PRESENT STATUS OF ION COOLER RINGS

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Abstract

With an exploitation of technique of strong phase-space-compression, beam cooling, it becomes possible to study experimentally a new phase of physics. Examples of the subjects presently performed or conceived are as follows.

A large number of partially stripped heavy ions accumulated in a ring, could be used for a unique atomic physics such as the dielectronic recombination with dense electron target which has not been performed in the traditional method. In the fields of nuclear and particle physics, the experiment with better precision of pion threshold phenomena and rare decay of vector mesons, are expected with simultaneous use of windowless internal target and beam cooling. The accumulation and cooling of radioactive ions produced in the process of target- or projectile-fragmentation, will open an experimental arena for the deep insight of nuclear structure. Extreme phase space compression with laser cooling, would give a chance to find out a condensation phenomena of beam crystallization with a large value of plasma order parameter.

In view of these scientific motivations, ion cooling rings have been constructed at many laboratories during this decade allover the world and severals are planned. This paper reviews on the present activities at major cooling rings presently in operation or under construction, from the point of view of accelerator technology.

I. INTRODUCTION

Storage rings were developed firstly for the collider experiment to get a large center-of-mass energy, and culminated in the discovery of weak bosons W and Z with the innovation of stochastic cooling.[1] Accumulation and cooling of anti-protons, are presently inevitable tool for the hadron colliders so as to obtain a good luminosity. Being stimulated by this marvelous technology, ion cooling rings have been built in this decade for the study of nuclear- and atomic-physics where electron coolers are employed instead of stochastic cooling, taking advantage of its fast cooling at relatively low energy [2] and its possible use as an electron target. The first period of ion cooling rings could be defined as the beginning of ICE experiments in 1979 [3] and the successful operation of LEAR. The success of stacking of cyclotron beams with the combination of multi-turn injection and RF stacking and the stochastic cooling of low energy beams in TARN[4] , shortly thereafter showed the possibility of cyclotron injector. Following these activities, many laboratories started the construction of ion cooling rings. The electron cooling system installed in LEAR in 1987[5], was a first second-generation of electron cooling device, routinely operated successfully. In 1988 electron cooling was in operation at IUCF and MPI Heidelberg TSR, in 1989 at TARN II, and in 1990 at CELSIUS and ESR. ASTRID in Denmark is noteworthy of laser cooling equipment in 1990. The beam injection was performed at CRYRING at the end of 1990, and COSY in Julich is scheduled to be commissioned in 1992.

II. OPERATIONAL RESULTS OF ION COOLING RINGS

A. IUCF COOLER

The IUCF COOLER[6] is a 3.6 T.m ring that has been in operation since 1988. Beams are injected from the 200 MeV isochronous cyclotron with use of the stripping injection for H^{2+}, D^{2+}, $^{3}He^{+}$ ions and the RF-stacking for

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polarized beam. In both cases the electron - cooling- stacking method, is used. The stored current is around 1 mA for light ions and 0.3 mA for polarized beams. Cooling injection is applied with 0.4 sec interval and the current is presently limited by coherent instabilities. The proton beams are accelerated from 45 MeV to around 300 MeV to measure pion production cross section near threshold. Electron cooling is applied at the injection energy and then again at the flattop energy on each acceleration cycle. This "cool-ramp-cool" cycle allows cooling-stacking prior to acceleration. The cooled beam makes reduced demands on the ring aperture, increasing tolerance to closed orbit distortions during the rampig.

The electron-cooler with a maximum energy of 250 keV and a current of 2A, is routinely operating without trouble. They reported more than 7000 hrs of electron beam operation with 99 % reliability. Typical cooling time are a fraction of second for 200 MeV proton beams.[7]

Noteworthy is a polarized beam operation with use of Siberian Snake of the first kind to avoid the depolarization effect through the passage of resonances. The crown jewel of IUCF COOLER is a first demonstration of practical use of internal target with cooling.[8]

B. TSR

The Heidelberg heavy ion storage ring TSR[9] was commissioned in 1988 and was the first heavy ion cooler ring, especially used for atomic physics experiments. Injector is a combination of tandem and post-linear- accelerator with an energy of around 10 MeV/u. Several injection schemes were used at TSR, namely multi-turn injection, RF-stacking and RF-stacking with simultaneous phase space cooling. Due to the good beam quality of the injector (momentum spread $\Delta p/p = 2\times10^{-4}$ and emittance $\varepsilon = 1.5\ \pi$ mm.mrad) and the large acceptance 120 π mm.mrad and momentum acceptance of the ring + 3 %, they finally obtained the stored current up to 18 mA, that is more than 3×10^{10} C^{6+} particles.[10]

Outstanding is the first observation of collective motion of the stored particles with high density. Schottky noise spectrum shows the double peak structure, where the peak splitting is proportional to the square root of the beam intensity. This splitting comes from the beam induced waves co- and counter-rotating with beam.[11]

Another fruitful result is the first success of laser cooling of $^7Li^+$ and $^9Be^+$ in the cooler ring.[12] The frequency of the Argon laser was set to be in resonancne with ions at the low-energy side of the beam velocity distribution. On the other hand the frequency of the counter propagating dye laser was set to the high-energy side and was swept towards lower energies. Ions which came into resonance with the light of the dye laser experienced absorption-emission process and were decelerated due to the transfer of photon momenta. The initial and cooled velocity distribution were measured by detecting the fluoresent light perpendicular to the ion beam. They obtained a cooled ^7Li ions with temperature of 3 K from the initial value of 300 K.

C. LEAR

In view of the high intensity heavy ion beams at SPS and LHC, several schemes of ion accumulation and cooling are designed at CERN.[13] Stacking and cooling in LEAR is one of key issues for this program. They demonstrated the ability to store and accelerate dense heavy ion beams.[14] Oxygen ions are injected from the LINAC I at 11 MeV/u. The longitudinal stacking method where the RF systems with harmonic number 1 and 2, are employed. During the stacking process, electron cooling was applied to prevent the dilution of phase space. They obtained an average intensity of 8×10^9 charges, corresponding to 20 LINAC burst in 30 injections. The electron cooling experiments were made on O^{8+} beam at the injection energy, which corresponded to the electron energy of 6.23 kV and 250 mA current. The final value of the momentum was measured to be around 4×10^{-4} and emittances were of the order of 3 π mm.mrad. After the beam injection, they accelerated the ions to 408.5 MeV/u within 8 seconds and were extracted with ultra-slow extraction method.

D. TARN II

Following the successful achievement at TARN I ring , TARN II was constructed at INS, Univ. of Tokyo and is in operation since 1989. It has a magnetic rigidity of 5.8 Tm with the circumference of 78 m.[15] Again the injector is a isochronous cyclotron with K number of 68. TARN II was built essentially for the study of accelerator physics including the electron cooling, RF acceleration and beam extraction. Possible use of TARN II in the scientific fields of atomic and nuclear physics are presently discussed.

The electron cooler with a maximum electron energy of 120 keV, is used for the study of electron cooling.[16] The momentum spread of 10^{-5} was attained for the 20 MeV proton beams and also the splitting of Schottky noise signals were observed which indicated the collective phenomena.

The detection of neutral beams created in the cooling section gives a useful information on beam quality. The emittance of cooled beam measured with this method gives a numerical results $\varepsilon x = 0.85\ \pi$ mm.mad and $\varepsilon y = 2.0\ \pi$ mm.mrad and the ion beam size of Ax = 2.1 mm and Av = 1.5 mm. Cooling stacking method was tried to give the intensity increase of 20 after 30 injection in a time of 2 min, resulting in the stored prticle number is 10^8.

The beam acceleration was successfully attained up to 120 MeV/u for the alpha particles. The RF acceleration system, composed of an RF cavity of single gap, ferrite-loaded, can produce 2 kV acceleration voltage. The frequency range is covered from 0.6 to 8.0 MHz corresponding to the proton top energy of 1100 MeV. Phase and radial orbit feedback loops in the low level RF electronic sysem are routinely used for the beam acceleration at the low intensity beam less than 10^7. The slow beam exraction with third integer resonance is tried and the beam spill time of 0.7 sec was successfully achieved.[17] Study on the detailed extraction scheme is in progress.

E. ESR

The ESR at the GSI in Darmstadt is designed to store and cool ion beams as heavy as uranium. The maximum energy is 830 MeV/u for ions with charge to mass ratio of 0.5 and 550 MeV/u for fully stripped uranium.[18] The typical scientific objectives for ESR are the atomic physics of heavy ions with electron and laser photons, the accumulation of radioactive beams produced with the target fragmentation by the injector synchrotron SIS and cooler and sretcher for SIS. After the first beam injection from SIS to the ESR at the beginning of March 1990, they performed the beam accumulation and cooling experiments with use of mainly Ar^{18+} ions. Two bunches are transferred from SIS to ESR and the preliminary test of RF stacking was performed.

The electron cooling experiments show the improvements of momentum spread from the initial value 7×10^{-4} to 1×10^{-5} within the cooling time around 1 sec.[19] They also observed the double peaks of the cooled Ar ion beams. Due to the relatively low intensity beams, the enhancement of the sensitivity of several kinds of beam diagnostic system, such as beam position monitor etc. are required.

F. CELSIUS

CELSIUS is a storage-cooling-acceleration ring for protons and other ions from the Gustaf Werner Cyclotron in Uppsala. The ring, with a maximum rigidity of 7 Tm, corresponding to a proton energy of 1360 MeV, is intended for intermediate-energy physics, elementary-particle physics, and heavy-ion physics with internal targets.[20] The dipole magnets were previously used in the ICE ring at CERN and are solid-core combined function type. The acceleration time is therefore as long as 22 sec in order to suppress the eddy current effects. With the multi-turn injection, the number of stored protons was 10^8, using cyclotron beam pulse with of 30μ s, whereas more than two orders of magnitude higher intensity was attained with stripping injection, converting 96 MeV ions of H^{2+} into pairs of 48 MeV protons in a 20μ g/cm2 carbon foil. They tried also the cooling accumulation method and the equilibrium between injection and losses was attained at 10^{10} protons stored.[21] The beam acceleration was performed with the ferrite loded RF cavity. The maximum voltage is 1.6 kV and the frequency range is from 0.4to 5.0 MHz. They accelerated the protons to 1105 MeV just under the transition energy with a phase loop stabilization. Radial orbit feedback loop is not presently installed which is inevitable for transition energy crossing.

The electron cooler is completed with a maximum energy of 300 keV and current of 3 A. Electron cooling experiments were performed at the proton injection energy of 48 MeV, when the electron energy is 26 keV. The momentum width of 2 x 10^{-4} was obtained with cooling and the splitting of Schottky peaks were observed. The large 4 pai detector WASA, is being constructed for the investigation of extremely rare particle decays and rare reactions. The frozen hydrogen pellets are conceived as internal targets to achieve the necessary counting rate.

G. ASTRID

ASTRID at Aahus is a small 2.0 Tm ring of 40 m circumference. In this ring it is aimed at two different purposes, namely a storage of heavy ions injectd from an electrostatic accelerator of 30 - 200 keV, and a synchrotron light source with a maximum electron energy of 600 MeV. Presently they make mainly on laser coolin experiments with heavy ions. The experimental set-up for cooling is similar to that at TSR and they stored the $^7Li^+$ beam at 100 keV. The longitudinal temperature as low as 1 mK was realized, correspnding to a momentum spread $\Delta p/p = 10^{-6}$. Rapid intrabeam relaxations in the initially transversely warm and longitudinally cold beam were observed.[22]

H. CRYRING

CRYRING is a heavy ion storage ring with a magnetic rigidity of 1.4 Tm being built at Manne Siegbahn Institute of Physics at Stockholm.[23] Injector is a four-rod RFQ linac with the injection energy of 10 keV and the output energy of 300 keV with the charge to mass ratio larger than 0.25. Ion sources are cryogenic EBIS source with the repetition of around 1 Hz. The ring has a large acceptance $\varepsilon x = 200\ \pi$ mm.mrad, $\varepsilon y = 100\ \pi$ mm.mrad to allow a low energy ions. The beam is injected with multi-turn injection method and is accelerated to the final energy 96 (q/A)2 MeV/u with a non-resonant drift-tube cavity. The frequency range is large, 10 kHz to 1.5 MHz, and the gap voltage is 3700 V with the RF power of 10 kW. The ramping is 150ms for the low energy partially stripped ions. The electron cooler will cool highly charged heavy ions with energy from 3.6 MeV/u, requiring 2 keV elecrons , up to the highest ion energies, 13.5 keV electrons. It shall also be used as an electron target for atomic-physics experiments. Beam injection was firstly done at the end of 1990 from RFQ linac. Installation of e-cooler is scheduled in the autumn 1991.

I. COSY

The COoler SYnchrotron at Julich is a light ion and medium energy accelerator which has a circumference 184 m and two long straight sections 40m in length each.[24] Two long straight sections are designed to be matched at the end of circular sections so as not to disturb the symmetry in the ring. One section is dedicated for internal target experiments and the other is used for electron cooler, RF cavity and beam diagnostic system. Injection will be done from Julich isochronous cyclotron with charge sripping method of 80 MeV H^{2+} ions. Acceptance is 130 π mm.mrad for horizontal direction at the momentum spread $\Delta p/p = + 0.5$ % and several times 10^{10} protons are expected to be stored.

The electron will be provided to increase the injection efficiency and 22 keV electron cooler is designed fitting to the injection energy of 40 MeV. In a later step, the electron energy will be increased to 100 keV to allow electron cooling at 200 MeV protons. Noteworthy is a installation of wide band 2 GHz stochastic cooling system which will be used at medium energy range 800 - 2500 MeV. The cooling time at 2500 MeV is around 1 sec for 10^8 particles and 24 sec for 10^{10} particles. The acceleration to the top energy is performed with an RF cavity of 5 kV gap voltage and at the flat top the internal target experiments or ultra slow extraction of third integer resonance will be performed.

First injection and commissioning is scheduled in 1992 and the first experiments will start in 1993.

J. OTHER RING PROJECTS

A very large cooler synchroron, ADRIA, circumference 267 m, rigidity 22.5 T.m is planned at the INFN at Legnaro in Italy.[25] Injector will be a ALPI Superconducting-Postaccelerator under construction. The scientific motivation is put on the production and accumulation of exotic radioactive beams.

In the Soviet Union, several ring projects are proposed. At JINR, the complex of shaping ring (4 Tm) and synchrotron ring (11 Tm) are designed to accumulate exotic neutron rich ions with lifetime longer than 0.1 sec and to make an internal target experiments. At the Kurchatov Institute, small cooler ring (3 Tm) is proposed to perform a precision nuclear physics experiment. At the Institute for Nuclear Research (INR,Kiev), a heavy ion storage ring (4.3 Tm) is planned for beam acceleation up to 400 MeV for proton and 200 MeV/u for heavy ions. The injector is a U-240 isochronous cyclotron.

III. CONCLUSION

Experiences and knowledges concerning the ion cooler rings, have been integrated over the past decade at many laboratories. It is proved that the electron cooling could be effectively used for the non Liouvillian handling of beams such as accumulation of ions with cooling stacking method. Nuclear-and atomic physics experiments so far performed, though they are still preliminary stage, show the un-heard usefulness of the cooler ring. The laser cooling attained miliKelvin temperature which is three orders of magnitude less than that of e-cooling. The physics utilizing these excellent features, has just started and more elaborate and hard works will be needed in the fields of accelerator and physics, to come to the real fruition in the next decade.

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