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CRYRING - A SMALL STORAGE AND ACCELERATION RING FOR HEAVY IONS

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INTRODUCTION

CRYRING is a facility for research in atomic, molecular and nuclear physics using a cryogenic electron beam ion source, CRYSIS, together with an RFQ linear accelerator as injector into a synchrotron ring, which can be used both for acceleration, deceleration and storage of very highly charged, heavy ions. (CRYRING stands for CRYsis-synchrotron-RING, RFQ for Radio Frequency Quadrupole and CRYSIS for CRYogenic Stockholm Ion Source.) A lay-out of CRYRING in an available laboratory area is shown in Fig. 1.

In the ring itself experiments with a circulating heavy ion beam and merged or crossed beams of electrons, laser-photons, neutrals and ions will be possible. Crossed ion beams will be available from a 400 kV accelerator. Injectors for negative (hydrogen) ions and electrons (intended for cooling as well as experiments) are included in the project. Regarding the extraction of accelerated heavy ions for nuclear and atomic spectroscopy, it should be emphasized that the project aims at very heavy ions (Xe-U) which will be energetic enough to overcome the Coulomb barrier of heavy target nuclei.

The different injectors can be separately used for experiments when not in operation for CRYRING. It should also be emphasized that since CRYSIS is a pulsed ion source, beam-sharing will be simplified, making it possible to run two or perhaps even three different experiments simultaneously.

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CRYSIS

CRYSIS is a pulsed ion source with a maximum 10 kV, 2 A electron beam giving an anticipated current density of 10^3 - 10^4 A/cm^2 in the 1.6 m long confinement volume. The source is expected to deliver up to about $3 \cdot 10^{11}$ charges per pulse. The repetition rate will be 10--10^3 Hz. The source is the result of a co-operation with the CRYEBIS group at Orsay[1], and a schematic drawing of this latter source is presented in Fig. 2. In the future a new electron gun will be installed, allowing higher electron beam energy and intensity.

To improve the performance of CRYSIS an ion injector will be connected in 1986. The injector will be an improved version of the system used at SATURNE[2], and is, in principle, a small isotope separator with an r=50 cm analysing magnet (cf. Fig. 3). Isotopically pure, singly charged ions can then be produced and via an inflection system be fed into the main ion source. The ion injection will allow the experiments at CRYSIS to be carried out with known charge states and known isotopes (e.g. not mixing $^{132}Xe^{44+}$ and $^{129}Xe^{43+}$).

The efficiency of CRYSIS can be expected to be increased since no unwanted isotopes will be introduced into the system. Also, experiments (acceleration) with low abundance isotopes will be possible. Finally, the ion injector will help to achieve a good vacuum in CRYSIS and the rest of the system.

RFQ

CRYSIS is mounted on a 50 kV platform, which means that the extracted ions will have a maximum energy of a few tens of keV. To raise the energy to a proper

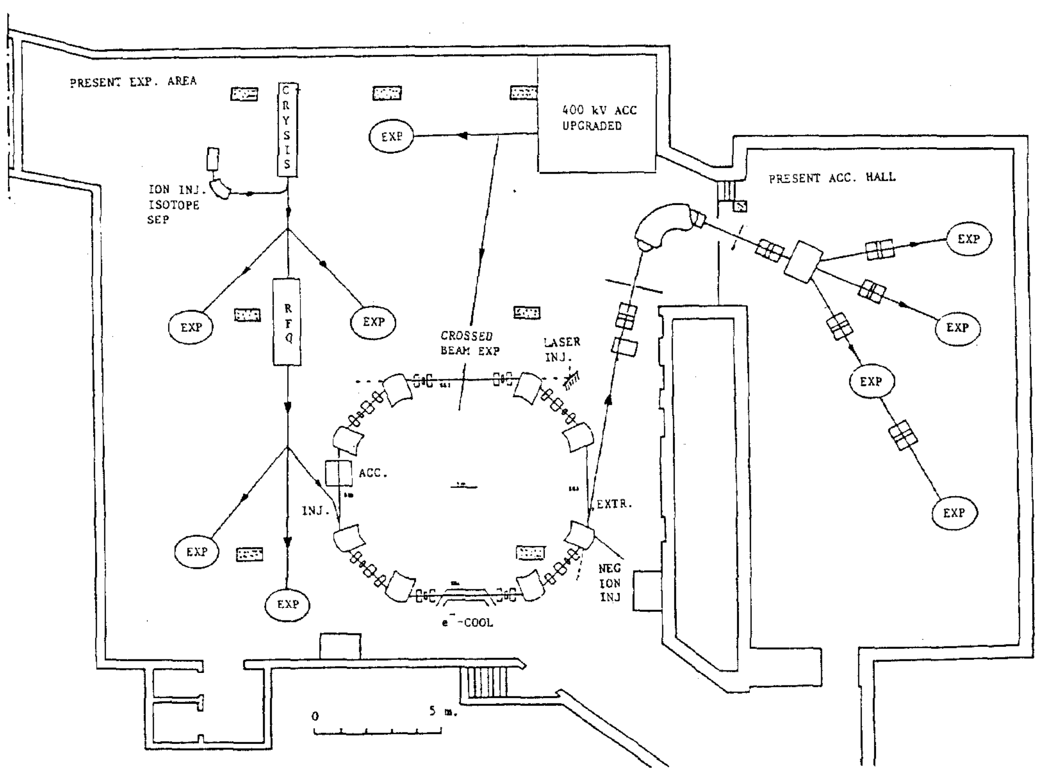

Fig. 1. Lay-out of CRYRING.

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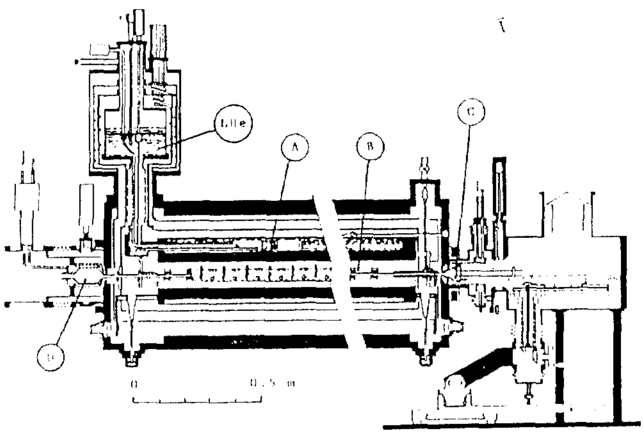

Fig. 2. Schematic drawing of CRYEBIS, the "twin brother" of CRYSIS.

A. Superconducting coil
B. Electrode system
C. Electron gun
D. Electron collector

value for injection into the ring, an RFQ linear accelerator of the 0-mode- $\lambda/2$ -type will be used. The design of this has just started and will be carried out in collaboration with the Frankfurt group[3].

The design aims at an RFQ which will accept ions with $0.1 < Q/A < 0.5$ and accelerate them from 5 keV/u to an output energy of 250-300 keV/u. The injection energy of the RFQ is in accordance with the 50 kV acceleration that can be achieved at the output of CRYSIS. However, in an initial design a $Q/_A$ value of ~ 0.3 is anticipated with injection and final energies equal to ~ 10 and 400 keV/u, respectively. Since the RFQ will be relatively close to the ring, special attention has to be given to the vacuum, which will be in the 10^{-12} torr region.

SYNCHROTRON RING

CRYRING is planned to be a versatile acceleration and storage ring to be used for several physics programs. The lattice design is optimized for the storage mode and the merged beam experiments. A detailed report on the present state of the lattice studies is given in the preceding paper[4]. Both of the two operational modes demand a fast cycling/ramping of the magnets. In acceleration mode (= extracted beam) the cycling frequency should match the CRYSIS cycling mode, i.e. ~10 Hz for the actual high charge states. In storage mode the vacuum conditions in combination with the relatively low injection energy means an ion life-time in the region of a few to tens of seconds why adjustments of the ion energy have to be done with a fast magnet ramping. The demand for a duty factor $\gtrsim 25$ per cent also implies that fast switching to a stable magnet field and a slow, third order resonant extraction is considered. Extracted intensities of the order of one particle nA are foreseen.

VACUUM

The ultimate vacuum requirements for CRYRING depend on the mode of operation. Whereas the acceleration mode needs a vacuum of 10^{-10} torr, the storage mode asks for 10^{-11} and 10^{-12} torr at ion energies of 5 MeV/u and 0.1 MeV/u, respectively. Due to the high charge states of the CRYSIS ions and the low ion energies considered the losses are mainly due to electron capture. The results from a study of the required vacuum under different operational conditions are summarized in Table 1.

TABLE 1

Vacuum requirements in CRYRING under different operational conditions.

ion	torr		
	a	b	c
Ar^{18+}	$5\cdot10^{-9}$	$3\cdot10^{-10}$	$2\cdot10^{-12}$
Kr^{34+}	$1\cdot10^{-9}$	$5\cdot10^{-11}$	$1\cdot10^{-12}$
Xe^{44+}	$5\cdot10^{-10}$	$2\cdot10^{-11}$	$7\cdot10^{-13}$
Pb^{64+}	$2\cdot10^{-10}$	$7\cdot10^{-12}$	$5\cdot10^{-13}$

a. Acceleration mode, 10 per cent losses.

b. Storage mode, 5 MeV/u, $T_{1/2}$ = 60 min.

c. Storage mode, 0.1 MeV/u, $T_{1/2}$ = 3 sec.

e^--cooling

The most powerful way of cooling the stored beam seems to be electron cooling. The ion beam is merged with an intense monoenergetic electron beam over a straight 1 m long section of the circumference of the storage ring (cf. Fig. 1). The electron beam will in general be highly anisotropic in that the longitudinal velocity spread is compressed by the electrostatic acceleration, while the transverse velocity spread

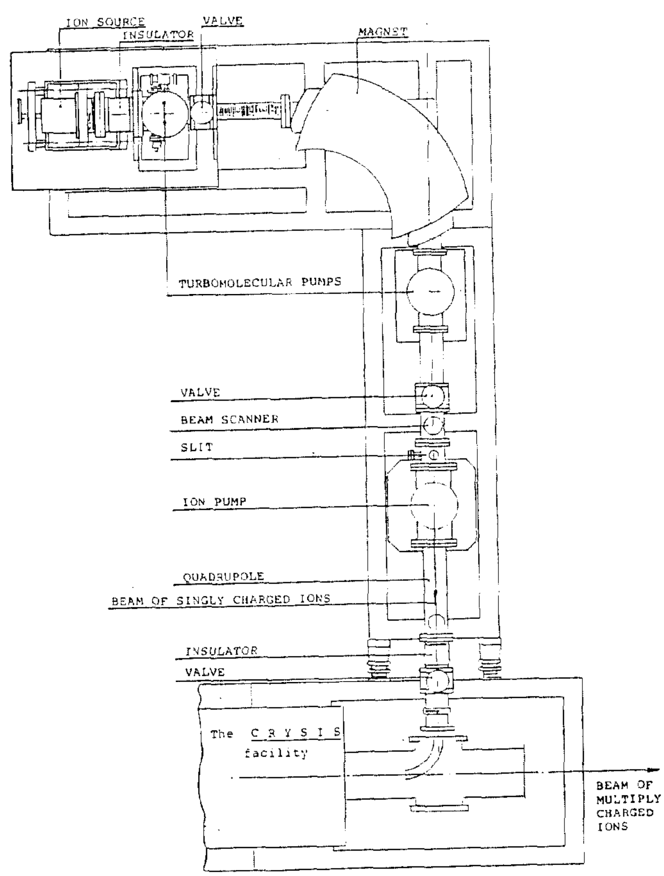

Fig. 3. Ion beam injector for CRYSIS.

is unaffected by it. To a first approximation (neglecting intrabeam scattering) we may consider longitudinal and transverse cooling as independent processes. It then turns out that the transverse one in general is most restrictive (highest ultimate velocity spread).

In a simplified (non-relativistic) calculation of transverse colling, assuming electron beam characteristics given at 50 eV by $j_e = 1\ A/m^2$, $\theta_e = 5x10^{-2}$ and at 5 keV by $j_e = 1000\ A/m^2$, $\theta_e = 5x10^{-3}$, we arrive at the following cooling times and equilibrium divergences:

Ion	Energy MeV/u	Cooling time s	Ion divergence mrad
Ar^{18+}	0.1	3.6	0.18
Ar^{18+}	10	0.036	0.018
Pb^{64+}	0.1	1.5	0.081
Pb^{64+}	10	0.015	0.0081

There are mainly two electron-ion recombination processes that may hinder the electron cooling of highly charged ions:

(i) Radiative electron capture.

This process has a cross section which diverges as the relative velocity of the ions and the electrons tends to zero. Its effect can most easily be given as a characteristic time constant τ_r expressible as

$$\tau_r = \frac{10^5}{A}\,\tau_c$$

where τ_c is the characteristic cooling time. This shows that the radiative electron capture is not a serious problem.

(ii) Di- (or many-) electronic recombination.

For partially stripped ions the possibility of electron impact excitation of the core followed by resonant capture of the slowed-up electron may lead, through radiative relaxation, to a stable ion of a lower charge state. This type of recombination is known (from astrophysical and fusion plasmas) to be effective for keV electrons impacting highly charged ions and becoming bound to high Rydberg levels. In the electron cooling situation the electrons typically have energies below 1 eV in the center-of-mass frame. Such electrons may become accelerated in the strong Coulomb field of a partially stripped ion and may excite the core, but in general they will thereby loose so much energy that they never reach the dense set of Rydberg levels, but get kicked out by the relaxing core. This should in particular be true of all highly charged ions having rare-gas electronic structure, such as Kr^{34+}, Xe^{44+} and Pb^{64+}. For another type of ion the processes described above may lead to an effective recombination, namely if the ion core has a very small excitation threshold, e.g., below 1 eV. Then the cooling electrons may end up in Rydberg levels with binding energies much smaller than 1 eV. But because of static and motional electric field gradients, the loosely bound electrons will field ionise promptly, thus restoring the original ionic charge state. Thus it seems that also this recombination process will be harmless.

EXPERIMENTAL CHARACTERISTICS

CRYRING will provide a variety of heavy ions of widely different charge states and energies from a few eV per nucleon directly after CRYSIS, to a few hundred keV after the RFQ and up to about 10 MeV per nucleon after acceleration in the ring.

For nuclear physics CRYRING makes available a wide range of accelerated heavy ions through CRYSIS. The scientific program is centered around nuclear spectroscopy and hyperfine interactions at ion energies close to the Coulomb barrier.

CRYRING has several unique advantages for atomic and molecular physics:

* A wide range of charge states is obtainable with CRYSIS.
* An intensity increase of the stored beam is made possible by re-circulation of ions.
* Quality increase of the stored beam is made possible by long storage times.
* Quenching of metastables is made possible by long storage times.

The present scientific program includes dynamical and structural studies of highly charged ions interacting with neutral and ion species, electrons and photons, solid surfaces and crystal lattices.

The discussed experimental technique using the stored beam includes three different set-ups:

(i) Crossed beams, using a 400 kV accelerator for the external ion beam.

(ii) Merged beams, using an external beam of H^-.

(iii) Merged beams, using the electron cooler beam of e^-.

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