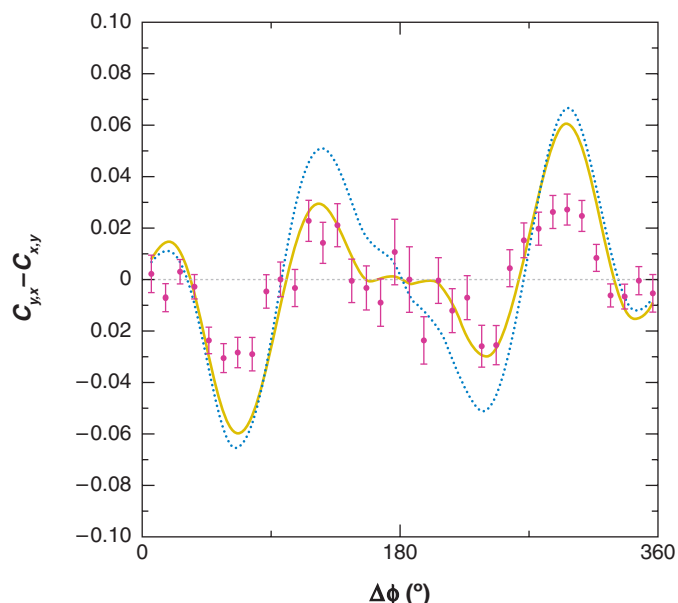
Experimentally determined polarization of the neutron (*upper panel*) and a proton (*lower panel*) in  $^3\text{He}$  versus the momentum of the nucleon. The curves indicate the limits of a PWIA model. Reprinted with permission from Milner RG, et al. *Phys. Lett. B* 379:67 (1996). Copyright 1996 by Elsevier (130).



accurately reflects the phase space covered by the experiment (133). As with elastic scattering, including a 3NF in the calculation did not systematically improve the overall agreement with the data (**Figure 11**).

In the past, evidence for a 3NF has often been claimed on the basis of a limited data set for which including a 3NF in the calculation happened to improve the agreement with the data. An example is the measurement of the proton and deuteron analyzing powers and the correlation coefficient  $C_{y,y}$  at 197 MeV for center-of-mass angles from  $70^\circ$  to  $120^\circ$  (134). The experiment was carried out with a laser-driven polarized proton target (Section 4.1.3) in the G region.

In connection with a pion-production experiment, the small-angle differential cross section of pd elastic scattering was measured with a 200-MeV proton beam (135). An internal target of HD gas was used, making it possible to relate the cross

**Figure 11**

The vector correlation coefficient  $C_{y,x} - C_{x,y}$  in pd breakup versus the coplanarity angle  $\Delta\phi$  of the two protons in the final state, measured with a vector polarized beam and target. For  $\Delta\phi = 0$  or  $\pi$ , or for a two-body final state, this observable is zero by parity conservation. The dotted and solid curves represent a Faddeev calculation with and without a three-nucleon force. For details, see Reference 132. Reprinted with permission from Meyer HO, et al. *Phys. Rev. Lett.* 93:112502 (1994). Copyright 1994 by the American Physical Society.

section normalization to the well-known pp cross section. The experiment revealed that Faddeev calculations underestimate the forward cross section by up to 20%, independent of the force model or whether a 3NF is included.

## 5.4. Atomic Physics

**5.4.1. Di-electronic recombination.** When a positive, but not fully stripped, ion captures an electron, the binding energy may be used to excite an already present atomic electron. Calculations of this di-electronic recombination (DR) depend strongly on how the electron-electron interaction is treated. At the time of Cooler commissioning, new models were being developed, and it was realized that the new technology made an electron target (the cooling beam) readily available and could yield new data to test these models (136). Because the electron excitation energy is discrete, the DR process has resonant character, with the corresponding peaks occurring at relative electron-to-ion bombarding energies of up to 50 eV. In the Cooler measurements, a beam of non-fully stripped ions orbited the storage ring once and then was stopped in a Faraday cup (the vacuum was not good enough to actually store such a beam). Recombination took place with the cooling electrons in the C region and led to neutral atoms that did not round the next corner and could be easily detected. By controlling the cooling beam energy, the electron energy in the rest frame of the atoms could be ramped over the region of interest, resulting in a measurement of DR in  $^3\text{He}^+$  (137, 138). Similar measurements of DR were carried out with  $^6\text{Li}^+$  ions (139, 140).

**5.4.2. Nuclear polarization of molecules.** A fraction of the polarized atoms in a storage cell recombines to form  $\text{H}_2$  molecules, and one would like to know to what

extent the protons in these molecules are still polarized. Recombination takes place when a polarized atom colliding with the cell wall meets an unpolarized atom that has been adsorbed on the wall. The nuclear polarization of the resulting molecule is thus  $1/2$ . The internal molecular field  $B_c$  of these molecules precesses about the external field  $B$ . At each subsequent wall collision, the polarization decreases by  $B_c/B^2$ . The predicted nuclear polarization of the molecules then depends on the external field and the number of wall collisions. A dedicated measurement of the polarization of  $H_2$  molecules was carried out with a longitudinally polarized proton beam on a longitudinally polarized target (141). The target polarization was measured by observing the pp spin-correlation coefficient  $A_{zz}$ . The formation of molecules was enhanced by admitting the target atoms into a recombination cell with copper walls. The external field dependence of the remaining nuclear polarization of  $H_2$  was in agreement with the theoretical expectation.

**5.4.3. Spin exchange in polarized deuterium.** When two atoms with antiparallel electron spins collide, both spins flip with a high probability. In a gas where mixed hyperfine states are present, such as in tensor-polarized deuterium targets, this effect modifies the populations of the substates such that they approach the spin temperature equilibrium. The rate at which this happens depends on the collision rate and thus on the density. This effect was demonstrated with a deuterium target with mixed vector and tensor polarization. Elastic scattering of unpolarized 135-MeV protons was used to measure both polarizations. The observed tensor depolarization was measured as a function of the gas density in the target cell, and was consistent with theoretical expectations (142).

## 6. AUTHOR'S COMMENTS

The Indiana Cooler represents a unique technological and intellectual achievement by a comparatively small group of dedicated people, working together with the desire to reach their common goal. I well remember the joy and pride of those involved when a cooled beam passed through an internal target for the first time. Studying how the new tool may be used for nuclear science was like opening the door to an unknown land, and tackling the technical challenges that presented themselves was a fascinating task for the scientists involved. During the following decade, the modest-sized Cooler project contributed a number of landmark experiments to nuclear and accelerator science, and became recognized as a world-class research facility. It was certainly a privilege for me and my Cooler colleagues to be a part of this effort.

### SUMMARY POINTS

1. The Indiana Cooler was constructed and operated between 1983 and 2002 at the IUCF. The facility consisted of an ion source, an injector, and a storage ring. Its declared goal was to explore the new technology of electron cooling and to demonstrate its usefulness in nuclear and particle physics.

2. Electron cooling is a method to contract the phase volume of a stored beam. It makes the use of internal targets possible and provides a beam of small emittance and momentum spread for beam dynamics studies.
3. Manipulation of beam properties becomes possible in a storage ring. Experiments made use of the possibilities to accelerate or decelerate the beam, to select its time structure, and to choose the polarization direction of the stored beam and flip its sign.
4. The Cooler research program is an example of how a new technology, applied to an existing field of research, can lead to significant advances.
5. Nuclear physics research with the Cooler benefited from the unique experimental environment offered by internal targets in a storage ring. This was demonstrated, for instance, by the study of reactions near threshold. The large, precise data sets of spin-correlation coefficients in pp and pd scattering and reactions involving polarized proton and deuteron beams and targets could not have been measured anywhere else in the world.
6. The Cooler provided a unique laboratory to explore stored-beam dynamics, including nonlinear behavior and beam instabilities. The understanding gained, as well as the related technical developments, has influenced the design of new accelerators. Examples include the management of depolarizing resonances encountered when accelerating a stored beam to high energy and the development of methods to counter intensity-limiting phenomena.

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