Review of Heavy Ion Storage Rings

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Abstract

Heavy ion storage rings appeared on the accelerator landscape since ion beam cooling proved to be applicable routinely. In spite of quite different scientific motivations two aims are common to all projects: beam accumulation to high currents and cooling to excellent quality. Atomic and nuclear spectroscopy of high precision is planned or already practiced by means of targets and detectors installed in rings, making direct use of the high quality and luminosity of cooled, circulating beams by this way. There are already remarkable results from running machines which might be also relevant to the progress in other fields of heavy ion acceleration.

1 INTRODUCTION

The history of small size heavy ion storage rings began in the mid–seventies when the large accelerator centers CERN and Fermilab decided to build test rings, ICE [1] and ECE [2], for application studies of beam cooling methods invented shortly before. Electron cooling (EC) had been proposed by Budker [3] in 1968 and investigated systematically at the INP/Novosibirsk [4] in following years. Somewhat later the paper on stochastic cooling (SC) had been published by Van der Meer [5] followed soon by successful tests of the method at the intersecting storage rings ISR at CERN [6]. EC and SC studies at ICE led soon to impressive successes with $\bar{p}$–accumulation for the colliding experiments in the SPS and to the decision for LEAR [7]. This ring combined both beam cooling techniques with low energy storage which was feasible not least due to developments in ultra–high vacuum techniques at the ISR. Practically all storage rings to be discussed here have been stimulated by the "small ring" conception for and by operational results at LEAR, to a certain extend also by results from ECE.

2 OPERATED AND PLANNED RINGS

2.1 *Light and heavy ion storage rings*

A closer look at basic parameters of existing and planned facilities suggests to us to subdivide the family of ion storage rings into light ion and heavy ion groups.

The light ion rings aim at nuclear physics with — as far as possible polarized — light ion beams, at a few 100 MeV/u up to 2.5 GeV/u (see table 1 and refs. there). Existing cyclotrons, improved in most cases, serve as injectors for p–, d– and He beams. Heavy ion beams up to Ar or Kr would be available after installation of high charge state ion sources (ECR), either in cyclotrons or in connection with new low beta injectors (e.g. RFQ at TarnII). Ring circumferences C are between 60 m and 185 m, maximum magnetic rigidities $B_{max} \times \rho$ between 3.6 Tm and 11.7 Tm. Access to the medium energy range is given by ring operation in synchrotron mode.

The domaine of low energy heavy ion storage rings is atomic physics at energies from 0.01 MeV/u to about 30 MeV/u (table 2, left). Typical values are 35 m to 60 m for C and 1.5 Tm to 2.5 Tm for $B_{max} \times \rho$. Both the ion species and charge states depend strongly on existing injectors. Electrostatic tandem accelerators, at TSR upgraded by an rf–linac, deliver totally stripped light or partially stripped heavy ions for injection. An alternative way to get highly charged ions has been chosen for the CRYRING by the combination of a CRYEBIS with an RFQ–linac.

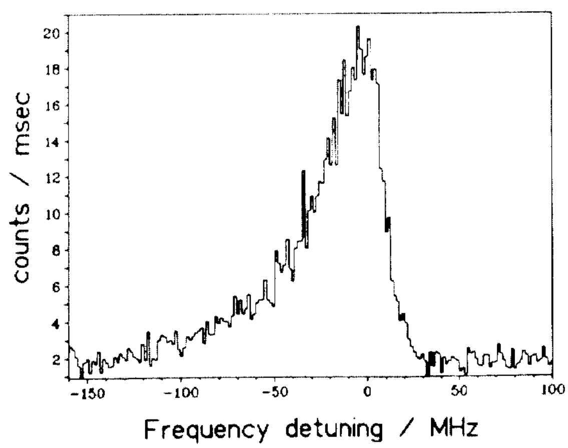

Figure 1: Laser excitation spectrum of a Li^+ beam at about 2 MeV/u after successive electron and laser cooling at TSR. The 35 MHz–width corresponds to a relative momentum spread (FWHM) $\delta p/p \approx 10^{-6}$, i.e. to a longitudinal beam temperature of 200 mK.

Experimental studies of the interaction between ions and laser light are presently major activities at rings of the low energy group. Laser cooling [15] of Li^+ or Be^+ beams has been demonstrated already at TSR [16] (see fig. 1) and ASTRID. Measured longitudinal beam temperatures from 200 mK at about 2 MeV/u down to 1 mK at 20 keV/u have been reported. Unfortunately, this method works only with special lowly–charged ions at low energies.

At the larger heavy ion rings rings (table 2, right) experiments with cooled beams of exotic nuclei or exotic few–electron ions at highest atomic number Z are attrac-

Table 2: Heavy Ion Storage Rings

	Low energy range[1]				*Medium energy range*			
Name	CRYRING	TSR	ASTRID	HISTRAP	LEAR[2]	ESR	LBL-SR	K10
Institute	AFI	MPI	Univ.	ORNL	CERN	GSI	LBL	JINP
Location	Stockholm	Heidelberg	Aarhus	Oak Rdg.	Geneva	Darmstadt	Berkeley	Dubna
C [m]	48.6	55	40	46.8	76.8	108.4	103	146.3
$B_{max} \times \rho$ [Tm]	1.4	1.5	1.88	2	6.6	10	9	10
B_{max} [T]	1.1	1.3	1.5	1.2	1.6	1.6	1.6	1.4
Injector	CRYEBIS	tandem	tandem	tandem	linac	Unilac	S-Hilac	U400M
	+ RFQ	15 MV+rf	6 MV	or RFQ	or PSB	SIS18	HIS18	K4
Ion mass A	20-208	12-130	4-238	12-197	16-208	20-238	20-238	1-84
Charge/mass Z/A	0.5-0.3	0.5-0.37	0.5-0.1	0.5-0.2	0.5-0.4	0.5-0.39	0.5-0.39	0.5-0.4
Injection at [MeV/u]	0.3	15-7	3-0.05	4-1.9	15/150	50-830	8.5-500	87-170
Energy [MeV/u]	24-9	27-13	41-2	47-0.2	5-400	3-830	5-708	87-830
e-cooling [MeV/u]	0.1-10	1-30	0.1-10	0.1-47	5-80	3-560	5-550	87-450
St. cooling [MeV/u]	—	—	—	—	175	500	500	—
Internal target	—	—	—	—	—	gas jet	—	gas jet
[molecules/cm^2]	—	—	—	—	—	10^{14}	—	10^{14}
UHV [mbar]	10^{-12}	10^{-11}	10^{-12}	10^{-12}	10^{-12}	10^{-11}	10^{-11}	10^{-10}
Proposal	1985	1985	1986	1986	1980	1984	1987	1992
Operation	1991	1988	1991	—	1984	1990	—	—
Reference	[17]	[18]	[19]	[21]	[7]	[24]	[25]	[26]

[1] A ring similar to TSR or HISTRAP has been proposed also at BNL [22]

[2] Reference to a possible use of existing or modified LEAR in the Pb-Project at CERN [8]

230 MeV/u in ESR.

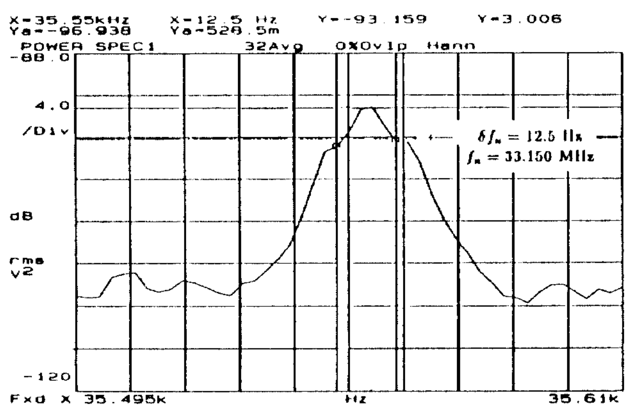

Figure 2: Schottky–spectrum of less than 1000 Bi^{+82} ions, stored and cooled in ESR at 230 MeV/u, corresponding to $\delta p/p \approx 6 \times 10^{-7}$.

Ultra–high vacuum (UHV): Whereas pressures from 10^{-9}mbar to 10^{-10}mbar are quite sufficient for light ion rings, heavy ion storage at low energy requires values near or even below 10^{-11}mbar. At about 1 MeV/u cross sections for capture or stripping may attain 0.1 to 1 Gbarn. With a mean pressure in the low 10^{-11}mbar–range in TSR, life times of partially stripped ions are 10 to 50 seconds. For H-like Bi^{82+} ions at 250 MeV/u in ESR, a life time of about 10 h is observed at 10^{-10}mbar. This time is long compared to that determined by radiative electron capture (REC) or dielectronic recombination (DR) in EC devices (see below). On the other hand, the 300 s live of the sulfur-like Bi^{67+} beam at same energy was limited by residual gas effects.

Electron cooling devices for energies from a few keV to 310 keV, currents from a few mA to 5 A, have been designed or are already in operation. As mentioned before, EC supports beam accumulation, compensates beam heating and prevents from momentum loss during internal target operation. In the case of highly–charged ions EC helps to avoid fast, unlimited growth of transverse emittances $\varepsilon_\perp$ and momentum spread $\delta p/p$ due to intra beam scattering (IBS). Cooling times, τ_{ec}, for protons typically in the order of 1 s, are reduced for heavy ions $\propto AZ^{-2}$. At given electron density in the cooler and given ion beam emittances, τ_{ec} increases with increasing energy $\propto \beta^3\gamma^5$. The dependence is by far not as strong if the adiabatic decrease of $\varepsilon_\perp$ and $\delta p/p$ during acceleration is taken into account. At ESR a low current beam of Bi^{82+} ions at 230 MeV/u is cooled within a few 100 ms from $\delta p/p \approx 10^{-3}$ and $\varepsilon_\perp \approx 10^{-5}\pi$ rad m. down to $\delta p/p \leq 10^{-5}$ and $\varepsilon_\perp \leq 10^{-7}\pi$ rad m. Under given EC conditions the REC life time, τ_{rec}, of highly charged ions decreases $\propto Z^{-2}$. Fortunately, this decrease is partly compensated by cooling rates increasing $\propto Z^2/A$.

Stochastic cooling using the filter method in all phase planes has been applied at LEAR for a long time. A similar SC concept at COSY shall provide cooling of proton beams above 1 GeV simultaneously to internal experiments or slow beam extraction. SC pre-cooling of hot beams of highly-charged, radioactive ions is in preparation at ESR. As the power of Schottky signals increases $\propto Z^2$, correction kickers are fed directly by amplified pick-up signals.

Internal targets, though generally very thin, deliver rather high luminosities due to the high circulation frequency f_0 of beam ions: $L = N_i f_0 n_t \ell_t$, where N_i is the number of stored ions, n_t the molecular density and ℓ_t the path length of ions in the target. Microparticles at TarnII and car-

Table 1: Light Ion Storage Rings

Name	COOLER	CELSIUS	TARN II	COSY	MSR	ISR
Institute	IUCF	MSI	INS	KfA	RCNP	INR
Location	Bloomington	Uppsala	Tokyo	Jülich	Osaka	Kiev
C [m]	82.1	81.8	77.8	184	125.2	56
$B_{max} \times \rho$ [Tm]	3.6	6.25	6.1	11.7	7.9	4.5
B_{max} [T]	1.6	0.89	1.5	1.7	1.65	1.5
Injector	cyclotr.	sy.sycl.	cyclotr.	cyclotr.	r.cycl.	cyclotr.
	K=220	K=190	K= 70	K=45	K=400	K= 70
Ion mass A	1-20	1-20	1-20	1-20	1-20	1-20 (40)
Charge/mass Z/A	1-0.5	1-0.5	1-0.5	1-0.5	1-0.5	1-0.5
Injection at [MeV/u]	220-55	190-45	68-10	45-11	100-35	70-9
Ion energy [MeV/u]	500-150	1160-390	1100-370	2500-460	1600-570	1600-600
e-cooling [MeV/u]	50-400	40-550	25-200	10-200	200	550
St. cooling [MeV/u]	—	—	7	≈2500	—	—
Internal target	gas jet	cluster jet	micropart.	fiber	gas jet	gas jet
[molecules/cm²]	10^{15}	10^{15}	10^{16}	10^{16}	10^{14}	10^{14}
UHV [mbar]	10^{-10}	10^{-10}	10^{-11}	10^{-11}	10^{-10}	10^{-10}
Proposal	1980	1983	1985	1985	1987	1991
Operation	1989	1990	1989	1992	—	—
Reference	[9]	[10]	[11]	[12]	[13]	[14]

tions for nuclear- as well as for atomic physicists. We find C-values from 80 m to 150 m, and $B_{max} \times \rho$ from 6.6 Tm to 10 Tm. All designs aim at the injection of totally stripped, heaviest ions and at accumulation and cooling of radioactive beams produced by means of fragmentation of primary beam particles in a thick target. This requires high injection energies, e.g. $\geq$ 50 MeV/u for xenon- and $\geq$ 400 MeV/u for uranium ions. Adequate injectors are synchrotrons or cyclotrons with high K-values as, e.g., SIS [23] at GSI or U400M at Dubna. Deceleration rather than acceleration of highly stripped ions is required at these rings, e.g. because of increased precision in X-ray spectrometry at low energy. LEAR, or a ring similar to it, can be counted to this ring group since acceleration of lead ions is going to be realized at CERN.

2.2 Design Marks and Special Components

Though small in size ion storage rings are nevertheless highly complex instruments. Most designs include more or less all capabilities of synchrotrons and, in addition, special devices for beam cooling, internal targets and other equipment required for in-ring experiments.

Flexible ion optics with variable lattice functions require separated function magnets and many quadrupole families. Many designs aime at large acceptances for different purposes. Large momentum acceptances , e.g. $\pm 1.8\%$ at ESR, need eventually shaping of chromaticity functions. Comfortable correction schemes for lattice functions and closed orbits are necessary for optimizing beam cooling and internal experiments.

Conventional magnets are used in all rings. The large number of magnet families requires many independently controlled power supplies. Precise tracking for synchrotron operation is realized by applying modern regulation concepts, e.g. parallel feed-in at ESR and COSY, and needs good timing and distributed computers with fast bus connection to power set interfaces.

Ferrite loaded rf-cavities working at low ion velocities require relative frequency swings of more than 10 for the synchrotron mode. The v_i range shall be extended at ESR by a dynamic change of the harmonic number during deceleration.

Beam injection and extraction by various methods apply fast ferrite kickers, electrostatic septa, septum magnets and fast orbit bumpers. Slow, eventually ultra-slow [27] extraction, is planned for COSY and ESR. Extraction using radiative electron capture (REC) in the EC-device or electron stripping in the internal target is considered at ESR as a promising way to conserve quality parameters of cooled internal beams for external experiments.

Beam accumulation is done by means of sophisticated procedures, especially by those people having to live low dc beams currents. Multi-turn injection, if possible using stripping foils instead of septa, is supported by EC at IUCF-Cooler, CELCIUS, TarnII, TSR, ASTRID and COSY. At TSR and TarnII this betatron stacking is combined with rf-stacking, quite similar to the procedure practiced at the booster ring MIMAS [20] at Saclay. At ESR, both the bunch-to-bucket injection and rf-stacking are supported by EC in a pulsed, time shared mode. A fast sequence of repeated kicker injections of a dc beam simultaneous EC to a small rf-bunch is planned at K-10, requiring kicker pulses with high repetition rates and precise synchronisation with the circulating bunch. A somewhat different scheme [8] has been applied for the accumulation of O^{8+} ions in LEAR.

Schottky- and BTF (beam transfer function) measurements using modern low noise rf-techniques, fast digitizers and spectrum analysers allow the precise determination of all important beam and ring parameters also with dc beams. With cooled beams of highly-charged ions these methods can be extended to extremely small numbers of stored ions N_i. Figure 2 shows a longitudinal Schottky scan for less than 1000 Bi^{82+} ions stored and cooled at bon fiber targets at COSY are considered because of their small size, high density, and weak interference with UHV. So far, only supersonic gas or cluster jets have been operated successfully at IUCF, CELSIUS and ESR. Actual operational values for $n_t \ell_t$ are $10^{15}\mathrm{cm}^{-2}$ for H_2-gas jet at IUCF, $10^{14}\mathrm{cm}^{-2}$ for H_2-cluster jet at CELSIUS, and $6 \times 10^{12}\mathrm{cm}^{-2}$ for Ar-gas jet at ESR.

Various detectors for primary and secondary particles, photons and electrons have become important tools in heavy ions storage rings. They are applied for experiments as well as for advanced beam diagnosis. Measurements of transverse beam profiles of secondary beams (see below) using position sensitive detectors deliver directly $\epsilon_\perp$-values. Similar information is also available from position sensitive detection of residual gas ions using channel plates. Photomultipliers or solid state X-ray detectors may deliver useful signals for optimizing the beam-target overlap and, if suitably calibrated, also for on-line monitoring of luminosy.

3 RESULTS WITH HEAVY IONS

Stored beam currents

Some selected values for accumulated ion numbers, N_i, and electrical beam currents, I_i, are:

Ring	Ion	Energy	N_i	I_i
LEAR [8]	O^{8+}	12.5 MeV/u	1×10^9	0.8 mA
TSR[1]	C^{6+}	6.1 MeV/u	3.7×10^{10}	18 mA
	Si^{14+}	4.1 MeV/u	6×10^8	1.0 mA
	S^{16+}	6.1 MeV/u	8×10^8	1.5 mA
ESR[2]	Ne^{10+}	250 MeV/u	2.5×10^9	7.0 mA
	Ar^{18+}	250 MeV/u	4×10^8	2.0 A
	Kr^{36+}	150 MeV/u	1×10^8	0.9 mA
	Xe^{54+}	250 MeV/u	4×10^8	6.0 mA
	Dy^{66+}	297 MeV/u	1×10^8	2.0 mA
	Au^{79+}	300 MeV/u	4×10^6	0.1 mA
	Bi^{82+}	230 MeV/u	5×10^7	1.2 mA
TarnII	N^{7+}	—	1×10^8	—
CELSIUS	O^{8+}	—	3×10^8	—

[1] M. Steck, priv. comm. 1991, [2] from ESR log

Parameters of electron cooled beams

• Very low values for $\delta p/p$ and $\epsilon_\perp$ are attained with low N_i. Emittance values corresponding to fig. 2 are $\epsilon_\perp \approx 4 \times 10^{-8}\pi$ rad m for both transverse planes.

• Due to IBS $\delta p/p$ is $\propto N_i^{1/2}$ at low and $\propto N_i^{1/3}$ at higher N_i, whereas values for $\epsilon_\perp$ seem to increase nearly $\propto N_i^{1/2}$ everywhere (see [28] for more details).

• BTF results at higher beam currents indicate that the Keil-Schnell limit may be exceeded by factors between 6 and 10. However, EC seems to prevent from unlimited growth of oscillation amplitudes. Transverse instabilities are much more serious, but can be damped actively as done at LEAR and at ESR. With ions in charge states above 30, IBS tends to determine $\delta p/p$ more and more and damps obviously longitudinal oscillations.

• REC is the dominant limitation of beam life for highly-charged ions. Nevertheless, a life time τ_{rec} of about 1 h was attained with 50 mA EC current for Bi^{82+} ions at 230 MeV/u without major reduction of beam quality. At high energies, the REC in the EC device is compensated by electron stripping in the internal target, i.e. beam loss is determined then only by nuclear and wide angle Rutherford scattering.

• Multi-charge operation: REC makes it possible to breed lower charge states from primary ions. Fully stripped and H-like Kr ions, and even three charge states of Bi- or Au ions have been stored and cooled simultaneously in ESR.

Experiments using EC beam as target

The variation of energy between ions and electrons is done by pulsing the electron accelerating voltage or by applying the desired voltage difference to a drift tube in the cooling section. Experiments on REC, DR and laser induced electron capture (LIREC) into high-n states have been performed at TSR and ESR by measuring changes in capture rates.

Internal target experiments

Luminosities between $10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $2 \times 10^{28}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ are presently available at the ESR with N_i between 8×10^7 (Bi^{82+}) and 2×10^9 (Ne^{10+}). Due to higher jet densities (see table 1) and $N_i \geq 10^{10}$ the luminosity values at IUCF-Cooler and at CELSIUS are 2 or 3 orders of magnitude higher. Capture and stripping cross sections, X-ray spectra in coincidence with REC, nuclear fragmentation of circulating ions have been measured so far. Figure 3 shows a multi-peak Schottky spectrum of various secondary nuclides produced in the internal target from primary $^{163}Dy^{66+}$-nuclei. Many secondary products are stored and cooled simultaneously to the primary beam. Measurements of production cross sections seem to be feasible this way.

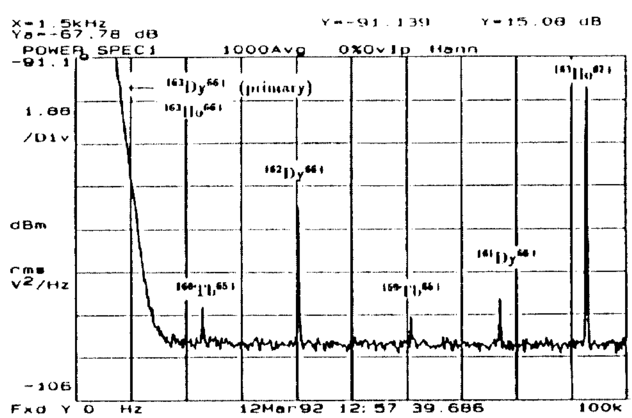

Figure 3: Longitudinal Schottky-spectrum of stored and cooled nuclear fragments produced from primary $^{163}Dy^{66+}$ (large cut band) at 297 MeV/u in the internal Ar-jet of ESR. The larger rightmost peak for $^{163}Ho^{67+}$ comes from the bound-β^- decay of $^{163}Dy^{66+}$ into the H-like $^{163}Ho^{66+}$ after electron stripping in the jet. The small width Schottky-bands from secondary products, corresponding to $\delta p/p \approx 1.8 \times 10^{-6}$, indicate much lower heating rates. Due to dispersion these nuclei cease passing through the target and travelling furtherly within the intense pri-

mary beam, where they would be heated by IBS.

Decay of stored exotic nuclei

There are some stable nuclei ceasing to be stable once the electron cloud has been removed by stripping. They may decay by emission of an electron to a bound state (1s), because Q-values are too low for emission into continuum. In recent experiment at ESR, primary $^{163}Dy^{66+}$ nuclei decayed during long term storage to H-like $^{163}Ho^{66+}$ ions. The amount of daughter nuclei as a function of storage time was measured after electron stripping in the internal target either by counting the $^{163}Ho^{67+}$ with particle detectors or by storing them simultaneously to the primary beam and recording Schottky scans (see fig. 3). A preliminary value for the decay constant is $2 \times 10^{-7} s^{-1}$.

Cooled radioactive beams, mass spectrometry

A mixture of nuclear fragments of ^{20}Ne injected at 300 MeV/u have been cooled sucessfully in ESR by applying EC. With the planned SC pre-cooling, secondary beams can be accumulated also and used for experiments. In the ^{20}Ne-run, nuclei with same nucleon/proton ratio (isotones) have been separated in Schottky spectra with a resolution of less than 100 keV. Scans with higher resolution have shown that relative errors of peaks shown in fig. 3 are in the low 10^{-7}-range, yielding an A/Z accuracy of about 2×10^{-6}, taking into account the measured momentum compaction of 0.16. Even higher precision could be achieved with more precise measurements of local momentum compaction.

4 CONCLUSION

First operational results confirm that heavy ion storage rings are versatile instruments for atomic and nuclear physics offering experimental access to new physical systems with highest precision. Non-destructive, precise measurements of masses and life-times of stored and cooled exotic nuclei are setting expamples for novel methods in experiments with heavy particles.

Using cooled beams many important measurements of beam and ring parameters are feasible with highest accuracy. Precise information about local chromaticities, higher order effects and betatron resonances makes it easier to provide suitable correction. Measurements of longitudinal and transverse BTF for space charge dominated bunched or coasting beams in a wide frequency range will allow to predict precisely corresponding limits for beam intensity and quality.

What might be learned from results at small heavy ion rings for other fields of accelerator technology? As far as large colliders are concerned, e.g. RHIC at BNL or the Pb-option for LHC at CERN, our first, preliminary results do not exclude that IBS might set limits markedly below desired or even below required luminosities unless efficient beam cooling at highest energies is feasible. On the other hand, if EC should be considered as a tool for phase space compression of heaviest ions in low charge states, e.g. for heavy ion induced fusion (HIF) research, there is a deficit of experimental information about beam loss by DR during cooling times in the order of minutes. Investigations are possible now and should be done in next furture. Nevertheless, astrophysical studies with matter heated and compressed by short, intense bunches of highly-charged heavy ions are planned at SIS/ESR in next future [29].

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