The Molecular Ion Research Facility in Lanzhou (MIRFL)

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Abstract:
Exploiting the advantage of the high magnetic rigidity (9.4Tm) of the HIRFL-CSRe, the recently launched Molecular Ion Research Facility in Lanzhou (MIRFL) project at the Institute of Modern Physics in Lanzhou can open a new window for dissociative recombination research by extending the mass range of molecular ions up to 150 amu.

1. Introduction

Dissociative recombination (DR) of polyatomic molecular ions plays an important role in the production of molecules and free radicals (molecules with unpaired electrons) in many types of plasma, natural or man-made. In interstellar molecular clouds, networks of bimolecular ion-molecule reactions are terminated by dissociative recombination. In addition to molecular clouds, dissociative recombination plays an important role in fusion edge plasmas, planetary ionospheres, plasma-enhanced combustion, plasma etching of microelectronic structures, and in mass spectrometry of biological molecules[1]. Due to the fundamental importance of the DR reaction in astrophysics, atmosphere physics, plasma physics, chemical physics, and biophysics, and many other areas of research, numerous works can be found in the literature[1-13]. The reason cooler-storage rings have been proven so powerful in the study of dissociative recombination derives from the fact that the ions are stored at a high energy (~MeV), while at the same time the electron-molecular ion collisions can be studied at meV energies owing to the merging of the electron and ion beams. The interaction region is about one meter in length, and neutral reaction products from this region come out with an energy of MeV. Magnetic separation is used to extract the neutral products from the stored ion beam, and the high beam energy makes it possible to separate neutral products based on their energy. Since the neutral products move with essentially the same velocity, the energy is a direct measure of their mass, and hence the neutral-particle detector works, in principle, as a mass spectrometer. However, the time resolution in the detector is not sufficient to differentiate between particles that arrive within a few nanoseconds, and instead a grid technique is used to obtain the branching ratios. A grid with known transmission is placed in front of the detector and blocks some particles from being detected. This leads to a redistribution of the pulse-height spectrum, which can be related to the branching ratios by means of a transmission matrix. In order to separate peaks in the pulse-height spectrum, high beam energy is required[14].

There are presently three cooler-storage rings in the world which are used for molecular ion physics; ASTRID in Aarhus, Denmark, CRYRING, Stockholm, Sweden, and the Test Storage Ring, Heidelberg, Germany. These three storage rings are characterized by a magnetic rigidity of 1.4-1.5 Tm and they all have electron coolers which serve the dual purpose of phase-space cooling the stored ion beam and acting as targets for electron-molecular ion collisions. Very active
molecular ion physics programmes have been conducted at these cooler-storage rings during the last decade, and they have been the core facilities for a European Commission research training network during the last four years. One of the most important results reported from these studies is the DR reaction rate of the $\text{H}_3^+$ molecular ion $^{[2,15-19]}$, since these data are used to determine the cosmic-ray ionization rate, $\zeta$, of $\text{H}_2$ in diffuse molecular clouds $^{[20]}$.

$$\zeta = k_e n(e) n(\text{H}_3^+) / n(\text{H}_2),$$

where $k_e$ is the DR rate for the $\text{H}_3^+$ molecular ion, $n(e)$ is the electron density, and $n(\text{H}_3^+)$ and $n(\text{H}_2)$ are the number density of $\text{H}_3^+$ and $\text{H}_2$, respectively. However, the low magnetic rigidity of the three European rings is now becoming a bottleneck which cannot be overcome. For molecular ions exceeding a mass of 100 amu, the present generation of small, 1.4-1.5 Tm, storage rings run into considerable problems, and these problems are principle rather than technical. The only solution is to go to cooler-storage rings with much higher rigidity, and the only option on a world-wide scale is the HIRFL-CSRe in Lanzhou which has a magnet rigidity of 9.4Tm.

The HIRFL-CSRe facility in Lanzhou is shown in Fig.1. This facility is mainly composed of two parts, the main ring CSRe and the experimental ring CSRe. The Molecular Ion Research Facility (MIRFL) at CSRe includes a molecular ion source, the 320 kV platform, an injection beam line, an ultra-cold electron target, a weak beam measurement device, and a neutral particle detection system. Taking into account the high magnetic rigidity of 9.4Tm of CSRe, and combining the new injection beam line, the new platform may offer unique opportunities to dissociative recombination (DR) research by extending the mass range of molecular ions up to 150 amu and, especially for ions with $m>70$ amu. Since the present HIRFL-CSRe facility has only a single injector SFC, adding a new injector MIRFL may increase significantly the running efficiency of the HIRFL-CSRe system. The designs of the injection beam line, the bumper for injection into CSRe, and the ultra-cold electron target have been finished. The technical design of the MIRFL will be presented in detail in this paper.

Fig. 1 The layout of HIRFL-CSR
2. General design of the MIRFL

The layout of the MIRFL is shown in Fig. 2. It consists of a molecular ions injection beam line, an electron target, a neutral particle detector system, and the beam diagnostic system. The molecular ions of 40–150 amu at 320keV can be injected into CSRe by using a special designed bumper together with the existing injection coils in the ring, and then will finally be accelerated to $10^1$–$10^2$ MeV. The electron target with a photoncathode can produce an ultra-cold electron beam to serve as the electron target for DR study. The neutral particle created in the DR reaction between the molecular ions and the electron target will be detected by a neutral particle detector system.

![Diagram of MIRFL Layout](image)

**Fig. 2 The layout of MIRFL**

2.1 The Molecular ions injection beam line

The molecular ion injection beam line includes the molecular ion source, the 320kV platform, the dipole and the quadrupole magnets, the vacuum system and the beam diagnostic devices. The ion-optical transmission of the injection beam line is shown in Fig. 3.

![Diagram of Injection Beam Line](image)

**Fig. 3 The optical transmission of the injection beam line**
2.2 The injection into CSRe

The existing injection system of HIRFL-CSRe consists of one magnetic septum, four dipole coils, and three quick pulse kickers (see Fig. 2). During the single-turn injection, the auxiliary coils in the four main dipoles are used to create a bump in the stored-ions orbit to allow injection. The injected beam is then deflected into the central orbit by the downstream kicker (see Fig. 2). In the newly designed MIRFL, with the pre-acceleration of the 320kV high voltage platform, the circulation time of the stored molecular ions in CSRe is expected to be about 100–250µs. However, in the currently available injection system, the flat-top time of the kickers is about 0.4–0.8µs, much shorter than the circulation time of the stored molecular ions. Thus, a new injection system including a slow bumper should be used.

The new MIRFL injection system includes a new bumper together with the existing injection coils in the CSRe. The bumper will be installed at the position indicated by BD42Pxy1 shown in Fig. 4, and is used to change the orbit of the stored molecular ion beam so that to match with the downstream displaced orbit.

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**Fig. 4** The position of MIRFL’s injection bumper

**Fig. 5** Injected beam orbits
Fig. 6 The horizontal and vertical beam envelopes for stored molecule ions

Table 1 Parameters of injection components during injection

| Septum   | Coil1 | Coil2 | Coil3 | Coil4 | New bumper |
|----------|-------|-------|-------|-------|------------|
| 145mrad  | 0.1mrad | 8.0mrad | 1.6mrad | 8.4mrad | 3.5mrad    |

Table 2 Parameters of the injection bumper

| Number of cells | Strength            | Maximum magnetic density | Effective cell length | Overall cell length | Aperture                | Ramping time | Flat-top time |
|-----------------|---------------------|--------------------------|-----------------------|---------------------|-------------------------|--------------|--------------|
| 1               | 3–5mrad             | 250G                     | 350mm                 | 500mm               | (150+150)mm×70mm        | <100µs       | 100–250µs    |

With this design, a simulation of the beam injection was performed. Fig. 5 plots the orbit of the injected ion beam. Fig. 6 demonstrates the horizontal and vertical beam envelopes of the molecule ions injected into the CSRe. The parameters of the various injection components and the new bumper during the injection are listed in Table 1 and Table 2.

Combining the existing magnetic septum and the four auxiliary coils with the new bumper, the molecular ions injection can be realized without the influence of the present injection system of the CSRe.

2.3 Ultra-cold electron target

An ultra-cold electron target will be equipped in CSRe, and will be located at the first quadrant (See Fig. 2). It consists of an acceleration section (including the electron gun), an interaction section, a collector, solenoid and toroid sections, high voltage system, vacuum system and cooling
system. The main parameters of electron target are listed in table 3.

To improve the resolution, an electron target with ultra-low temperature electron beam is necessary. In order to reduce the transverse temperature of electron beam, the maximum magnetic field generated by superconductor solenoid at the cathode position is up to 3.5T, and the guiding magnetic intensity amounts to 0.01-0.05T. Hence, magnetic expansion ratios up to 100 are possible. For strongly magnetized electron beam, the transverse temperature is suppressed. However, the transverse temperature of electron beam could be reduced to 2meV by further development of the photocathode electron source.

Table 3 The main parameters of electron target

| Parameter                          | Value          |
|-----------------------------------|----------------|
| Max. energy of electron beam      | 10keV          |
| Length of E-target                | ~ 2.0m         |
| Superconducting solenoid (E-gun)  | ~ 3.5T         |
| Magnetic intensity                | <500Gs         |
| α                                 | <100           |
| Photocathode diameter             | 2 mm           |

2.4 Diagnosis system for weak ion beams

An accurate current measurement of stored molecular ion beam is essential for experimental study of the DR. For high-mass molecular ion beams, the beam current from the source may range from several nA to tens of nA. The existing diagnostic system of CSRe has a sensitivity of only ~1µA. Therefore, a new diagnostic system capable of measuring the current of weak beams needs to be developed. The new beam diagnostics system should be able to measure continuous or pulsed beams in nA range.

For the bunched beam current measurement, a high sensitivity technique has recently been developed by the Manne Siegbahn Laboratory, which is a combination of a Bergoz Integrating Current Transformer (ICT) and a capacitive pick-up (PU), has reported lower limit of 100 pA.[21]. The ICT apparatus can measure an absolute value of the ion current with a sensitivity of 1nA rms, and the PU device can obtain a relative current value with sensitivity down to 100pA rms. The signals of PU are calibrated with that of ICT at relatively high ion current. This technique will be implemented in the HIRFL-MIRFL project.

For the coasting beam current measurement, a set of micro-channel-plate (MCP) will be used to collect the neutral particles from the interaction of ions and residual gas in the ring. A multi-channel-scaler (MCS) with small time interval can be applied to record the output signals of MCP. Assuming that the signal of MCP is proportional to the absolute of the ion current, the ion current is thus obtain by the MCS data multiplying with a constant scaling factor.[22]

3. Project schedule

The physical design of HIRFL-MIRP was finished in spring 2010. The main components will be finished in the middle of 2012. The preliminary experiments are planned in 2013.

4. Summary

Exploiting the advantage of the high magnetic rigidity (9.4Tm) of the HIRFL-CSRe, the
HIRFL-MIRFL project can open a new window for dissociative recombination research by extending the mass range of molecular ions up to 150 amu. The design of HIRFL-MIRFL as well as the relevant technical problems has been described. A new bumper with a 100–250µs flat-top time has been designed to allow injection of 320 kV molecular ions into the CSRe ring. An ultra-cold electron target with 2meV transversal temperature has been designed for use in the MIRFL. The diagnostic system for weak ion beam will be built for CSRe in collaboration with the Stockholm group.

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