BNL-62841
CONF-9406180--5

Sixth international Conf. on EBIS Sources, Stockholm, Sweden
June 20-23,1994

The BNL EBIS Program: Status and Plans*

E. Beebe, J. Alessi, A. Hershcovitch, A. Kponou, K. Prelec

AGS Department, Brookhaven National Laboratory

Upton, NY, 11973-5000

R. W. Schmieder

Div. 8347, Sandia National Laboratory

Livermore, CA, 94551

Abstract

Recently an Electron Beam Ion Source (EBIS), on long term loan from Sandia National Laboratories, has been put into operation at Brookhaven National Laboratory. This source is being primarily used as a test device to answer questions relevant to the eventual design of an EBIS-based heavy ion preinjector for RHIC; a secondary objective is to determine parameters of an EBIS capable of delivering fully stripped light ions up to neon for medical applications. Such a source can easily produce all ions in charge states as needed, but the challenge lies in reaching intensities of interest to RHIC (2-3 x 10^9 particles/pulse). The source studies are planned to address issues such as scaling of the electron beam current in stages up to 10 A, possible onset and control of instabilities, external ion

*Work performed under the auspices of the U.S. Department of Energy

injection, parametric studies of the ion yield, charge state distributions and emittance of the extracted ion beam, ion cooling in the trap, and other technical and physics issues.

Introduction

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has been under construction for several years and is scheduled to be commissioned in 1999. The Brookhaven Tandem Van de Graaff accelerator presently serves as an injector for the AGS Booster and supplies ions up to gold for the fixed target heavy ion program at the Alternating Gradient Synchrotron (AGS); it will initially serve as the preinjector for RHIC as well. However, since the beginning of the RHIC project we have been considering an alternate approach: high charge state heavy ions would be produced in a source, accelerated in an RFQ followed by a short linac, and then injected into the Booster. In principle such a preinjector should be simpler to operate than a Tandem, offering a full spectrum of ion species and allowing for future increases in RHIC luminosity. However, a high charge state heavy ion source that would satisfy RHIC requirements still does not exist, but could be developed by scaling up of a device now available. The rest of the preinjector, an RFQ and linac, is a technology already available from industry. In another paper submitted to this conference [1] we have shown that such a source would satisfy requirements of the large hadron collider (LHC) at CERN as well.

This new preinjector for RHIC must be able to compete with and even surpass the Tandem performance. From the point of view of the RFQ and linac it would be preferable that the source produces ions in charge states as high as possible, to make the preinjector more compact and efficient, but other considerations such as the AGS extracted beam intensity may influence the selection of the optimum charge state. We have considered several possible approaches to developing such an ion source [2] and have concluded that scaling-up of an EBIS should be more straightforward than would be the case for other approaches (ECR, laser driven source). An EBIS delivers highly charged ions of virtually any species starting from either atoms or low charge state ions injected into the trap. The source DIONE, used in the injector for the Saclay synchrotron SATURNE, has produced ions of gold in charge states around 50+ [3]; similar experience has been reported for the Stockholm source, CRYSIS [4]. Another advantage of an EBIS is its fundamentally pulsed mode of operation which can be matched well to a synchrotron with respect to the pulse length. (In an EBIS the total charge accumulated in the trap can essentially be extracted in a pulse short enough for an efficient single-turn injection into a synchrotron.) The evolution of charge states depends on the electron beam energy and on the product of the electron beam current density and ion confinement time, so that the desired charge state is easily optimized by variation of these parameters. While ion yields from existing EBIS devices are lower than those required for RHIC by at least an order of magnitude, this can be partially attributed to the fact that before the advent of large colliders such as RHIC and LHC (CERN) there was little need for high intensities of high charge state heavy ions.

Parameters of an EBIS for RHIC

RHIC will be capable of accelerating and storing a whole range of ion species, from protons to gold (and beyond). For the ion source, the most difficult requirements exist for the heaviest elements. It is a safe conclusion that if the source can deliver beams of heaviest ions, it should be able to operate satisfactorily for lighter species as well. This is why we have limited our considerations to ions of gold, as the heaviest species that may be produced abundantly in the Tandem Van de Graaff preinjector. However, an EBIS is not limited to gold and can, in principle, produce any ion in high enough charge state to be of use in RHIC.

The proposed acceleration scheme of gold ions (Fig.1), based on an EBIS, begins with the source producing ions of gold in charge states with a peak around 35+; a different charge state may eventually be selected, depending on the optimization of the rest of the acceleration system. After acceleration in an RFQ and a short, 15 MV superconducting linac, ions are injected into the Booster in one turn. It has been shown that up to four linac pulses could be stacked in four Booster turns over an injection interval of 300 ms [5], increasing the intensity proportionally; as an alternative to the stacking in the Booster we may consider stacking of several Booster pulses in the AGS, with similar results. Ions in the Booster would be captured in three bunches, accelerated to about 380 MeV/u, extracted, stripped to bare nuclei and injected into AGS. This cycle will continue with acceleration of three bunches of fully stripped ions in AGS, extraction and then transfer to RHIC. With 57 bunches per RHIC ring it will take 2 x 19 AGS cycles to accomplish the filling of the collider. The design intensity of RHIC is 10^9 fully stripped gold ions per bunch; assuming an overall transfer efficiency between the source and RHIC of 25%, this scheme will require that EBIS deliver 3 x 10^9 particles per source pulse. Higher intensities per RHIC bunch (or relaxation of EBIS parameters, if a higher intensity is not needed) could be achieved either by using the stacking in both Booster and AGS, or by reducing the number of bunches in the Booster.

Based on the operating experience of existing EBISs and using simple EBIS scaling rules, we have estimated parameters of a device for RHIC preinjector (Table I). The most challenging scaling up is the required increase in the electron beam current by at least an order of magnitude compared to what has been achieved so far in other devices. However, the relatively modest charge state allows a relaxation of other parameters, such as the electron beam current density and electron energy.

Research and development at BNL using the Test EBIS "SuperEBIS"

Before embarking on the design of an EBIS with parameters as described in Table I we shall have to address many issues and test the scaling up of source characteristics with its parameters. Fortunately, we have obtained on a long term loan the Sandia National Laboratory's "SuperEBIS" [6] and we plan to use it for this purpose as a Test EBIS. Its components were transported to BNL, missing elements (electron gun, the support structure, external ion sources, instrumentation, controls, etc.) were fabricated or acquired, and the device assembled. As originally designed, Sandia SuperEBIS was intended for atomic physics experiments with heavy ions up to uranium, in very high charge states (helium-like), but with comparatively low intensities. Such an EBIS operates with electron beam voltages up to 100 kV, electron beam current densities above 1000 A/cm^2, with electron beam currents on the order of 100 mA. Our requirements are different, calling for intermediate ion charge states ($q/m < 0.2$) but very high ion intensities. This fact has necessitated substantial modifications of the original design in order to approach parameters of an EBIS for RHIC, especially of the electron gun and electron collector.

A schematic of the Test EBIS and associated devices is given in Fig.2. It consists of a vertical bore, nine coil, unshielded superconducting solenoid. The coils are powered by three independent power supplies to produce a solenoidal main field with fringe fields tailored by upper and lower bucking fields. At present, we use a maximum field strength of less than 1.7 T, but we expect to be able to operate up to 3 T. In the present configuration, the electron gun cathode is immersed in the fringe field at a level of 400-800 G. A system of drift electrodes, with a 6.25 mm internal diameter, is mounted inside the cold bore of the magnet. The effective trap length when operating with intermediate potential barriers in the neutral gas injection mode is about 80 cm. Potentials on axial drift electrodes are controlled by custom built high-voltage power supplies with a dynamic range of

1 kV and 10 μs risetimes. A dc bias can be imposed which allows the application of potentials up to 5 kV to the trap region with respect to laboratory ground.

The power supplies controlling the electron beam launch and collection are mounted on a high-voltage platform which is expected to operate as high as 20 kV with respect to laboratory ground potential. Propagation of the electron beam is possible only when an accelerating potential is applied to the platform making the cathode sufficiently negative compared to all source drift tubes. The electrons are decelerated just before reaching the collector and the power dissipated there is only a fraction of the beam power. The advantage of this scheme is that only the collector supply must provide the full current while the anode and accelerator supplies are used to monitor electron beam losses and can be set to switch off the beam when losses exceed a preset limit. There will be a computer on the high-voltage platform to control and monitor the power supplies; a computer at the laboratory ground will provide a graphical user interface and perform the conversions and necessary calculations.

Our R&D program for the next four to five years is based on this Test EBIS and two smaller test stands to be built, one for testing external ion sources and the other for developing and testing electron guns and magnetic field configurations for electron beam launching. Many issues will have to be addressed prior to the design of the RHIC EBIS. First, we have to increase the electron beam current in steps to the 10 A level, measure at each level the ion yield and charge state distributions for a number of species, and compare the results with expected scaling. External ion injection will be studied to provide a variety of ions (especially metallic) required for RHIC. Possible sources of instabilities will be investigated to see whether they might develop as the electron beam current is increased. Fast extraction (~10 μs) of ions will be studied because of advantages of single turn injection into the Booster. In summary, the plan is to accomplish the following:

- to increase the electron beam current in steps from 0.1 A to 3 A;
- to operate the Test EBIS at the level of 3 A, with ions up to uranium;
- to demonstrate propagation of a 10 A electron beam in the EBIS;
- to start the design of the RHIC EBIS.

Program Status and Results

Commissioning and initial tests were made with the electron gun geometry as designed at Sandia National Laboratories and fabricated at BNL. A 1 mm diameter LaB_6 cathode was used to produce electron beam currents up to 110 mA and current densities of 100-400 A/cm2. The apertures in the gun have been increased to accommodate a 2 mm diameter cathode, which should be able to produce currents up to 0.5 A. With a 3 mm diameter cathode we should be able to reach an electron beam current of 1 A, as predicted by the EGUN code (see Fig.3). For even higher currents we may have to consider a different emitter (oxide, dispenser) if large enough LaB_6 cathodes are not available.

For a selected group of elements, neutral gas injection is the simplest and most commonly used method for introducing the species to be ionized into an EBIS. Ions in low charge states are first formed in the gas injection region and then allowed to reach the main trap region by decreasing the value of the potential applied to the electrode separating the two regions during the injection period. Transfer of ions using this method is called "electronic injection" following an early description of this process by Donets [7]. Figure 4 shows a time-of-flight (TOF) spectrum of argon, using this type of gas injection. Argon charge states from Ar^{11+} through Ar^{16+} are observed after an injection period of

50 ms and a confinement period of 300 ms. Contaminant peaks of H^+, He^{2+}, and He^+ are present due to a helium leak (that was to a large degree fixed since this experiment) and residual hydrogen background. The total charge extracted in this case was 925 pC during an extraction pulse of duration 75 μs FWHM, corresponding to a rather high neutralization degree (77%) of a 76 mA electron beam.

External ion injection into an EBIS has been demonstrated in the past at Saclay [8] and Stockholm [9]. It is somewhat more difficult to implement but is expected to provide a better performance for our long term goal of producing high intensity pulses of moderately charged metallic ions. Impregnated zeolite ion sources [10] and microMEVVA ion sources [11] have been designed and fabricated as interchangeable modular units to serve as injectors for our Test EBIS. The zeolite sources are useful for producing ions of Na, Cs, and Tl, whereas the microMEVVA source can produce a broader range of metallic ions (we have operated it with Al,Ti, Ta, and U).

External ion injection can be made in both fast and slow modes. In the fast mode, the potential of the proximal EBIS trap barrier electrode is lowered for a brief interval ($\Delta t<1$ ms) to allow ions from the injector to enter the trap region. The injector beam energy is chosen such that ions are reflected by the distal trap barrier potential and are retarded to the order of 10eV inside the trap region, thereby increasing the linear ion current density inside the EBIS. Those ions which do not complete a round trip during the injection interval are captured and can be ionized further. Low transverse energy is required to insure the high degree of overlap of the injected ion beam with the electron beam which is essential to efficient ionization. The fast mode of ion injection has the advantage of a well defined confinement period and a shorter overall cycle time, since the injection interval is relatively brief.

In contrast, the slow ion injection mode allows for some accumulation of ions during a relatively long injection period (10-100 ms). Ions are injected with an energy sufficient to traverse the barrier potential and propagate through the source with typically an energy of 100 eV with respect to trap electrodes. Ions which are further ionized before completing a round trip are captured in the trap. This mode is rather easy to initiate with both lower current ion sources and unoptimized ion optics. Once this mode has been achieved, it is relatively easy to fine tune the ion optics and injector beam energy and make the change to the fast injection mode.

After testing of both sources we decided to use a sodium impregnated zeolite source to try the first external ion injection into our EBIS. The source produces ~10 μA beams of Na+ in a dc mode of operation, with emitter lifetimes of ~100 hours. In order to extend the emitter lifetime we operate in a pulsed extraction mode, producing beams only during the EBIS injection period. To be able to quickly optimize both the EBIS injection and extraction efficiencies, it is convenient to operate with a repetition rate of 5 Hz or higher.

Typically, extraction from the auxiliary source is made at 5 kV and the beam is decelerated to 1-3 kV, which is the potential of the EBIS trap region electrodes. Primary Na+ beams of about 5 μA are obtained at a Faraday cup just downstream from the EBIS electron collector. Improvements to the control system have greatly facilitated the ion injection procedure. After an ion injection time of 15 ms and a confinement time of 50 ms, the most probable charge state was Na^{7+}, with the highest state of Na^{9+} (Fig.5).

Modifications are underway to develop a control system to facilitate setting and monitoring all potentials and intervals through a graphic oriented PC interface. Also, modifications of the beamline are underway to allow introduction of a harp-type beam profile monitor and a compact retractable emittance head which has been designed and partially constructed at BNL. The balance of the construction was completed at Manne Siegbahn Laboratory with initial testing made at the Stockholm EBIS (CRYSIS) facility. Construction of the external ion source test stand has begun; it will be followed by the design and construction of the more complex test stand for electron guns and various EBIS components.

Acknowledgements

This work was performed under the auspices of the U.S. Department of Energy. We would like to thank D. Boeje, L. DeSanto, B. Erickson, W. Hensel, R. Lockey, D. McCafferty, D. Raparia, P. Stein, and W. Tramm and F. Usack of BNL for their contributions to the EBIS project. We thank P. Schoch and J. Schatz of the RPI Plasma Dynamics Group for providing us with the zeolite emitters and ion source which were used as the external ion injector to the EBIS during these studies. The contributions of L. Liljeby and A. Pikin to the HV platform control system and cryogenics, respectively are greatly appreciated. We would also like to thank M. Bjorkhage, A. Engstrom, S. Framling, A. Paal and U. Rosengard for their help during the testing of the BNL harp-type profile monitors and compact emittance head at the Stockholm EBIS.

References:

[1] H. Haseroth and K. Prelec, Possible Applications of an EBIS in Preinjectors for Large Heavy Ion Colliders; this Symposium.

[2] J. Alessi and K. Prelec, AGS Div. Tech.Note 383, Oct. 1993 (unpublished).

[3] B. Visentin, et al., Metallic Ion Beam Production with DIONE EBIS, this Symposium.

[4] A.I. Pikin, E.N. Beebe, M. Björkhage, Å. Engström, and L. Liljeby, The Stockholm Heavy Ion Source CRYSIS, this Symposium.

[5] Y.Y. Lee, AGS Div. Tech. Note 362, July 1992 (unpublished).

[6] R.W. Schmieder, et al. Rev.Sci.Instrum. **61**, 259 (1990).

[7] E.D. Donets in "The Physics and Technology of Ion Sources", edited by I.G. Brown (Wiley, New York 1989), Chap.12.

[8] J. Faure, B. Feinberg, A. Courtois, and R. Gobin, Nucl. Instrum. Methods **216**, 449 (1984).

[9] E. Beebe, et al., Nucl. Instrum. Methods B **93**, 378 (1994).

[10] R.L. Hickok and F.C. Jobes, AFOSR Report No. TR-72-0018, 1972 (unpublished).

[11] I.G. Brown, in Ref.7, Chap.16.

Table Captions

Table 1 Parameters for an EBIS meeting RHIC Requirements

Figure Captions

Figure 1 Acceleration stages of a proposed EBIS-Based RHIC injection.

Figure 2 Schematic of BNL Test EBIS setup

Figure 3 EGUN simulation of a 1A electron beam launched from a 3mm Diameter LaB_6 cathode. The beam is extracted with 12kV on the first anode and decelerated by the 2nd anode to 10kV. (1grid unit = 0.1mm)

Figure 4 Argon TOF spectrum from the EBIS

Figure 5 Sodium TOF spectrum from the EBIS

Electron beam current	10A
Electron beam Voltage	20kV
Length	1.5m
Trap capacity	1.1×10^{12} charges
Yield, positive charges	5.25×10^{11}
Yield, Au^{35+}, design value	3×10^{9} ions/pulse
Yield, U^{45+}, design value	2×10^{9} ion/pulse

Table I
Parameters for an EBIS meeting RHIC requirements.

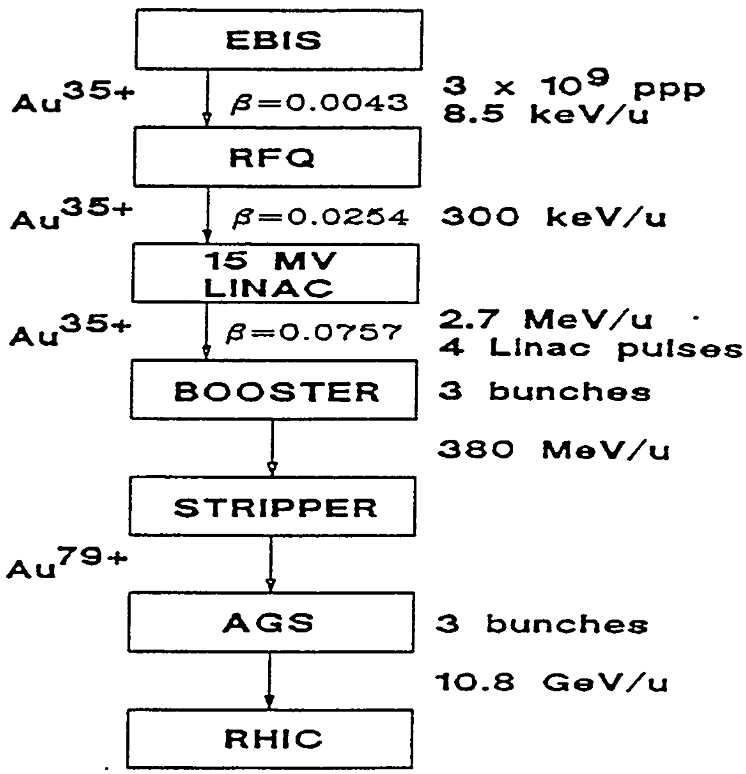

EBIS
Au35+
β=0.0043
3 x 10^9 ppp
8.5 keV/u
RFQ
Au35+
β=0.0254
300 keV/u
15 MV LINAC
Au35+
β=0.0757
2.7 MeV/u
4 Linac pulses
BOOSTER
3 bunches
380 MeV/u
STRIPPER
Au79+
AGS
3 bunches
10.8 GeV/u
RHIC

Figure 1

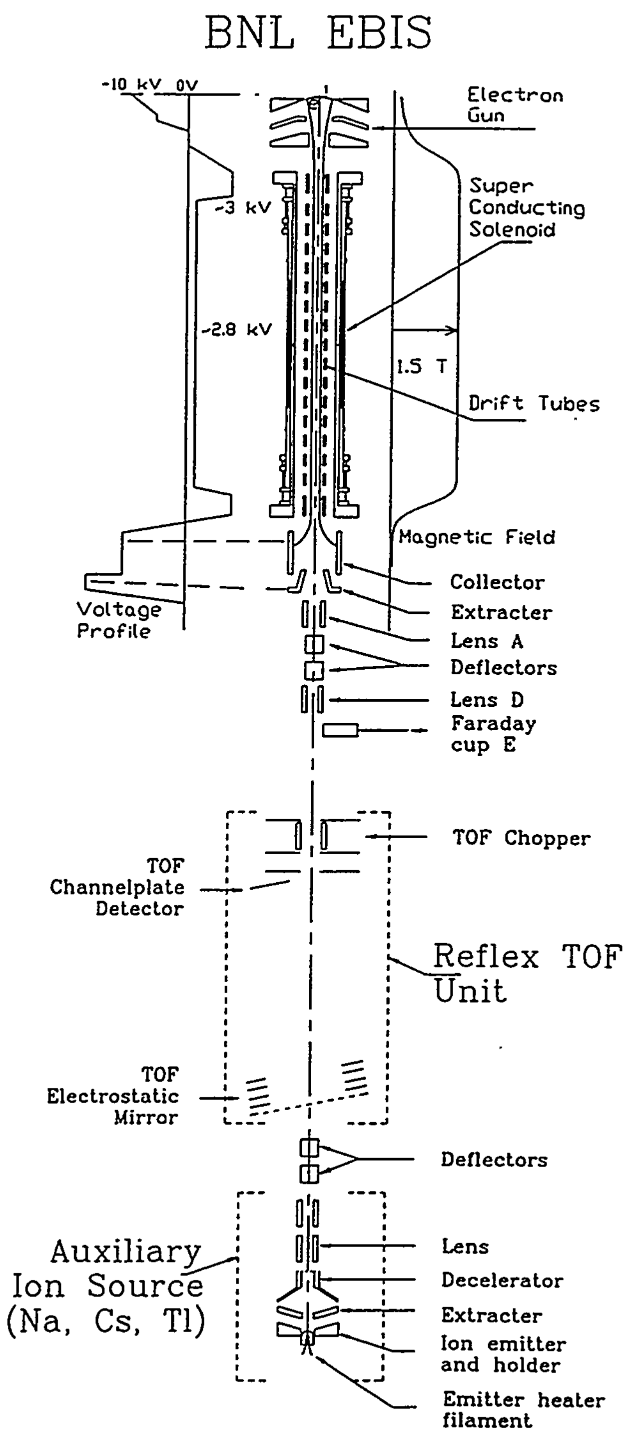
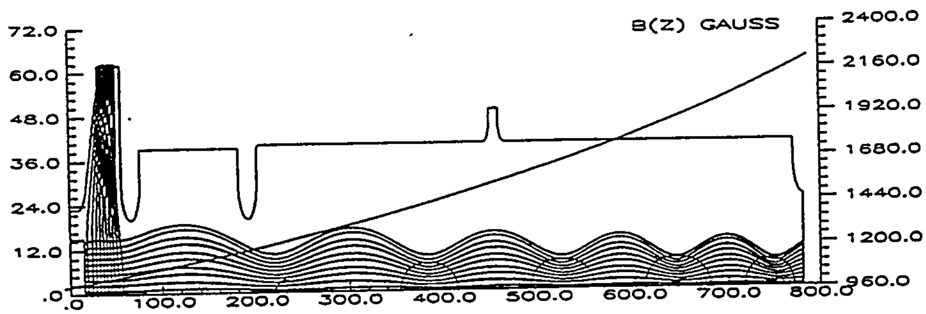

BNL EBIS
-10 kV 0V
Electron Gun
Super Conducting Solenoid
-3 kV
-2.8 kV
1.5 T
Drift Tubes
Magnetic Field
Collector
Extracter
Voltage Profile
Lens A
Deflectors
Lens D
Faraday cup E
TOF Chopper
TOF Channelplate Detector
Reflex TOF Unit
TOF Electrostatic Mirror
Deflectors
Lens
Decelerator
Extracter
Ion emitter and holder
Emitter heater filament
Auxiliary Ion Source (Na, Cs, Tl)

Figure 2



B(Z) GAUSS
72.0
60.0
48.0
36.0
24.0
12.0
.0
.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
2400.0
2160.0
1920.0
1680.0
1440.0
1200.0
960.0

Figure 3

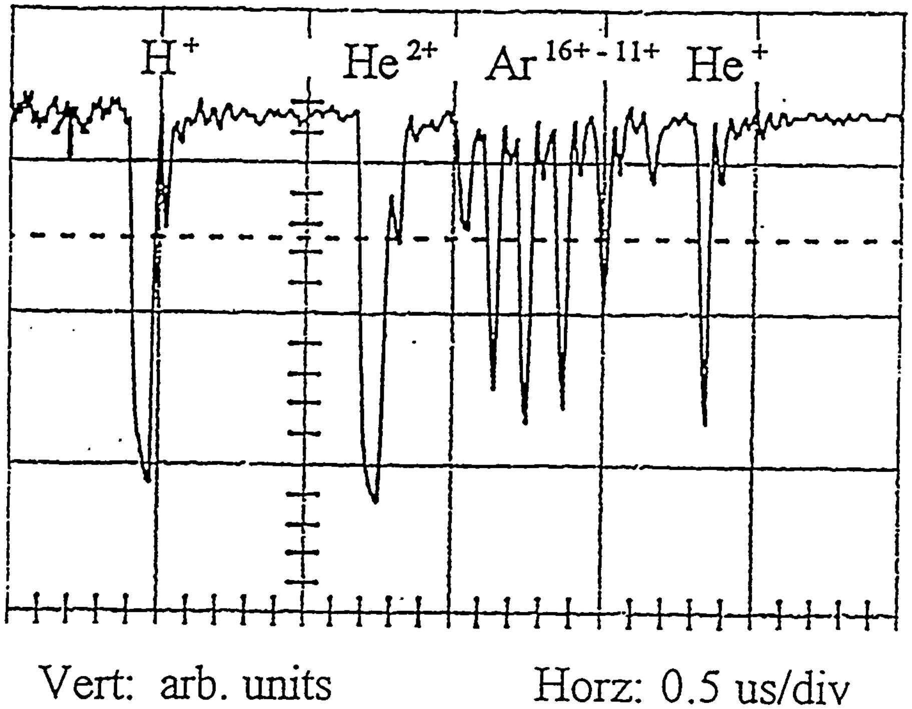


Figure 4

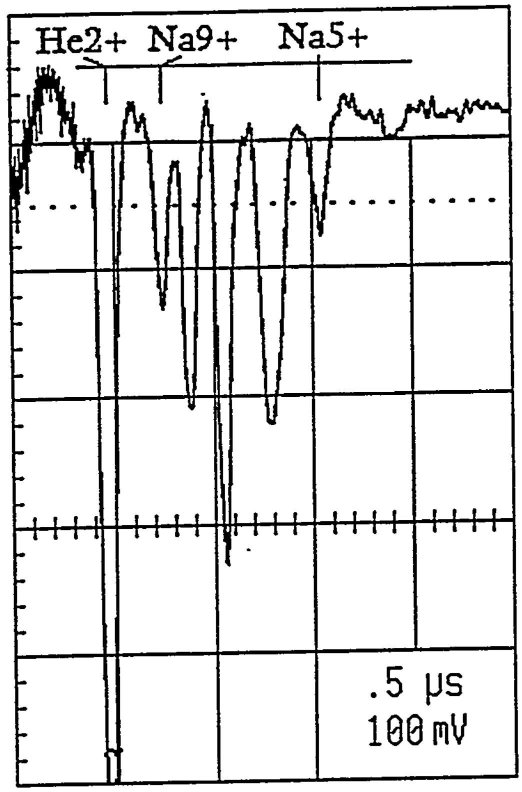


Figure 5

DISCLAIMER