PROTON BEAM HEAVY ION SOURCE*

A. Roy[†] and R. H. Davis

Department of Physics
The Florida State University, Tallahassee, Florida 32306

Abstract

The feasibility of a very heavy ion source which utilizes ionization by intense proton beams is being investigated as a possible injector for cyclotrons and other heavy ion accelerators. Calculated cross sections for ionization to high charge states are $\sim$10 times larger for protons at optimum energy (300-500 keV) than for electrons in working energy range of a few keV. Use of a superconducting solenoid to compress the proton beam and provide radial charge confinement is assumed in the feasibility model. Space charge repulsion produces magnetron motion of the heavy ions and a natural radial zoning with respect to charge state q which requires a correction for the magnetron period fraction spent in the ionizing flux. The radial zoning of different charge states also suggests a possible method of selective extraction. Preliminary calculations with no space charge compensation by electrons have been carried out for 400 keV protons with beam currents of 10, 25, and 100 mA, a solenoid length of 1 m and a magnetic field of B = 5T. Radial size parameters have been computed for yields of U^{+25} up to 1 pμA. Yields of 1 μA appear feasible without compensation of heavy ion space charge while compensation or other modification appear necessary for higher yields to avoid impractical radial dimensions.

Proton Beam Ionization

In most heavy ion accelerator systems, ions are initially accelerated in a low charge state, pass through a stripper to raise the charge state, and are accelerated again. The sequence of energizing and stripping is simple but suffers two adherent disadvantages: charge state dispersion and straggling in both energy and angle.

An alternative approach to the production of heavy ion beams in high charge states is to confine the heavy ion in an intense flux of ionizing radiation for sufficient time to raise the charge state to the desired value. The heavy ion is constrained while the stripper medium is run past it.

In previous investigations of this approach electron beams provided the ionizing flux. Following the work of Donets[1,2] in 1967, electron beam ion source (EBIS) projects were initiated at several laboratories. Considerable progress has been made in the development of EBIS during the intervening years[3,4,5] and a new generation of EBIS have been designed, some of which incorporate superconducting solenoids.

The investigation of a proton beam ion source (PROBIS) is motivated by the large cross sections for ionization by protons, recent advances in small accelerator technology, and the availability of superconducting solenoids. Figure 1 shows the schematic arrangement of a superconducting solenoid which confines ions laterally with respect to the proton beam. In this configuration the heavy ions A^{+q} move to the right against the proton flux which is compressed by Brillouin flow.[6] The lower part of Fig. 1 is a schematic of the potential along the solenoid axis which qualitatively anticipates a need for a partial space charge neutralization by electrons at the low-q end of the solenoid. The slope of the effective potential is required for the ejection of heavy ions once prepared in the high charge state. One extraction method is introduced at the end of the paper.

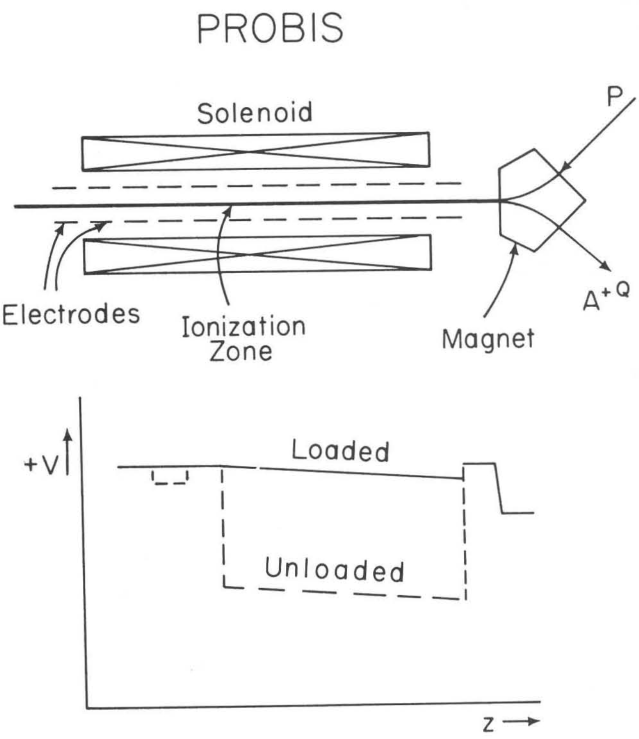


Fig. 1--Schematic diagram of PROBIS

The advantage of protons over electrons as an ionizing flux is shown in Fig. 2. The difference in cross sections is especially important for the higher charge states. The curve for a proton flux was calculated using the results of McGuire and Richard[7] and the curve for an electron flux was obtained from the cross section formula given by Bethe[8] with the modification of Becker et al.[9] included.

The necessary ionization exposure time τ_Q to reach charge state Q in a 100 mA beam of protons is plotted against proton energy in Fig. 3. Negligible magnetic compression (0.8 A/cm^2) is assumed. It is evident from the values of τ_Q that Brillouin flow and the consequent magnetic compression are necessary in practical applications.

Feasibility Model and Results

The proton beam and confined positive ions form an axially positive charge distribution. No heavy ion space charge compensation is assumed in this analysis which is both simplifying and conservative. As the results of the analysis will show, a relaxation of this assumption appears advantageous in future feasibility calculations. Positive ions are repelled by the axially symmetric positive charge distribution and the situation is analogous to that found in the

0018-9499/79/0400-2151$00.75 ©1979 IEEE

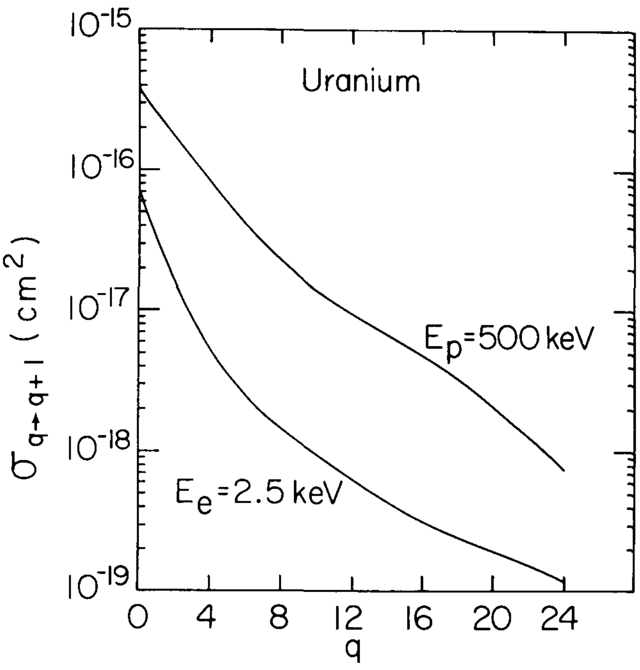


Fig. 2--Cross sections for ionization of U^{238} from charge state q to q + 1 by protons and by electrons.

magnetron.[10,11] For a given potential difference V through which the heavy ion charge +q falls, the maximum radial excursion or magnetron radius r_{mq} is related to q by

$$r_{mq} \propto \left(\frac{1}{q}\right)^{1/2} \qquad (1)$$

The potential V(r) as a function of r does depend upon the charge distribution within the cylinder of radius r which makes the radially zoning of eq. 1 even more sensitive (3/4 instead of 1/2 power as shown by Hull[10] for electrons).

If the proton beam is magnetically compressed by Brillouin flow to a radius r_0 = 0.1 mm (theoretical limit 0.05 mm), a disadvantage of magnetron motion is immediately apparent in that the heavy ion spends only a fraction of the magnetron period in the ionizing flux. More space charge (assuming no compensation) must be supported to provide a given ionization rate. The difficulty is compounded by the fact that more space charge drives the heavy ion charge distribution further out, i.e. r_{mq} increases and the exposure time fraction η_q defined as the fraction of the magnetron period spent in the beam is further reduced. An illustrative example is shown in Fig. 4.

Also plotted in Fig. 4 is η_q/r_0^2 which demonstrates the advantage of increasing the flux density by magnetic compression, reduction of r_0, since the increase in the ionization rate dominates over the decrease in the exposure fraction η_q. The calculations in Fig. 4 were carried out for $r_{m20} = R_T$ = 5 cm.

Instead of a self-consistent space charge calculation which is beyond the scope of this feasibility study, approximate account of the space charge effects have been taken by first determining the average charge state of the heavy ion space charge distribution from the step-by-step ionization cross sections. Adjacent exposure fractions are approximately equal, $\eta_q \approx \eta_{q+1}$ so that the population ratio n_{q-1}/n_q given by

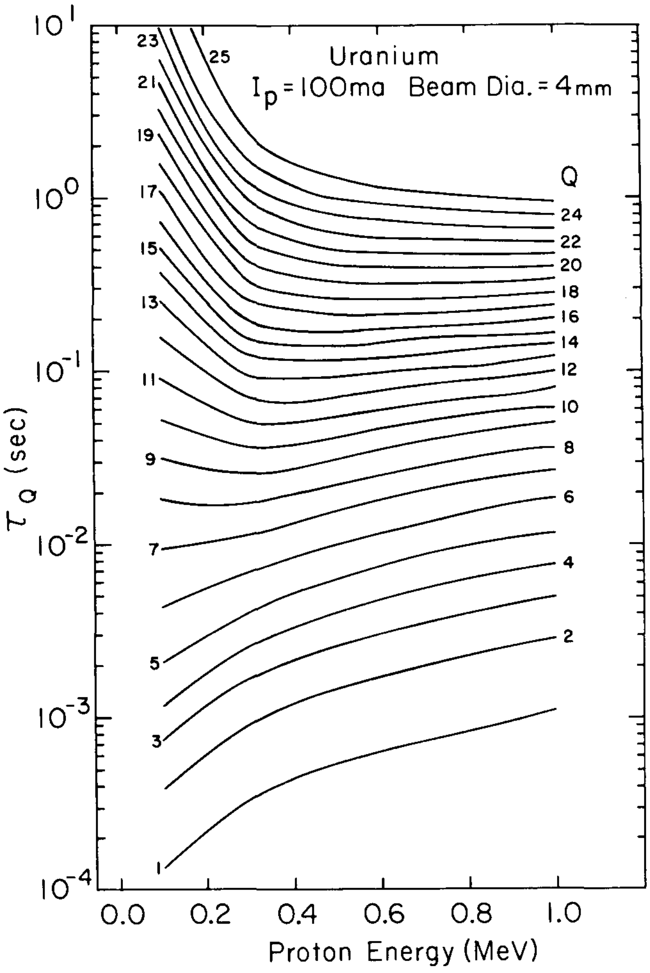


Fig. 3--Ionization times required to reach charge state Q for various proton energies.

$$n_{q-1}/n_q = (\eta_q \sigma_{q\to q+1})/(\eta_{q-1} \sigma_{q-1\to q}) \qquad (2)$$

depends on the ratio of cross sections. These ratios were used to determine the average value of $q=q_{ave}=20$ which is nearly constant over a wide range of conditions.

Next the magnetron voltage V_m, i.e. the voltage difference necessary to draw a particle out to the magnetron radius, was determined for $q=q_{ave}=20$ as a function of magnetron radius r_{m20}. The difference between V_m and V_B (potential due to beam space charge) was calculated for a range of r_{m20} values. This difference is the potential available for the confinement of heavy ion space charge.

The heavy ion space charge within r_{m20} was assumed to have a constant volume charge density for ease in evaluation of the heavy ion space charge per unit length χ_{HI} from the voltage difference $V_m - V_B$,

$$V_m - V_B = \frac{\chi_{HI}}{4\pi\varepsilon_0} \qquad (3)$$

Knowing the total heavy ion space charge and the schedule of charge state population n_q, the number of ions in charge state q = 24 have been determined and the production rate of Q = 25 is given by

$$\frac{dn_{25}}{dt} = n_{24}\, f_p\, \eta_{24}\, \sigma_{24\to 25} \qquad (4)$$

where the new parameter f_p is the proton flux.

0018-9499/79/0400-2152$00.75 ©1979 IEEE

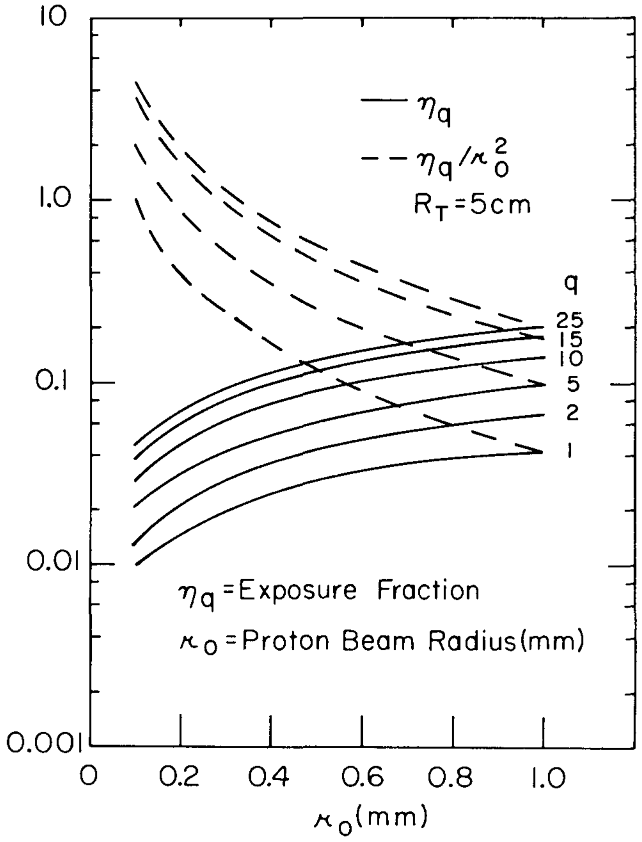


Fig. 4--Plots of η_q and η_q/r_0^2 as functions of r_0, the proton beam radius.

The yield Y_{25} of mass A = 238 particles in charge state Q = 25 is plotted in μA as a function of the magnetron radius r_{m20} in Fig. 5. Since the magnetron radius for q = 1, r_{m1}, is 5 to 10 times larger than r_{m20} depending upon the space charge distribution, practical difficulties are met for values above r_{m20} = 10 mm. For r_{m20} = 10 mm, yields of at least 1 μA are expected for proton beam currents of 25 and 100 mA.

It is apparent that a yield of 1 pμA requires unacceptably large magnetron orbits for low values of q, i.e. $q \lesssim 4$. To avoid this difficulty, several options can be considered: segmenting the source into low and high q sections, injecting a beam with $q \gtrsim 4$, or space charge neutralization of the proton beam and a large fraction of the heavy ion space charge. Because of the natural availability of electrons released in the ionization process, the latter option appears attractive.

Tables I and II give a number of the parameter values obtained in these calculations.

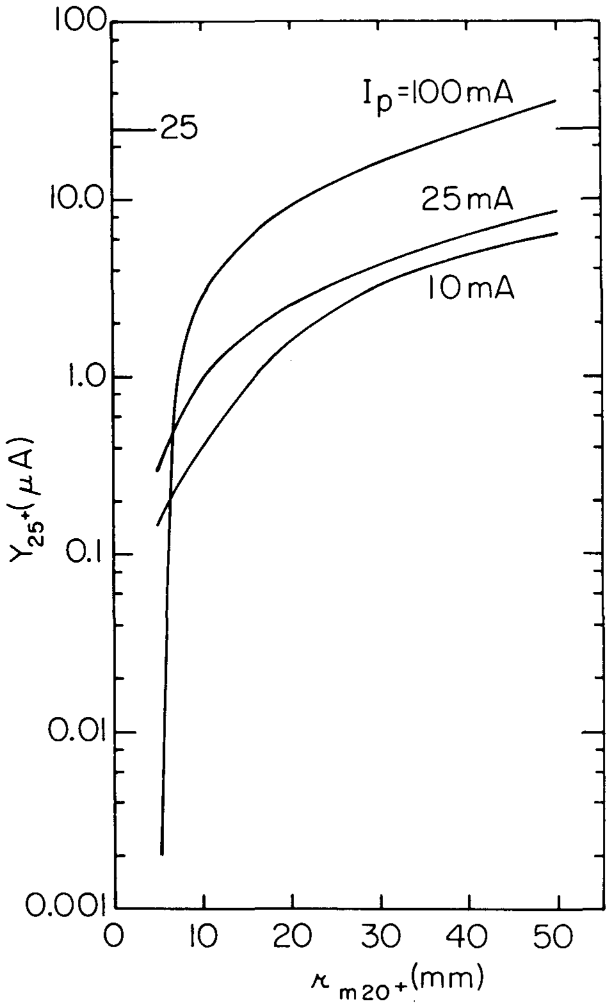


Fig. 5--Calculated yield in μA of U^{+25} as a function of magnetron radius for q_{ave} = 20.

Table I

r_0 = 0.1 mm, E_p = 400 keV, L = 1 m, B = 5T

I_p (ma)	f_p (A/cm^2)	Ionization Time τ_{25} (m s)
10	31.8	33.4
25	79.6	13.4
100	318.2	3.34

Extraction

This PROBIS model incorporates continuous production of the heavy ions with equilibrium populations established for all q. In contrast, batch processing carries a heavy ion population sequentially through values of q up to the design value with an output repetition rate determined by the confinement time. The confinement times in Table II are larger than they would be for a batch process but even if the ionization times of Table I are used, which are lower limits, duty cycle problems arise in injection. The yield values in Table II and those shown in Fig. 5 are upper limits since no losses have been taken into account.[12]

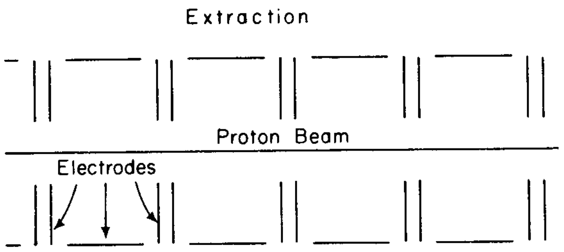
A problem with continuous production is that of selectively extracting the desired charge state from the ion population which includes all values of q. The radial zoning which is exaggerated in this feasibility model because of charge compensation exclusion does present a possible method of selective extraction and axial zoning which is illustrated in Fig. 6.

An arrangement of electrodes which axially divides the ionization zone into cells is schematically

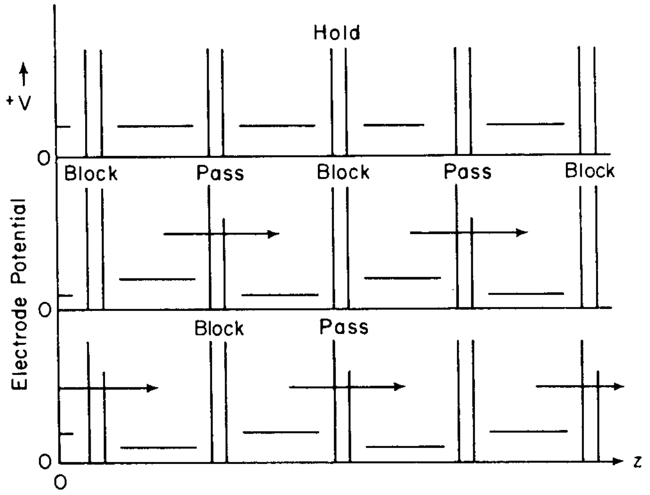
Table II

r_0 = 0.1 mm, E_p = 400 keV, L = 1 m, B = 5T

R_{m20} (mm)	η_{24}	Confinement Times t_{c25} (m s) I_p=10 (mA)	25	100	Yield of Q = 25 (μA) 10	25	100
5	0.050	668	268	66.8	0.145	0.305	0.002
7	0.040	835	335	83.5	0.241	0.548	0.964
10	0.032	1044	419	104.4	0.4	1.0	2.92
20	0.020	1670	620	167	1.63	2.51	9.4
50	0.011	3036	1218	304	6.4	8.8	34.7



(a) Electrode Geometry



(b) Electrode Voltage Sequence

Fig. 6--Schematic of an extraction system which utilizes magnetron motion.

illustrated in Fig. 6a. In Fig. 6b, voltages on the electrodes are qualitatively shown in time sequence. In the top row the heavy ions are in the "hold" phase. The middle row shows an arrangement of electrode voltages such that a small accelerating voltage would exist near the beam axis at the electrodes labelled "pass". Reciprocally, electrons would move in the opposite direction of the arrows. Since the accelerating voltage exists only near the axis of the proton beam, heavy ions with the largest q, having smaller magnetron radii, will pass preferentially from one cell to the next. The bottom row of Fig. 6b shows the "pass" and "block" arrangement for transfer of heavy ions between the next pair of cells, which again selectively passes the ions with the largest q and consequently the smallest magnetron radii.

Using the emittance formula of Becker *et al.*[9], values of emittance have been estimated which range from 1.3 mm - mrad(MeV)$^{1/2}$ for 10 mA proton beam to 2.5 mm - mrad(MeV)$^{1/2}$ at 100 mA proton beam. This calculated value is considerably larger than that obtained by Becker *et al.*[8] for an EBIS source but is acceptable for a number of accelerator systems. Further, a relaxation of the space charge compensation exclusion is expected to reduce the value.

*Supported in part by the National Science Foundation.

†On leave of absence from Tata Institute of Fundamental Research, Bombay, India.

References

1. E. D. Donets, V. I. Ilyushchenko, and V. A. Alpert, preprint JINR P7-4142 DUBNA 1968.
2. E. D. Donets, V. I. Ilyushchenko, and V. A. Alpert, Int. Conf. on Ion Sources, First, Saclay, 1969.
3. E. D. Donets, IEEE Trans. NS-23, 897 (1976).
4. Rpt. of Workshop on EBIS and Related Topics, Darmstadt, B. H. Wolf and H. Klein, eds., No. GSI-P-3-77 (1977).
5. R. W. Hamm, Ph.D. Dissertation, Texas A&M University, Los Alamos Scientific Laboratory Rpt. LA-7077-T, Dec. 1977.
6. G. R. Brewer in *Focusing of Charged Particles*, ed. A. Septier (Acad. Press, N.Y.) 1967, p. 73.
7. J. M. McGuire and P. Richard, Phys. Rev. A8, 1379 (1973).
8. H. Bethe, Ann. Physik 5, 325 (1930).
9. R. H. Becker, H. Klein, and W. Schmidt, IEEE Trans. NS-19, 125 (1972).
10. A. W. Hull, Phys. Rev. 18, 31 (1921).
11. J. C. Slater, *Microwave Electronics*, D. Van Nostrand Co., Princeton, New Jersey (1950).
12. R. L. Darling and R. H. Davis, Rev. Sci. Instr. 43, 481 (1972).

0018-9499/79/0400-2154$00.75 ©1979 IEEE

** DISCUSSION **

M. CHAUDHRI: Are the results you have shown entirely from calculations, or do you have some experimental data too?

R. DAVIS: The results presented here are calculated. We plan to design, build, and test a system as soon as funds become available.

J. ORMROD: Could you comment on the emittance of the beam?

R. DAVIS: Yes. For the proton beam assumed here, the emittance values fall in the range 1.3 to 2.5 mm mrad $(\mathrm{MeV})^{\frac{1}{2}}$.