NEW DEVELOPMENTS AT THE IUCF COOLER RING

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As the fifth anniversary approaches of the first scientific publication from internal target experiments in the IUCF Cooler, we present selected examples of recent research activity and of concurrent facility development.

1 Introduction

The Indiana University Cyclotron Facility (IUCF) is a laboratory operated as a national user facility in intermediate energy nuclear physics by the National Science Foundation and Indiana University. The date of this conference almost coincides with the twentieth anniversary (4 October 1975) of first beam on target from the 200 MeV isochronous cyclotron at IUCF. In April 1983, construction funding was received for a major facility upgrade, to add an electron-cooled storage ring for internal target experiments. The IUCF Cooler produced its first cooled beam five years later, on April 16^{th} 1988, and has developed into an increasingly useful research tool over the intervening years.

The Cooler is both a storage ring and a synchrotron. Beams from the IUCF cyclotrons are injected and accumulated to increase the circulating current, then raised to any energy within the 3.6 T-m rigidity limit of the ring. The six-sided Cooler has four internal target sites, plus one side each filled with cooling and injection components. Cooling may be performed both during injection and again after acceleration. Electron cooling reduces all phase space dimensions of the stored beam, improving emittance, energy spread, and time spread by more than an order of magnitude, giving very precise and reproducible beam definition for scattering and reaction experiments.

More than 60 Cooler experiments have been approved for running time since the ring startup, and the machine now operates for more than half the research beam time of the laboratory. The remainder of the IUCF experimental program, while utilizing the direct external beams of the cyclotrons, gives Cooler users an opportunity for ring access to prepare targets and detectors for their experiments.

2 Physics Research with the IUCF Cooler

2.1 *Meson production near Threshold*

Threshold physics is well-suited to exploitation of cooled beam properties. A recent review is available[1].

2.1.1 *Beam Properties*

Electron cooling combined with the phase stability provided by an rf cavity in the ring locks the stored beam to a precisely specified and stable orbit frequency, so the beam velocity is determined by the ring circumference. If the lattice has a high transition energy (γ_t = 4.75 in the IUCF Cooler) then the change in orbit circumference due to a change in bending magnet field strength is suppressed by a factor $1/\gamma_t^2$. For example, by determining the beam position in a dispersed straight section to 1 mm, the circumference of the orbit is determined with a precision of 10^{-5}. For a pion threshold near 300 MeV, the momentum is known to 1.8 10^{-5} and the (relative) kinetic energy to 10 keV.

The beam energy resolution after cooling into a phase stable bucket is far better than for the uncooled beam. Neglecting space charge, the resolution could be determined directly from the measured time spread of the narrow microbunch after cooling. However it has been shown[2] that the longitudinal collective potential spreads the beam in time by an amount proportional to the 1/3 power of the beam current, and this spreading in time masks the energy resolution. An upper bound to the resolution in the pion threshold experiments is about 30 keV.

Energy variability has proven to be remarkably quick and easy (a few minutes per energy change at most) so that a multi-point excitation function is easily obtained.

The combination of precisely-specified energy, narrow energy spread and rapid energy change is the set of beam characteristics permitting detailed exploration of the rapidly-changing cross sections encountered near a production threshold.

2.1.2 *The pp→ppπ^0 reaction*

Measured[3] in 1990, this process has quantum number selectivity that strongly suppresses the normally-dominant contribution from the Δ resonance. Theoretical calculations of the single non-resonant diagram expected to give the dominant contribution underpredicted the observed total cross section by a factor of five. Explanations invoking heavy meson exchange[4,5] now give an excellent fit to the measurements, but recoil corrections and perhaps off-momentum sensitivity may contribute to the full description.

In medium energy physics, meson exchange effects at the 10% to 20% level are considered worthy of note. It is quite surprising to find an example where meson exchange increases the amplitude by more than a factor of two.

The 31 energies included in the excitation curve of ref. 5 showed no evidence of structure arising from the opening of competing meson thresholds.

2.1.3 *The pp→pnπ$^+$ reaction*

Measured with a quite different detection arrangement employing a 6^o bend in a "straight" section to separate forward reaction products from the stored beam, the results have recently been published[6], and a followup measurement using a polarized beam has had a first run. Polarization asymmetry adds information on contributions from competing amplitudes.

2.1.4 *The pp→dπ$^+$ reaction*

Measurements have been obtained[7] to within about 80 keV of threshold using polarized beam. The work is soon to be submitted for publication.

2.1.5 *The pd→pdπ^0 reaction*

This process was found[8] to have an unexpectedly small yield in the near-threshold region which was later understood[9] in the context of the underlying np→dπ^0 process as arising from the deuteron form factor.

2.1.6 *The pd→^{3}Heπ^0 reaction*

This threshold is within the energy range of the IUCF cyclotron and has been studied in an earlier external beam experiment[10]. Recently it has been employed in the Cooler as a calibration reaction for a magnetic channel being used in a search for double meson production.

2.1.7 *The pp→^{3}Heπ$^-$π$^+$ reaction*

An experiment to measure the yield of this process close to threshold near 400 MeV is underway[11]. The detection method has been shown to have a sensitivity to cross sections well below 10^{-33} cm^2

2.2 *Few Nucleon Scattering Experiments*

The Cooler ring has been used for a number of measurements in this field, described briefly below.

2.2.1 *Beam Properties*

The Cooler has been used to accumulate polarized protons since 1990. Beam currents of a few hundred nA from the cyclotron are raised in current by a factor of 10^3 using kicked injection, rf stacking and electron cooling. The process takes a few minutes. The beam may then be accelerated to a different energy for the scattering experiment and cooled again while interacting with an internal target.

The preferred location for these experiments is a non-dispersed straight where a small diameter target cell can be fixed in position without interfering with accumulation or acceleration, both processes requiring most of the momentum aperture.

The combination of a polarized beam of variable energy with a pure polarized target makes possible the measurement of spin correlation or "triple scattering" parameters. The targets[12] are very thin (10^{13} to 10^{14} nuclei/cm^2), so the cooled beam lifetime is quite long in the presence of the target material, and the slow accumulation does not reduce the macroscopic duty factor very much. A typical time cycle might have 2-5 minutes for filling the ring, a few seconds for acceleration and cooling, then 5 to 15 minutes for data acquisition.

2.2.2 *Asymmetry in pp scatter in the Coulomb-Nuclear Interference Region*

The shape of the asymmetry distribution at 185 MeV was determined in the Cooler[13], while an auxiliary experiment in the direct cyclotron beam established an absolute calibration[14] at one angle. The shape in the interference region exhibits some sensitivity[15] to the magnetic moment scattering contribution.

2.2.3 *Quasi-Free Scattering in p + 3He*

By comparing quasi-free scattering with n+p or p+p in the final state, the question of the extent to which polarized ^{3}He serves as a polarized neutron target can be addressed[16]. This is an issue of some importance for planned ^{3}He experiments in the polarized electron beam at HERA.

2.2.4 *Spin Correlation Program in p+p*

An experiment with a polarized proton target completed its production running in 1994, with more than 10^7 events recorded. Analysis is nearing completion[17], and spin correlation parameters A_{xx}, A_{yy} and A_{xz} will be available at 198 MeV with very tight statistical and systematic uncertainty limits.

In an extension of this study, spin correlation parameters are being measured[18] at a set of energies from 250 to 450 MeV. The detection apparatus has been extended in angular range, and a method of checking beam polarization after acceleration is in development to reduce the systematic uncertainties in comparing results at different energies.

2.3 *Accelerator Physics Experiments*

The Cooler has proven to be an interesting test facility for exploration of a number of beam physics issues. The laboratory provides access for beam studies on the same competitive basis as for subatomic physics, and about 20% of the running time goes to this type of research.

2.3.1 *Beam Properties*

The ring has ample space for auxiliary components. It was the long straight sections that made possible, for example, insertion of a strong solenoid and quadrupole rotators for the feasibility demonstrations of the Siberian Snake principle. The cooled beam has very small emittance, allowing fine structure of the transverse phase space to be mapped in fine detail in the non-linear orbit mechanics studies.

2.3.2 *Spin Manipulation Physics*

Studies of the manipulation of polarized beam properties began with the first polarized beam injection in 1989. Since that time an extensive and continuing program has been carried out[19]. The behavior of full and partial snakes, their influence on resonance crossings, snake resonances, synchrotron sideband resonances, and induced spin-flip transitions are among the topics studied.

During this work, it was observed that the imperfection resonance energies were shifted about 2 MeV by the combined solenoid/steerer arrays of the electron cooling straight, which were acting as an inadvertent partial Type III snake (giving spin precession about a vertical axis).

2.3.3 *Non-Linear Mechanics*

The cooled beam is kicked and a fast digitizer records the coherent betatron oscillations for a few thousand turns thereafter. The resonant island structure near a Q_x=15/4 resonance has been mapped[20]. There have also been studies of synchrotron-betatron coupling and related phenomena.

3 Cooler Development and Future Plans

The IUCF Cooler is still evolving in its technical capabilities. In this section recent performance developments are outlined, and future directions are indicated.

3.1 *Accel-Decel Mode*

The storage ring was originally configured to act also as an accelerator. However it has been possible to operate it also as a synchrotron decelerator. The advantage of this mode is that the beam which remains in the ring at the end of a data-taking interval can be returned to the injection energy for "topping up" by the next injection, rather than being thrown away prior to the return to the injection energy. Each successive injection then adds to the stored current, and over the course of a number of complete cycles, the stored current rises to a level well above that obtained in a single filling.

The deceleration, of course, takes the ring magnets through a different part of the hysteresis curve, and gaps in the original field mapping database had to be filled to permit a sufficiently accurate tracking by the various types of ring magnets through the deceleration process. The first useful operation in this mode took place in December 1994.

A measure of the present status of this development activity is the observed small loss in intensity for beam taken through a complete accel-decel cycle. The less than 1% loss per cycle is now negligible compared to the loss due to finite beam lifetime during the experiment.

For polarized beams, it is also necessary to ensure that the beam polarization survives both acceleration and deceleration. A run in July 1995 showed a polarization survival after an accel-decel cycle of 96±4% of the initial polarization. Further improvement is anticipated with tighter control of tune variations during the ramping.

When beam is dumped after each cycle, it is normal practice to reverse the spin direction at the ion source on alternate cycles for sytematic error control. When beam is retained over many cycles this method of alternation is not available. However an alternate method has been developed. A "spin flipper"[21] is used to reverse the spin direction of the stored beam once per cycle, while the ion source is also reversed on alternate fillings. In this way beam with spin up is added to a spin up stored beam on one cycle and spin down beam to spin down stored beam on the next. The frequent alternation is thus obtained without dilution. The flipper method retains about 98% of the polarization per flip.

The accel/decel mode may be of particular interest for higher energy rings where the beam loss due to target interactions is lower, and the ability to return the beam to a lower energy for recooling and further accumulation may have even more favorable effect on the average luminosity during an experiment.

3.2 HIPIOS - a more intense polarized source

Within the past year a new, more intense polarized source[22] has come into operation which permits more rapid beam accumulation in the Cooler ring. With the original commercial source in use since 1979, the highest intensity and fill rate observed in the Cooler was about 0.5 mA at 0.1 mA/min. With the new HIPIOS source, corresponding numbers are 2.4 mA and 0.25 mA/min.

There are still some transmission losses in the beam lines between accelerators and in the injection process, so these numbers are expected to improve with further experience. The HIPIOS source has been available to Cooler users for about one year.

3.3 CIS- a new injection alternative

In 1994, construction funding was received for a new Cooler Injection Synchrotron (CIS) which is intended to provide an alternate path for Cooler injection. The CIS design will have a commercial RFQ and 7 MeV linac feeding a synchrotron with 1/5 the circumference of the Cooler. The ring should provide a Cooler polarized beam fill in seconds rather than minutes. The primary benefit will be to experiments using thicker targets of higher Z which give shorter beam lifetimes. The present slow filling methods limit the luminosity for such experiments.

3.4 LISS - a higher energy future upgrade for IUCF

The experimental utility of the Cooler in the range below 1 GeV/c has prompted interest in the prospect for applying the same cooled-beam internal-target techniques over a wider beam energy range. The laboratory is developing a proposal[23] for a synchrotron using the present Cooler as injector. The new machine would have a racetrack geometry with long straight sections for internal target experiments. Beams up to about 20 GeV/c would be produced.

4 Conclusion

Cooling rings are no longer a novelty, but are beginning to take their place as an enabling technology in several fields, including atomic, nuclear, particle and beam physics. The Indiana Cooler has produced new information on threshold meson production, on polarization phenomena, and on the beam physics of spin and orbit dynamics. The strengths and limitations of these devices in internal target experiments are becoming better understood, and the future of this technology is promising.

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References

1. H. O. Meyer, Acta Physica Polonica **B26** 553 (1995).
2. T. Ellison et al, Phys. Rev. Letters **70** 790 (1993).
3. H. O. Meyer et al, Phys. Rev. Letters **65** 2846 (1990); Nucl. Phys. **A539** 633 (1992).
4. T.-S. H. Lee, D. O. Riska, Phys. Rev. Letters **70** 2237 (1993).
5. C. J. Horowitz, H. O. Meyer, D. K. Griegel, Phys. Rev. **C49** 1337 (1994).
6. W. Daehnick et al, Phys. Rev. Letters **74** 2913 (1995).
7. R. Segel, private communication.
8. H. Rohdjess et al, Phys. Rev. Letters **70** 2864 (1993).
9. H.O. Meyer, J. A. Niskanen, Phys. Rev. **C47** 2474 (1993).
10. M. A. Pickar et al, Phys. Rev. **C46** 397 (1992).
11. W. Jacobs et al, IUCF Annual Scient.&Techn. Report, 1995.
12. W. A. Dezarn et al, Nucl. Instrum. Methods **A362** 36 (1995).
13. W. K. Pitts et al, Phys. Rev. **C45** R1 (1992).
14. B. v. Przewoski et al, Phys. Rev. **C44** 44 (1991).
15. K. Pitts, Phys. Rev. **C45** 455 (1992).
16. M. A. Miller et al, Phys. Rev. Lett. **74** 502 (1995).
17. W. Haeberli, Proc. Polarized Target Conf., Köln, June 1995.
18. B. v. Przewoski et al, IUCF Annual Scient.&Techn. Report, 1995.
19. R. A. Phelps et al, Phys. Rev. Lett. **72** 1479 (1994).
20. S. Y. Lee et al, Phys. Rev. Letters **70** 591 (1993).
21. B. v. Przewoski et al, to be published, Rev. Sci. Instrum. **66** (Dec. 1995).
22. M. Wedekind et al, Proc. 1993 IEEE Particle Accel. Conf., p. 3184, IEEE 93CH3279-7.
23. Visit IUCF on the World Wide Web: http://www.iucf.indiana.edu:80/publications/LISS.html for more information on the LISS proposal and its scientific motivation.