SOME METHODS OF GENERATION OF MULTICHARGED IONS OF RADIOACTIVE AND STABLE ISOTOPES

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Abstract

Cyclotron facilities are known to accelerate non-relativistic particles most efficiently. The energy gain of accelerated ions is defined as $W = k\cdot(Z/A)^2$, where Z/A is a specific charge. Of special importance for applications is the development of ion sources for producing high-intensity beams of multicharged ions with the emittance providing minimum particle losses during the acceleration.

This paper presents a special technique of increasing the charge of both radioactive and stable isotopes by means of multiple passing through an electron cloud heated by ECR-condition in a magnet trap. The gain in the specific charge $Z/A \geq 0.1$ is shown to be achievable practically without losing the beam intensity.

1 SOURCE OPERATION AND CONCEPTUAL LAYOUT [1]

A charge gain for radioactive and stable ions may be obtained by their passing through an electron cloud kept in the magnet trap and heated under the ECR-condition.

1.2 Multicharged ion source

A conceptual layout of the source is given in Figure 1.
Essentially, it includes a single-stage ion source, reverse transport ring, injector and extractor.

To heat electron a 14 GHz-generator is used. A mirror ratio within the source chamber should be not less than two. The ECR-region must be as long as possible to increase the efficiency of ion stripping in collisions with electrons. The chamber should be at a low pressure ($<10^{-8}$ Tor) to reduce recharging and scattering losses and to avoid the inside discharge. Electrons produced by a separate outer source are injected into the chamber, accelerated while crossing the ECR-region and trapped with forming a high-energy electron cloud. The electron source with a current of ~ (0.01÷0.1)A and an energy of W_e ~ (0.5÷2) keV must be installed on a high-voltage platform.

The reverse transport ring consists of two cylindrical capacitors and four dipole magnets. Each capacitor deflects an ion beam by 180°. The magnets provide the dispersion of orbits for ions with different charges. The voltage drop across the capacitor with the gap δ is given by the equation

$$\Delta V = 2V_0 \frac{\delta}{r_0}$$

where V_0 is the source extraction voltage, r_0 is the radius of the central orbit. ΔV is easy to get since $\delta \ll \tau_0$.

An electrostatic capacitor is characterized by the absence of orbit dispersion. Thus, such a capacitor allows a beam of ions with different charges to pass through. The orbit dispersion occurs near the dipole magnets. The injector and the extractor are placed in the region with the maximum dispersion. The maximum space between orbits occurs in the middle of the ring and is defined by the equation

$$\Delta y = lLB\sqrt{\frac{l}{2V_0E_0}}\left(\sqrt{Z_1} - \sqrt{Z_2}\right)$$

where

l is the magnet size along the beam,

L is the distance between the centers of the first and second magnets,

B is the magnetic induction,

V_0 is the energy of single-charged ions in the transport ring,

E_0 is the rest energy,

Z_1, Z_2 are the ion charges.

The energy of ions circulating in the ring depends on the source extraction voltage. Before entering the source, the ions are decelerated up to the energy of ~ $1\cdot Z$ keV to ensure the most effective interaction with electrons. If l=10cm, L=50cm, V=50kV, then for the Argon-ions with Z_1=2, Z_2=1 the orbit dispersion Δy=1.2cm. This value is high enough to allow the injection of single-charged ions. The extraction of the ions of Ar^{+4} occurs at a reasonable dispersion of Δy=0.8cm. The transport ring perimeter is about 6m. The revolution time required for an ion to pass the ring depends on the ion type and charge and lies within the range of (10^{-5}÷ 10^{-6}) s. The life of a radioactive isotope τ must exceed the ionization time τ_z, so

$$\tau > (\tau_Z + N\tau_t) = \tau_Z(1 + \tau_t/\tau_0) = \alpha\tau_Z,$$

where N is the number of ion revolutions along the closed path, τ_t is the revolution time, τ_0 is the time required for an ion to pass through the stripping chamber, $\alpha = 1+\tau_t/\tau_0$ is the device characteristic.

1.2 Laser ion source. Transformation of charge and current pulse shape

The additional stripping of ions described above may be applied to improving beam parameters for further acceleration.

It is well known that the laser irradiation of a hard opaque target at the near-critical radiation density ($q=10^8$W/cm^2) gives rise to a high-temperature dense plasma with the concentration $n>10^{19}$cm^{-3}. Such plasma basically consists of single-charged ions. An increase of the radiation density brings into existence of multicharged ions but this fraction is small. Besides, the laser pulse (~10ns) is several orders of magnitude shorter than the effective injection time in accelerators.

The laser source described can be modified by adding a pulse inflector at the stripping chamber inlet to transform the ion bunch time structure and to raise the beam intensity. All the ions of the same energy are delivered to the central orbit without regard to their charges. These ions circulate along the reverse transport ring passing through the stripping chamber at every turn. The inflector electric field should be relieved during the revolution time ~ ($10^{-5}\div10^{-6}$) s which exceeds the laser pulse duration. The inflector should be located in the ring in the region of zero orbit dispersion, that allows the injection of multicharged ions. Having attained a certain charge, the ions pass through the deflector and then are accelerated.

From the calculation below, the average time of reaching the multicharged state is ~ ($0.1\div1.0$) ms. This range matches the capture time for an ion synchrotron. The statistic nature of the stripping dictates different durations of gaining the charge for different ions varying within tens and hundreds of periods of revolution. Thus, the beam extracted from the ring consists of identical highly charged ions and is time-extended.

2 NUMERICAL CALCULATION

The calculation is made on the assumption that the ions of Ar^{+1} are injected in an infinitely long electron cloud with the beam intensity $Q_1=1\cdot10^8$s^{-1}. The ions of Ar^{+4} (Z/A = 0.1) are assumed to be extracted in a channel to an accelerator with an intensity Q_4. On single passing through the stripping chamber, the ions with Z=+1 leave the system. Collisions with electron have no marked effect on the path of the ions with the energy of ~ $1\cdot Z$ keV. So the efficiency of gaining the charge is governed by such elementary processes as the stepwise electron impact ionization and charge exchange with neutral atoms. The concentration variation n_Z for ions in passage through the electron cloud are defined as

$$\frac{dn_Z}{dt} = n_{Z-1}n_e\rangle\sigma_{Z-1,Z}\upsilon_e\langle - n_Z n_e\rangle\sigma_{Z,Z-1}\upsilon_e\langle_{ex}$$
$$- n_0 n_{Zt}\rangle\sigma_{Z,Z-1}\upsilon_Z\langle_{ex} + \frac{Q_Z^+(t)}{V_b} - \frac{Q_Z^-(t)}{V_b}$$

where

$n_{å}$ is the electron density,

n_0 is the density of neutral atoms,

υ_e and υ_Z are the relative velocities of interacting particles,

σ_z and σ_{ex} are the cross sections of the stepwise ionization and charge exchange respectively,

Q_Z^+(t) and Q_Z^-(t) are Z-charged ion beams injected in and extracted from the electron cloud at the time point t,

V_b is the ion bunch volume inside the electron cloud.

Parameters used in the calculation:

neutral gas pressure p~10^{-8} Tor, electron temperature T~40 keV, $n_e=1\cdot10^{12}$ cm^{-3} and $5\cdot10^{12}$ cm^{-3}, ion beam intensity of Ar^{+1} $Q_1=1\cdot10^8$ s^{-1} , energy of ions injected in the stripping chamber ~1 keV, plasma length to reverse transport channel length ratio ~ ($1/5 \div 1/7$).

The time dependence for the beam of Ar^{+4} with intensity Q_4^- is shown in Figure 2. If $n_e=5\cdot10^{12}$ cm^{-3}, the beam intensity reaches fast (in ~ 150 mks) the steady level which is about 30% Q_1.$^+$ It indicates that the injected ions are effectively transformed into multicharged ones with Z=+4. Then, the ion current of Ar^{+4} is 0.021nA, and the number of revolutions in the transport ring is about 200. Figure 3 gives simplified injection and extraction paths of ions with different charges and equal energy.

3 CONCLUSIONS

The approach of gaining the ion charge presented is based on the concept of the multiple passing of an ion beam through an electron cloud kept in a magnet trap. The electrons are assumed to be heated by means of ECR up to the energy level required for stripping. It is worth noting that this technique does not become inoperative with increasing the charge of extracted ions, however, the stabilization period for Q_Z^- is extended.

4 REFERENCES

[1] E.A.Lamzin at al. Bulletin of Russian University of People's Friendship. Physics, No 1, pp.97-105, 1993.

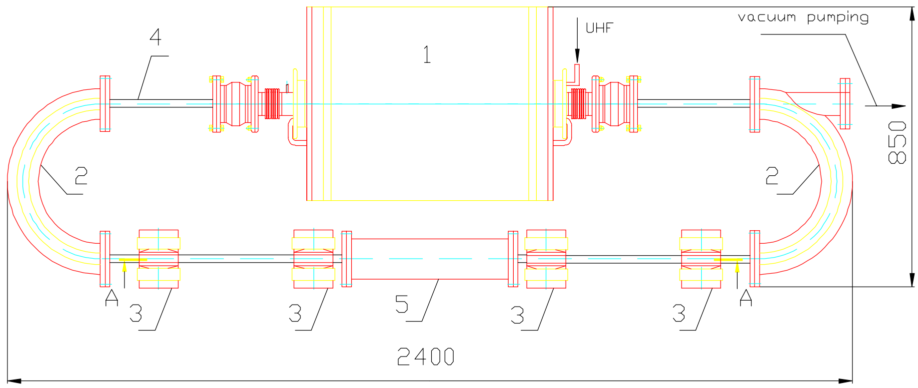

Figure 1: Conceptual layout of a multicharged ion source: 1 - stripping chamber; 2 - cylindrical capacitors; 3 - dipole magnets; 4 - vacuum chamber; 5 - beam line.

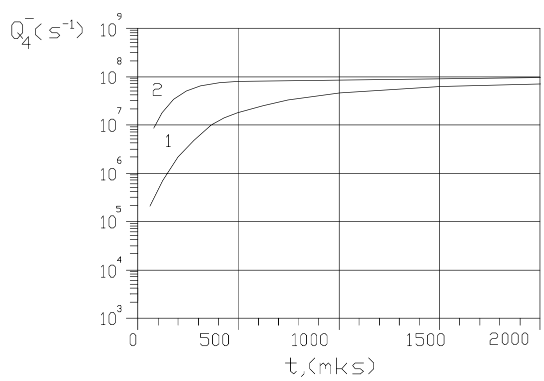

Figure 2: Output flux of Ar^{+4} ions with intensity Q_4^-, n=1·10^{12} cm^{-3}: 1 - electron cloud with $n_{å}$=1·10^{12} cm^{-3}; 2 - electron cloud with $n_{å}$=5·10^{12} cm^{-3}.

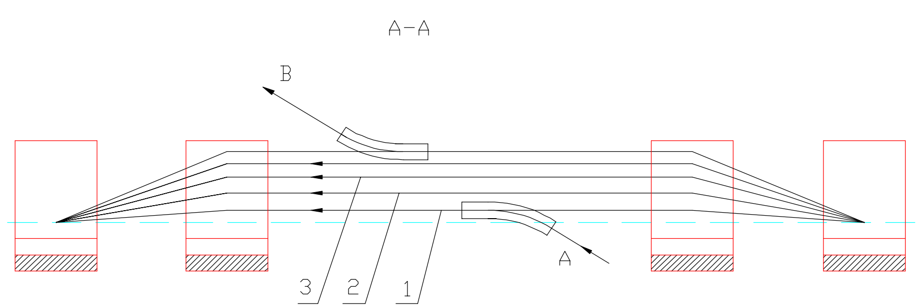

Figure 3: Orbit positions at the beam line 1,2,3... - orbits of ions with Z=1,2,3 ...; A - single-charged ion injection trajectory; B - 5-charged ion extraction trajectory.