Heavy Ion Storage Rings

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Summary

The success of phase space cooling of proton and antiproton beams by electron cooling and stochastic methods as well as the impressive developments in the technology of heavy ion accelerators have initiated a large number of heavy ion storage ring projects allover the world. The class of the small rings designed for low energy ions of typically less than 10 MeV/u is almost exclusively dedicated to atomic physics, as the new test storage ring TSR at the Max Planck Institut für Kernphysik in Heidelberg, that has achieved first electron- and lasercooling of heavy ions. TSR is closely followed by the projects ASTRID in Aarhus and the CRYRING in Stockholm. The large Storage Ring ESR at the GSI Darmstadt, able to store and cool fully stripped uranium ions with energies up to 500 MeV/u has just entered the commissioning phase. This paper gives a review on the major storage ring installations presently in operation or under construction.

Introduction

At present more than 15 heavy ion storage rings.- Fig.1 shows as an example the Test Storage Ring TSR at the Max Planck Institut für Kernphysik Heidelberg -, are in operation, in the status of construction or advanced planning.

Already in the late sixties and early seventies vacuum technology at the ISR[4] advanced that far, that pressures in the 10^{-11}-10^{-12} Torr range could be maintained in a vessel as large as the ISR chambers. Heavy ion storage rings, where scattering and charge changing by stripping or electron capture in the residual gas mainly determines the lifetime of the ions, profited enormously from the developments of new material, pumps and heating procedures.

Ion sources now available as the EBIS-CRYEBIS[5] versions developed by Donets and Arianer and the ECR[6] sources by Geller provide today particles in high charge states with good intensities, that make the accumulation of 10^{10}- 10^{11} ions possible in the times determined by the dominant loss mechanisms of the rings. Even Tandems, notoriously known for their low intensity, have become useful injectors by the Thieberger type[7] pulsed negative ion sputter sources and inject for example heavy ion beams into the AGS.

No new installation today is conceivable without the RFQ invented by Kapchinskij[8] and brought to full applicability by the groups in Los Alamos and Frankfurt. The availability of powerful computer codes for lattice, magnet and cavity design as well as for beam dynamics investigations are widespread and have or will assure a fast pace in construction and successful completion of these heavy ion rings.

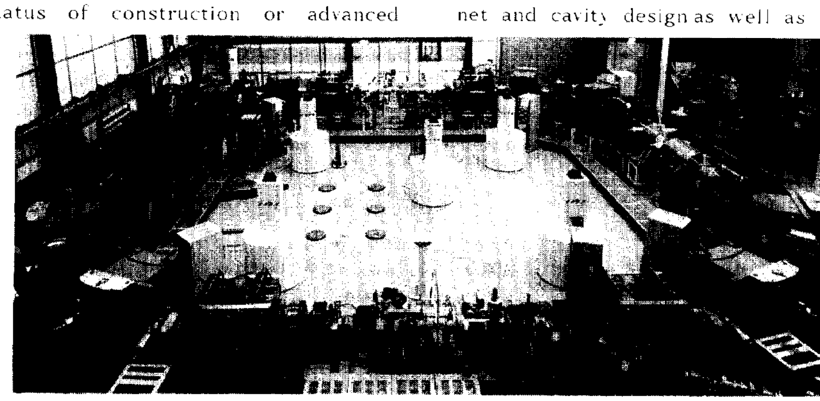

Fig. 1: The Heidelberg Test Storage Ring for Heavy Ions TSR.

The great success of phase space cooling that led to the discovery of the W and Z bosons at the CERN SPS as well as the impressive small cooler ring for low energy antiprotons LEAR surely gave the big impetus for these activities. Nearly all of the new machines will either use stochastic cooling[1] or electron cooling[2]. Even the newly developed method of laser cooling[3] demonstrated 1989 at the TSR in Heidelberg and also lately at ASTRID in Aarhus will influence the further developments of these rings.

Last not least all these projects were made possible only by other very important, although perhaps not quite that spectacular, further advances in accelerator physics and technology:

These new machines will provide exciting possibilities in many fields of physics. In accelerator physics the cooling processes themselves are a "hot" issue. The extreme phase space compression by electron and laser cooling may be carried that far, that the long range coulomb forces between the highly charged heavy ions will ultimately dominate the thermal motion in the beam leading to order phenomena and even beam crystalization.[9]

Heavy ions in almost any possible charge state together with photons of powerful lasers and the electrons of the cooler that can also be adjusted to a finite relative energy open up a unique new field of atomic physics, where for example the process of dielectronic recombination (DR) can be examined with unprecedented accuracy. The data thus obtained are of high importance for fusion plasma in which energy leaks out via the photons following the DR in contaminant ions[10]. Also X-ray production in thin hot stellar coronae is hoped to become accessible in the laboratory test bench cooler ring.

The domain of nuclear physics at the higher energy, proton or light ion cooler rings is clearly in precision experiments with thin internal targets. Electron cooling is essential to balance the heating in the gas jet or fiber targets due to multiple scattering. Luminosities obtainable with about 10^{10} protons of 200MeV stored in the CELSIUS ring[11] are in the range of some 10^{30} cm^{-2} s^{-1} for a gas jet target thickness of typically 10^{14} atoms/cm^2 up to 10^{32} $cm^{-2}s^{-1}$ for carbon fibers with diameters of about 5 μm.

Polarized atomic beam targets, which profit from the development of the storage cell by the Madison group are expected to give a target thickness also in the 10^{14} atoms/cm^2 range. The FILTEX experiment[12] at the TSR and later at LEAR will use such a cell to polarize stored protons or antiprotons by spin-dependent interaction of the circulating beam particles with the polarized hydrogen atoms. This might be the only viable way to polarize low energy antiprotons.

This article reviews the major storage ring installations presently operating or under construction.

The Storage Rings

In Table I alltogether 15 heavy ion storage rings are listed according to the maximum magnetic rigidity B*ρ of their dipole magnets. The information summarized there is meant to give only an overall description of the rings, like their sizes, their injectors, the ion species stored and specialties at the individual location. In the following most of the machines are described in more detail

Table I: HEAVY ION COOLER STORAGE RINGS

Location	Injector	Bρ (Tm)	C (m)	Cooling	Ions	Operation	Specialties
MIMAS/Saclay	CRYEBIS/RFQ	1.0	36.8	-	p,d,C,Kr	1987	Betatron Stacking
TARN I/Tokio	Cyclotron	1.2	32.0	Stochastic	p,He,C	1979-85	MT-RF-Stacking
CRYRING/MSI	CRYEBIS/RFQ	1.4	52.0	ECOOL	HI<Xe	1990?	Fast Ramp
TSR/Heidelberg	Tandem/Linac	1.5	55.4	ECOOL	p to J	1988	First Lasercooling
				Laser			First HI-ECOOL
ASTRID/Aarhus	Separator	2.0	40.0	Laser	He,Li,Ne,Ar	1990	SR-Lightsource
COOLER/IUCF	Cyclotron	3.6	87.0	ECOOL	p,p(pol.),He,Li	1987	First S.-Snake
LEAR/CERN	ECR/Linac	6.7	78.0	ECOOL	p,pbar,O	1982	HI- 1988
	Synchrotron			Stochastic			
TARNII/Tokio	Cyclotron/ECR	6.1	78.0	ECOOL	p.He,HI<Ne	1989	Double Op.Mode
CELSIUS/TSL	Cyclotron/ECR	7.0	82.0	ECOOL	p,HI<Kr	1988	Jet Target/ICE
ESR/GSI	UNILAC/	10.0	108.0	ECOOL	up to U	1990	Exotic Beams
	SIS-Synchrotron			Stochastic			
COSY/KFA	Cyclotron	11.7	184.0	ECOOL/ST.	p,light HI	1992	Hadronic Physics
ADRIA/INFN	Tandem/SC-Linac	22.5	266.	ECOOL	up to U	?	Exotic Beams
K4/K10/Dubna	U400-Cyclotron	4.0/10.0	88./110.	ECOOL	up to U	1994/95?	Exotic Beams
Kurchatov	Cyclotron	3.0	51	ECOOL	^3He to ^{20}Ne	?	Nuclear Physics
Kiev	U240 Cyclotron	4.5	56	ECOOL	p to Ar	?	Nuclear Physics

MIMAS

Although not equiped with phase space cooling devices, MIMAS [13], the low energy (187.5 keV/u) accumulator and booster ring for SATURNE is included in this survey because many other of the interesting features of heavy ion rings have been incorporated. MIMAS, as TARN I [14] surely belong to the pioneering heavy ion machines. MIMAS is a 8 period little fast ramping (5T/s) synchrotron with a maximum magnetic rigidity B*ρ of 1.0 Tm. It is injected with heavy ions from an EBIS source and a RFQ at a flat bottom of 0.125 Tm, with polarized protons and deuterons at 0.088 Tm and 0.125 Tm respectively. To have sufficiently long beam lifetimes at the corresponding low velocities, a vacuum of typically $5 \cdot 10^{-11}$ Torr is maintained. Multiturn injection is done decelerating the particles by a betatron core (U_{dec}= 500 V). The particles accelerated by two rf-cavities to full rigidity are ejected by fast kickers. Intensities of $1.5 \cdot 10^{11}$ protons, about 10^9 $^{12}C^{6+}$, 10^8 $^{40}Ar^{16+}$ and $2 \cdot 10^6$ $^{84}Kr^{30+}$ ions can routinely be transferred to SATURNE.

TARN I

TARN I ,- a 1.2 Tm ring of 32m circumference -, was operated between 1979 and 1985 as test accelerator ring for NUMATRON. Injected from the INS cyclotron it was the first small ring using a combination of multiturn injection and rf-stacking. With this combined method beams of p, $^4He^{2+}$, and $^{12}C^{4+}$ could be stored with intensities between 10^9 and 10^7. Experiments with stochastic cooling were performed at 7 MeV proton and 28 MeV $^4He^{2+}$ beams and gave results of a momentum spread improvement from 10^{-2} to $6 \cdot 10^{-4}$ for 10^7 He ions. TARN I stopped operation in 1985 to give room (and components) to the follow up project TARN II.

CRYRING

CRYRING[15] is a heavy ion storage ring with a magnetic rigidity of B*ρ=1.4 Tm and a circumference of 52 m. It is under construction for mainly atomic and molecular physics at the Manne Siegbahn Institute of Physics, Stockholm. Ions from a cryogenic EBIS source will be accelerated by a four-rod RFQ [16] to an energy of 0.3 MeV/u. Due to this rather low injection energy, ramping has to be done fast, i.e. in 0.2 s to the top magnetic rigidity . Together with the provisions for excellent vacuum this fast ramp should ensure beam lifetimes long enough to do experiments with the internal electron target ,- the electron cooler is a very attractive device for atomic physics itself -,and ion beam targets in crossed or merged geometry. As of June 1990 the status of the project is as follows: All magnets are delivered and aligned, the vacuum chamber is in production. The RFQ has been successfully tested with beam, the ECOOL system is being assembled. First injection could be expected for end of this year.

TSR

The Test Storage Ring TSR [17] ,- $B\cdot\rho$=1.5 Tm, circumference 55.4 m -, at the Max Planck Institut für Kernphysik Heidelberg , was the first ring in operation to store and electron cool as well as laser cool heavy ions. Commissioning of the ring started middle of 1988 with the accumulation of 73.3 MeV $^{12}C^{6+}$ beams. Already in fall of the same year experiments using the electron cooler were started [18]. First successful laser cooling of $^{7}Li^{+}$ and $^{9}Be^{+}$ ions [3] was demonstrated in 1989. To illustrate the large variety of ions that has been stored and electron cooled in the TSR in the last 2 years, table II shows cooled and uncooled beams ranging from protons to copper ions with lifetimes of 36 hours to a few seconds. The main loss mechanisms multiple scattering, stripping, electron capture in the residual gas and capture of cooler electrons are indicated.

Table II: Lifetimes of Cooled Beams in the T S R

Ion	Energy (MeV/u)	Pressure (10^{-10} mbar)	Beam Lifetime cooled (s)	Beam Lifetime uncooled (s)	Explainable by :
p	21.0	0.8	130000	11000	M.S.
d	6.1	1.0	24000	--	M.S
$^{7}Li^{1+}$	1.3	0.5	26	20	Str.
$^{9}Be^{1+}$	1.5	3.0	--	3	Str.
$^{12}C^{5+}$	4.3	4.0	11	10	Str.
$^{12}C^{6+}$	6.1	4.0	720	155	M.S.
$^{12}C^{6+}$	11.7	0.7	4100	17000	ECC
$^{16}O^{6+}$	3.4	2.0	16	14	Str.
$^{16}O^{7+}$	8.9	0.7	400		
$^{16}O^{8+}$	6.1	5.0	260	200	M.S.
$^{16}O^{8+}$	11.7	0.7		3600	M.S.
$^{28}Si^{14+}$	4.1	0.6	440	440	REC
$^{32}S^{16+}$	6.1	0.5	200	206	REC
$^{63}Cu^{25+}$	4.2	0.5	--	43	REC

M.S. Multiple Scattering, Str. Stripping, ECC Capture of Cooler Electrons
REC Capture of Electrons in the Residual Gas

TSR has a number of unique features:

--- Combined multiturn, rf-stacking and electron cooler stacking, that has produced particle stacks of intensities as high as $3 \cdot 10^{10}$ [19].

--- A large momentum acceptance of +/- 3% that will allow multi charge state operation. First tests with $^{63}Cu^{25+/24+}$ have been very promising.

--- A flexible optic can be tuned to a mini beta mode that was operated to build up stacks of 1.1 mA 21 MeV protons through a FILTEX storage cell replica of only 11 mm diameter and 25 cm length.

--- Laser cooling facilities that have produced extremely low temperature beams of less than 200 mK.

--- Simultaneous storage of d and $^{16}O^{8+}$ beams by cooler stacking [19].

TSR has been built with laminated magnets to ensure a fast ramping in the second phase of operation. A novel type of frequency variable cavity has been tested [20] and will be used shortly to accelerate or decelerate cooled ion beams.

ASTRID

ASTRID [21] at Aarhus is a small 2.0 Tm ring of 40 m circumference. It has to serve two quite different purposes, i. e. as a storage ring for heavy ions delivered by a low voltage (30 kV to 200 kV) separator and as a synchrotron light source with a maximum electron energy of 600 MeV. The ring was under vacuum late December last year, had its first $^{40}Ar^{+}$ beam of 100 KeV stored in February and demonstrated laser cooling already in May 1990. Laser cooling is the domain of the physics group at Aarhus and will be surely pursued vigorously to bring this technique to its limits whenever the ring will be available between the synchrotron radiation runs.

The COOLER at IUCF

The cooler storage ring at the IUCF in Bloomington, Indiana [22] ,- simply named "the cooler"-, is a 3.6 Tm six-sided ring, that came into operation end of 1987 and had its first electron cooled proton beam in April 1988. Beams with mass numbers A between 1 and 7 are injected from the 200 MeV isochronous cyclotron by either stripping (H_2^+, He^+) or kicker injection with simultaneous electron cooling. The Indiana ring has with 275 keV the electron cooler routinely operating with the highest electron energy of any of the present rings closely followed by CELSIUS and ESR. The first completed experiment [23] that used all the advantages of a thin internal hydrogen gas jet target of $5 \cdot 10^{14}$ to $1 \cdot 10^{15}$ atoms/cm^2 and an electron cooler ,- a pion threshold experiment with beam energies between 282 MeV and 325 MeV -, shows convincingly the clean experimental conditions only possible at such a ring. The first experimental proof [24] of the principle of the "Siberian Snake" for overcoming the intrinsic and synchrotron depolarisation resonances was just lately performed keeping the polarisation of the proton beam while passing resonances at 108 MeV and 177 MeV.

LEAR

Little must be said about LEAR, the machine that by its excellent performance has influenced almost all of the described projects. It is however not widely known, that LEAR can be operated with heavy ions[25] and has successfully done so for 184 MeV $^{16}O^{8+}$ and 115 MeV $^{16}O^{6+}$ with stochastic cooling resulting in beam lifetimes of 10 hours and about 20 minutes respectively at an average corrected vacuum of $4.5 \cdot 10^{-12}$ Torr. After the installation of the electron cooler LEAR is now ,-at least in principle-, a fully equipped heavy ion ring as ions as heavy as sulfur and later possibly lead are available at the CERN accelerators.

TARN II

TARN II [26] , the successor to the little pioneering ring TARN I is in operation at the INS since 1988 and has succeeded in electron cooling p, d and H_2^+ beams. It is a synchrotron/cooler ring for heavy ions up to Ne. Its maximum energy , corresponding to a magnetic rigidity of 6.1 Tm, is 1100 MeV for protons and 350 MeV/u for ions with charge to mass ratio of 0.5. One interesting feature of TARN II is, that it can be operated in two optical modes, one with a superperiodicity S = 6 as a synchrotron, giving small dispersion and small horizontal β-functions resulting in a large acceptance of 400 π mm mrad, and the other with S = 3 as a cooler ring with three zero dispersion straight sections from which one is needed for the electron cooler. The acceptance in this mode is reduced to 140 πmmmrad. Further features to note are an internal target and a slow beam extraction utilizing the third integer resonance.

CELSIUS

Well designed experimental equipment is obviously almost immortal, as the dipole magnets installed in the cooler storage ring CELSIUS[11] at the The Svedberg Laboratory in Uppsala are having already their third career after the g-2 and the ICE experiments at CERN. The solid-core combined function magnets have been supplemented, after an extensive search for an optimum permutation of the D and F sectors, by four quadrupole doublets to form a flexible 82 m circumference ring of 7.0 Tm. The four approximately 9 m long straight sections house a high voltage (300 kV) electron cooler , a cluster gas jet target, the rf-unit and the injection components. The ring is most effectively injected by stripping H_2^+ ions from the Gustaf Werner Cyclotron. Standard multiturn equipment is also installed to allow for the injection of beams from a polarized ion source to be delivered by a commercial manufacturer. An ECR ion source built in collaboration with the Institute of Physics at the university of Jyväskylä/ Finnland will soon be injecting beams up to Kr to make CELSIUS a heavy ion ring. The status of the ring is at present: First beam stored late 1988, first ramping to full rigidity and first experiments in 1989, first electron cooling May 1990.

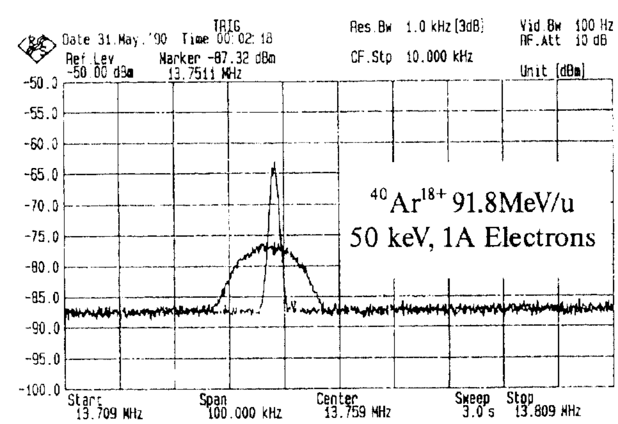

Fig. 2: First longitudinal Schottky spectra of uncooled and cooled $^{40}Ar^{18+}$ beams in the ESR.

ESR

Just in time for this conference and after a breathtaking short assembly period the Experimental Storage Ring ESR[27] at the GSI in Darmstadt has successfully cooled its first $^{40}Ar^{18+}$ beam of 91.8 MeV/u by 50 keV 1A electrons on May 28th 1990, only about 7 weeks after the first beam storage in the ring. Figure 2 shows the historic first longitudinal Schottky scan of a cooled and uncooled beam. The ESR (B·ρ = 10 Tm, circumference 108 m) can accumulate, store and cool ion beams as heavy as uranium. Energies range up to 830 MeV/u for ions with charge to mass ratios of 0.5 and 550 MeV/u for uranium. ESR has been built for the following primary goals:

--- Investigation of interactions between stored ions, target atoms, electrons and laser photons. Maximum Luminosity can be about $10^{30}cm^{-2}s^{-1}$.
--- Accumulation of secondary beams. The high intensity high energy "injectors" UNILAC and SIS allow the efficient production of radioactive exotic beams which can be cooled by stochastic pre-cooling and final electron cooling ($E_{el.max.}$= 320keV).
--- Cooler and stretcher for SIS
--- Reinjector for SIS. After stripping and cooling in the ESR the beams can be reinjected into the synchrotron where the energy of the fully stripped uranium ions can be raised to 1.35 GeV/u or lowered to values near the Coulomb barrier.

Routine operation for experiments can be expected at the ESR still for this year.

COSY

The COoler SYnchrotron[28] at the Forschungsanlage Jülich is a light particle, medium energy machine that is in the middle of its construction periode with the buildings almost finished and first hardware like prototype magnets being delivered. COSY will be injected by the JULIC isochronous cyclotron at the beginning mainly by stripping H_2^+ ions at an energy of 80 MeV. The ring has a 184 m circumference composed of two almost circular arcs and two very long straight sections of 40 m each configured in a telescopic optic for the electron cooler and two internal experimental stations. Electron cooling is planned to be done only with moderate energy of 40 keV to possibly 100 keV to compress phase space after injection and to rely on adiabatic shrinking during acceleration and stochastic cooling at the flat top energy. COSY will have to ramp up in 1.5 s from the injection rigidity of 0.92 Tm to the maximum value of 11.7 Tm corresponding to a dipole field of 1.67 T and a proton energy of 2.7 GeV. Although provisions are made for internal target experiments, much emphasis is on experiments with external beams and third integer resonance extraction will be available at the beginning of the experimental operation end of 1992 later followed by stochastic ultra slow extraction.

ADRIA

A very ambitious project has just recently been introduced at the INFN at Legnaro [29]. The large ,- circumference 267m, rigidity 22.5 Tm -, cooler synchrotron could have a 4 straight section geometry giving space for a 8 m long electron cooler with the highest energy yet of 500 KeV. The ring would be injected from the ALPI Superconducting-Postaccelerator under construction at the

Legnaro XTU Tandem. Much experimental emphasis is on the production and accumulation of exotic radioactive beams.

Ring Projects in the Soviet Union

There are as of now three proposals for heavy ion cooler rings in the Soviet Union, at the JINR Dubna, the Kurchatov Institute Moscow, and at the Institute for Nuclear Research Kiev.

K4-K10

The K4-K10 project [30] would bring a considerable extension of heavy ion physics research at JINR by improving the quality of beams from the cyclotron complex U400-U400M and by increasing the heavy ion energy to about 1 GeV/u. The project consists of the shaping ring K4 ($B\rho$ = 4 Tm) with electron cooling and the synchrotron ring K10 ($B\rho$ = 11Tm). The smaller ring (circumference 80m) will besides its cooler function have the task to accumulate exotic very neutron rich particles like ^{8}He, ^{9}Li ,^{11}Be ^{16}C and other radioactive nuclei with lifetimes longer than 100 ms. The large ring (circumference 120 m) will have cooling and internal target facilities to experiment with protons at energies of 2.5 GeV and with uranium at 650 MeV/u. A conceptual design report has been submitted and funding is hoped on a scale, that the project might be finished by 1995.

Kurchatov

A small ($B\rho$ = 3Tm, circumference 51 m) storage ring[31] with electron cooling has been proposed at Moscow to be injected from the Kurchatov cyclotron with beams as heavy as ^{20}Ne yielding after acceleration a maximum energy of 100 MeV/u. Precision nuclear physics experiments are the main interest at this machine.

Kiev

A somewhat larger cooler ring [32] ($B\rho$=4.5 Tm, circumference 58 m) has been proposed with similar intention at Kiev to be injected by the U240 cyclotron with beams up to Ar.

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