THE PROJECT OF THE HEAVY ION STORAGE RINGS COMPLEX OF THE JINR AT DUBNA

O.N.MALYSHEV[1], I.N.MESHKOV[2], R.Ts.OGANESSIAN[1], Yu.Ts.OGANESSIAN[1], V.V.PARKHOMCHUK[2], P.POKORNY[1], A.A.SERY[2], S.V.STEPANTSOV[1], Ye.A.SYRESIN[2], G.M.TER-AKOPIAN[1] and V.A.TIMAKOV[1]

[1]Joint Institute for Nuclear Research, Dubna

[2]Institute of Nuclear Physics, Novosibirsk, USSR

Abstract

Recently commissioned of Darmstadt SIS-ESR complex has started the new generation of Radioactive Ion Beams (RIB) facilities. We give in thes paper the brief description of the project of the heavy ion storage ring complex K4-K10 and discuss, for the specific case, methods which could provide the highest production rates of stored and cooled RIB's. Some numerical estimations are given for the processes of storing and cooling the primary and exotic beams.

I. Introduction

Soon after the invention of the electron cooling [1], the potential of this method was recognized especially in that case when it is used as a means to maintain the high quality of the beam in experiments exploiting a thin internal target placed on the orbit of a storage ring [2]. Building the heavy ion storage and cooler rings formed, during the eighties, a considerable part of general trend towards developing new accelerator and experimental techniques for atomic and nuclear physics. Several projects are either accomplished or close to commissioning [3-10].

We would like to discuss in this paper one of the possible future facilities, i.e. the project of heavy ion storage ring complex K4-K10 recently proposed in Dubna [11]. After the brief discription of the project, we shall present some considerations of proposed method of producing, storing and cooling the RIB's.

II. Brief discription of the project K4-K10

The layout of the storage ring complex K4-K10 is shown in Fig. 1 together with the heavy ion cyclotrons of the JINR (Dubna). The project includes two rings, K4 and K10*). The beam channels related to this project are also shown in Fig. 1. The most important of them are the channel guiding from the U400M cyclotron to the injection section of the ring K4 and the fragment separation channel. The momentum loss achromat technique will be utilized in the design of this separator channel.

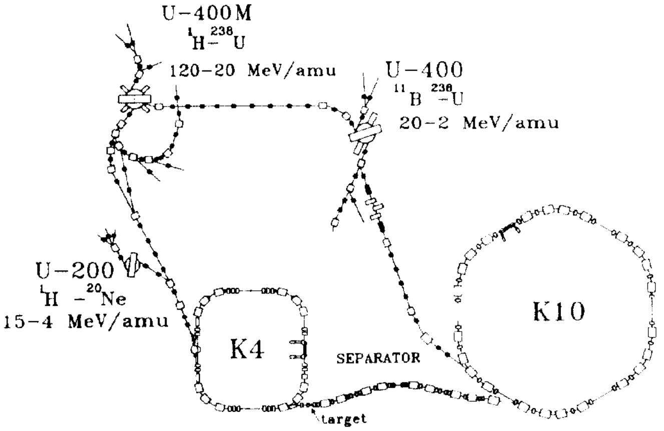

Fig. 1. The layout of the storage ring complex K4-K10.

Two cyclotrons, i.e. U200 and U400, are the working accelerators whereas the third one, U400M, is at present at the stage of commissioning. The mass and energy ranges of heavy ion beams by the cyclotrons are given in Fig. 1. The main injector of the storage ring complex will be the U400M. The charge states and intensities of some representative ions which will be accelerated by this machine are given in Table 1.

Two modes of operation of the U400M cyclotron are foreseen. The beams ranging from hydrogen to krypton will be produced by exploiting an sources whereas, for heavier ions extending up to uranium, the tandem mode will be used, in which case the U400 cyclotron will serve as an injector for the U400M. The values of mean currents for ions with mass numbers $A \leq 20$ and $A > 100$ in Table 1 are anticipated by taking into account the long term experience of running the U400 cyclotron in combination with different modifications of the PIG ion source. For the ions ranging from magnesium to

---

*) We mark the rings K4 and K10 and the complex K4-K10 by taking the abbreviation from russian "koltso" (ring) and the numbers 4 and 10 giving the magnetic rigidity of the rings in T m.

0-7803-0135-8/91$01.00 ©IEEE

TABLE 1

Estimated intensities of U400M beams.

Ions	Mean current of beam (s^{-1})	Number of beam ions per time interval of 1 μs
H_2^{1+}	$4x10^{13}$	$2x10^8$
$^4He^{1+}$	$6x10^{13}$	$3x10^8$
$^4He^{2+}$	$4x10^{13}$	$2x10^8$
$^7Li^{2+}$	$4x10^{13}$	$2x10^8$
$^{18}O^{5+}$	$2x10^{13}$	$1x10^8$
$^{20}Ne^{5+}$	$3x10^{13}$	$1.5x10^8$
$^{48}Ca^{10+}$	$3x10^{12}$	$3x10^7$
$^{86}Kr^{18+}$	$3x10^{11}$	$3x10^6$
$^{136}Xe^{33+}$	$2x10^{11}$	$1x10^6$
$^{208}Pb^{44+}$	$1x10^{11}$	$5x10^5$
$^{238}U^{48+}$	$1x10^{11}$	$5x10^5$

krypton, the published results are used which illuminate the data obtained by the working groups at GANIL (Caen), MSU (East Lancing) and LBL (Berkeley) in the course of operation of their cyclotrons with the ECR ion source. We give in the last column of Table 1 the beam intensities of the terms of the ion numbers delivered by the cyclotron within one microsecond, the time interval close to the period of the beam revolution in a storage ring. These values are given for the pulsed operation mode of ion sources.

Table 2 gives the basic parameters of the storage rings K4 and K10. Apparently, such a pair of coupled storage rings both equipped with the electron cooling sections, the RF accelerating/decelerating systems and having three injector cyclotrons will be capable of providing different options on selection of operational modes. We note that the highest energy of heavy ions, 500-800 MeV/nucleon, will be achieved in the case when ions, after the U400M, are successively accelerated first in the ring K4 and than in K10 being stripped every time before injection into the ring. Fully stripped ions as heavy as zirconium and hafnium will be accessible in the rings K4 and K10, respectively. Table 3 lists, for some typical beams, the ionic charges and maximum ion energies on the orbits of the rings.

TABLE 2

Basic parameters of the rings K4 and K10.

Ring		K4	K10
$B\rho_{max}$,	T m	4	10
Circumference	m	70	140
Acceptance, $\varepsilon_{\perp}$	π mm mrad	50	25
$(\Delta p/p)_{max}$,	%	1.5	1.5
Maximum cooling electron energy,	keV	100	250
Length of the cooling section,	m	3	3
Maximum electron current,	A	5	5
Cathode diameter,	cm	3	3
Range of the RF frequency,	MHz	0.5-3.4	0.3-2.1

TABLE 3.

Maximum energies (MeV/nucl.) of heavy ions of different charge states (q)

Ion	Cyclotron U400M Ion source or injector cyclotron U400		Ring K4 Injector cyclotron U400M		Ring K10 Injector ring K4	
	q	E/A	q	E/A	q	E/A
^1H	1	120	1	580	1	2200
^4He	1	30	2	170	2	830
^7Li	2	45	3	135	3	650
^{18}O	5	40	8	140	8	690
^{20}Ne	5	30	10	170	10	830
^{48}Ca	10	25	20	125	20	625
^{136}Xe	33	35	52	100	54	580
^{208}Pb	44	24	72	90	80	550
^{238}U	48	20	82	87	90	535

III. The possibilities of generating storing and cooling the RIB's.

We suppose that projectile fragmentation will be used for generating the RIB's. Cooled and accelerated in the ring K4 up to the maximum energy, the heavy ion beam, after the fast extraction, will be focused onto a production target positioned at the source plane of the fragment separator (see Fig. 1). As a result of fast extraction, the primary beam can be delivered to the target in the form of short bursts having variable time structure. This will considerably facilitate conditions of accumulating and cooling the RIB's in the ring K10. In the following we shall present some estimations of luminosity values which will be attainable for the cooled RIB's on the orbit of the ring K10.

The injection method adopted for the ring K4 is of significance for the rate of generating the RIB's. Two different methods of injection will be employed. For lighter ions extending up to neon, this will be the charge-exchange injection. In order to eliminate the transverce beam emittance blowing up during the injection the stripper will be positioned on the closed orbit bump generated on the nondispersive straight section of the ring.

Two typical situations are presented in Table 4 for $^7Li^{2+}$ and $^{18}O^{5+}$ beams accelerated in the U400M and injected by stripping in the ring K4. The limitation on the maximum number of the ions accumulated on the ring orbit occurs due to the space charge effect which sets automatically the minimum value of the transverse emittance of the stored and cooled beam.

The efficiency of the charge-exchange injection seems to be justified for ions not heavier than neon. It appears to be problematic for heavier beams due to

TABLE 4.
Charge-exchange injection in the ring K4.

Ion		^{7}Li	^{18}O
Injection energy,	MeV/nucl.	45	40
Thickness of the carbon stripper,	$\mu g/cm^2$	10	100
Number of ions injected per one microsecond		$2\cdot10^8$	$1\cdot10^8$
Number of ions on the ring orbit for which the transverse emittance $\varepsilon_\perp$=1π mm mrad is set after cooling		$1.6\cdot10^{10}$	$6\cdot10^9$
Cooling time,	ms	6	55
Maximum energy,	MeV/nucl.	135	140
Acceleration time,	ms	300	300
Total duration of the working cycle,	ms	310	360
Number of ions on the ring orbit limited by the transverse emittance $\varepsilon_\perp$=50π mm mrad		$8\cdot10^{11}$	$3\cdot10^{11}$

the increased target thickness needed for producing fully stripped ions. Therefore, we foresee for the beams of ions much heavier than neon the single turn injection which will be realized in the same straight section of the ring K4 where the charge-exchange injection is accomplished (see Fig. 1). We present some figures in Table 5 which illustrates the conditions of the single-turn injection for the case of the $^{48}Ca^{10+}$ beam extracted from the U400M cyclotron. The ions should be stripped to the charge state 20+ before the injection in the ring. The accumulation of Ca ions on the ring orbit will be accomplished by cooling the newly injected beam and its adiabatic capture into the stationary RF bucket.

TABLE 5.
Single-turn injection of $^{48}Ca^{20+}$ in the ring K4.

Injection energy,	MeV/nucl.	25
Revolution period in the ring K4,	μs	1.5
Number of ions injected per one turn		$3\cdot10^7$
Number of ions on the ring orbit for which the transverse emittance 1π mm mrad is set after injection and cooling		$1\cdot10^9$
Injection and cooling time,	ms	170
Number of ions on the ring orbit for which the transverse emittance 4π mm mrad is set after injection and cooling		$4\cdot10^9$
Injection and cooling time,	ms	1050
Maximum energy,	MeV/nucl.	125
Acceleration time,	ms	300
Total duration of the working cycle,	ms	1350

We give in Table 5 the number of accumulated by single turn injection and captured in the RF $^{48}Ca^{20+}$ ions ($N_\perp=10^9$) for which the transverse emittance $\varepsilon_\perp$ =1π mm mrad will be set as a result of manifestation of the space-charge instability. The accumulation and cooling time (170 ms) of such number of ions is also presented in Table 5. The number of accumulated ions of about $4x10^9$ is of practical interest as the sum of accumulation cooling times aproaches one second for this case, i.e. a factor of two longer than the ion acceleration time up to the maximum energy of the ring K4.

Inspecting Tables 4 and 5 one can see that, in connection with the problem of the RIB's generation, we are interested in accumulation on the orbit of the ring K4 such a number of ions for which the space charge instability is actual. We considered also microwave beam instabilities and come to the conclusion that this effects either would be of minor importance or one would easily found the means to suppress this effects in our case.

Some calculating parameters of different type radioactive ions which will accumulated and cooled in the ring K10 are presented in Table 6.

TABLE 6.

Primary beam	RIB	$T_{1/2}$, s	N	L, $cm^{-2}s^{-1}$ (injection energy)	E_{max}	L, $cm^{-2}s^{-1}$ (maximum energy)
^{7}Li	^{6}He	0.8	$3\cdot10^7$	$2\cdot10^{27}$	430	$1\cdot10^{27}$
^{18}O	^{8}He	0.122	20	$2\cdot10^{21}$	260	$1\cdot10^{20}$
	^{11}Be	13.8	$4\cdot10^7$	$4\cdot10^{27}$	500	$2\cdot10^{27}$
	^{15}C	2.45	$3\cdot10^7$	$2\cdot10^{27}$	580	$1\cdot10^{27}$
	^{16}C	0.747	$2\cdot10^6$	$2\cdot10^{26}$	520	$1\cdot10^{26}$
^{48}Ca	^{44}Ar	720	$3\cdot10^7$	$2\cdot10^{27}$	600	$1\cdot10^{27}$
	^{46}Ar	7.8	$4\cdot10^4$	$3\cdot10^{24}$	560	$2\cdot10^{24}$
	^{47}K	17.5	$5\cdot10^7$	$6\cdot10^{27}$	590	$3\cdot10^{27}$
	^{38}S	$1\cdot10^4$	$2\cdot10^8$	$2\cdot10^{28}$	630	$1\cdot10^{28}$

References

1. G.I.Budker, Atomnaja Energija 22, 346 (1967) (in Russian).
2. G.I.Budker and A.N.Skrinsky, Uspekhi Fiz. Nauk 142, 561 (1978) (in Russian).
3. R.E.Pollock. In Proceedings of the IEEE Accelerator Conference, Chicago, 1989. Edited by F.Bennett and J.Kopta (IEEE, New York, 1989), p.17.
4. D.Kraemer et al., Nucl. Instr. Meth. A287, 268 (1990)
5. P.Kienle, Nucl. Phys. A478, 847c (1988)
6. S.Kullander et al. In Proc. Int. School-Seminar on Heavy Ion Physics, Dubna, 1989. JINR D7-90-142, Dubna (1990), P.20.
7. A.Noda et al. IEEE Transactions on Nuclear Science, NS-32 (1985) 2684.
8. C.J.Herrlander et al., Phys.Scr. T22, 282 (1988).
9. R.Stensgaard, Phys.Scr. T22, 315 (1988).
10. S.A.Martin et al., Nucl.Instr.Meth. A236, 249 (1985).
11. Yu.Ts.Oganessian and G.M.Ter-Akopian, In: Heavy Ion Storage Rings with Electron Cooling (USSR Proposals and Projects Collection), I.V.Kurchatov Institute of Atomic Energy, Moscow, 1990, p.65.
12. H.Geissel et al., Projectile Fragment Separator, A Proposal for the SIS-ECR Experimental Program (1987).