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ELECTRON-ION RING PHENOMENA AND THE PROBLEM OF HIGHLY-CHARGED ION PRODUCTION

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1. Last time a problem of highly charged ion production is very important. We need high-charge ion beams in accelerators, ion spectroscopy, solid physics. A special interest represent cross-sections of ion productions, their interactions and phenomena in a very ionized gas. The main ion sources are based on heating and following plasma confinement by different methods. They are: PIG method, duoplasmatron and an electron-cyclotron resonance ion source. The ion beam is formed also in the laser source as a result of laser emission interaction with the substance.

The highest charged ions (up to Xe^{52+}) were obtained in the Donets EBIS in Dubna /1/. A very focused electron beam with energy up to 22 keV, density Ne up to $10^{11} cm^{-3}$ and the duration up to 10 s is used in EBIS. The main defect of this source is a small number of highly charged ions in a one pulse and a very low energy efficiency. So to receive 10^6 Xe^{52+} ions about 10^{19} electrons of the beam are needed. A maximum ion charge reached in all the types of sources is determined by the energy of ionizing electrons.

2. New possibilities of producing highly charged ions of heavy elements are created in the Collective Heavy Ions Accelerator at JINR /2/.

The typical electron ring parameters are:
Major radius $R = 3.5$ cm;
RMS small halfdimensions $a = 0.1$ cm;
Number of electrons Ne up to 10^{13};
Electron energy $E = 20$ MeV;
Compressed ring lifetime $\tau = 1$ ms;
Current density $j = 10^{23}$ cm^{-2} s^{-1}.

So ionization factor $j\tau = 10^{20} cm^{-2}$. It's enough to receive Xe^{20+} and U^{24+} ions. A number of Ni ions with charge Z is limited by the condition $Ni < Ne/Z$. Relativistic electron energy permits to ionize the inner shells of the heaviest elements. For this purpose we need to increase the lifetime of the electron-ion ring. So to produce Xe^{54+} and U^{90+} ions time about 1 s is needed.

The lifetime of the electron-ion ring and the possibility of highly charged ion production are limited by:

a) relativistic electron energy losses due to the synchrotron radiation;

b) increasing of the small electron ring dimensions by the electron scattering on trapped ions;

c) neutralization of the electron charge by the ionization of the background gas in the accelerator chamber;

d) decreasing of the ion charge as a result of electron capture in background gas;

e) technical difficulties of the electron-ion ring long time confinement.

3. Let's analyse these questions in detail.

a) The time behaviour of the electron ring major radius is determined by the equation:

$$\frac{dR}{dt} + \frac{R}{(1-n)B}\left(\frac{dB}{dt} - \frac{1}{2}\frac{d\bar{B}}{dt}\right) + \frac{R}{1-n}\,\frac{P}{E} = 0, \qquad (1)$$

where B_ is an axial component of the magnetic field inductions; $\bar{B}$, meanvalue of B in the electron ring; n field index; $P = \frac{2}{3}\frac{E^4 r_e}{m^3 c^5 R^2}$, radiation loss power; $E = \gamma mc^2$, electron energy; m, r_e, γ, mass, classical radius and relativistic electron factor; c velocity of light.

A characteristic time diminution of the electron ring radius by two times, due to the synchrotron radiation in the stationary magnetic field, is 20-40 ms.

b) Small dimensions depend on two factors except self and external electro-magnetic fields: diminution of dimensions due to the radiative frictions and their increasing due to the scattering of electrons on the trapped ions. Using the moments method [3] we can obtain the time variation law of transverse effective phase value $\epsilon = \gamma\omega a^2$

$$\frac{d\epsilon}{dt} = \frac{\gamma S}{\omega} - \frac{P\epsilon}{E}, \qquad (2)$$

where ω is a frequency of electron betatron oscillation; $S = \frac{r_e^2 c^3 Z^2 Ni}{4\pi a^2 R \gamma^2} \ln \frac{a\gamma}{137\, r_e}$ is the so-called collision integral.

The synchrotron radiation and scattering influence on small dimensions of electron-ion ring depends very strongly on the energy of electrons. So, with γ = 30-40 typical time of dimensions decreasing due to the synchrotron radiation is 30-60 ms, and the dimensions increasing due to the scattering with Ni = 10^{11} ions of Xe^{50+} is 20-30 ms.

c) It was shown in ref. [4] that the number of ions produced from background gas with thermal velocity U_T and density in dense electron rings is defined from equation $dN/dt = \sqrt{2/3\pi}\, U_T s n_0$, where s is surface area of the electron rings.

The N^{7+} ions are created in the ring during 5-10 ms. So, the electron ring will be neutralized by the ions from background gas with 10^{-9} Torr pressure during 50 ms.

d) Ion charge increases in the ring by the electron impact ionization. Ionization cross-section decreases with the ion charge increasing and the charge growth becomes slower. At the same time the possibility of charge exchange of the ions with neutral atoms (background gas) increases and it can limit the trapped ion charge when number of neutral atoms in accelerator chamber is large. In [4] it was found that for obtaining Xe^{54+}, and U^{90+} ions the background gas pressure in the chamber must be less than 10^{-9} Torr.

e) There are some difficulties in practical realization of electron ring long time confinement in the collective accelerator.

The simplest solution is to short out the current in the coils of magnetic system when the current reached maximum value. After that current, and therefore magnetic field, will change by the law $B = B_0 \exp(-t/T)$, where T is a decrement determined by the coil inductance and their active resistance. We have T = 50 ms in collective accelerator in Dubna.

4. The circumstances, given above show that it's difficult to contain electron rings in collective accelerator more than 50-100 ms. To produce the highly charged ions of the heavy elements a considerable increasing of the ring density is necessary. In [6] it was proposed to use the synchrotron radiation of relativistic electrons in a special generated nonhomogeneous magnetic field with index $n \leq 1$ to diminish electron ring dimensions. A system was calculated that permits to diminish the ring radius about two times during 5 ms. When we short out the magnetic system after supplementary ring compressing, its radius practically will not change because of the compensation of the magnetic field decreasing by the influence of synchrotron radiation. Moreover, the radiation friction exceeds the increasing of small dimensions due to the electron scattering on trapped ions in the initial time moment. The calculated time dependence of the electron ring and Xe, U ions parameters are shown in the table. The ring radius is determinated by equation (1). To find small dimensions we used equation (2) without considering the electron scattering. When, for example, Xe ions are about 10^{10} some increasing of transverse ring dimensions takes place after γ is less than 10. As a result, final small dimensions increase about 1.5 times compared to the table data. The table time is calculated from the electron ring formation.

Table

tms	Rsm	a mm	γ	$j_r \times 10^{22} sm^{-2}$	Z_{Xe}	Z_U
2.5	3.5	1.0	50	0.01	20	24
7.0	2.0	0.8	35	0.25	42	68
15	1.5	0.7	23	1.0	51	83
30	1.3	0.7	15	3.5	53	86
60	1.5	1.0	9.3	8.5	54	89
100	2.4	1.5	6.1	12.5	54	90

Electron ring dimension diminution makes weaker the requirements for the vacuum by 3-4 times.

5. The examination performed shows that it is possible to create new very effective source of highly charged ions and even nuclei of heavy elements on the base of the collective accelerator in Dubna. The source can operate with frequency 1 cps and in the pulse 10^{11}ions of Xe^{52+} and $5\cdot 10^{10}$ of U^{84+} ions (confinement time 20 ms), or $10^{10}$of Xe^{54+} and $3\cdot 10^{9}$ of U^{90+} ions (confinement time 100 ms), using 10^{13} electrons in every cycle.

REFERENCES

1. Donets E.D. Phys.Scripta, 1983, vol.T3, pp.11-18.
2. Sarantsev V.P., Perelstein E.A. Collective Ion Acceleration by the Electron Rings. Atomizdat, M., 1979.
3. Kazarinov N.Yu., Perelstein E.A., Shirkov G.D. JTF, 1980, vol.50, No.3, pp.549-555.
4. Perelstein E.A., Shirkov G.D. In: Problems of the Collective Acceleration Method. JINR, D9-82-664, Dubna, 1982, p.31.
5. Novikov V.G., Perelstein E.A. Authors certificate No.766384. OIPOTZ, 1983, No.4, p.351.
6. Alexandrov V.S. et al. JINR, P9-81-20, Dubna, 1981.

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Перельштейн Э.А., Ширков Г.Д. E9-85-4
Явления в электронно-ионных кольцах
и проблема получения многозарядных ионов

Рассматриваются явления в электронно-ионных кольцах при их длительном удержании в коллективном ускорителе тяжелых ионов. Основными факторами, ограничивающими время жизни электронно-ионного кольца и возможности получения многозарядных ионов в нем, являются: потери энергии релятивистских электронов на синхротронное излучение, увеличение малых размеров электронного кольца за счет рассеяния электронов на накопленных ионах, нейтрализация электронного заряда образующимися ионами из остаточного газа в камере ускорителя и уменьшение заряда ионов в результате перезарядки на остаточном газе. В результате анализа этих процессов показано, что время жизни электронно-ионного кольца в КУТИ может быть увеличено до $\sim 0{,}1$ с. Изучена возможность создания источника многозарядных ионов на базе КУТИ путем дополнительного уменьшения размеров электронных колец за счет синхротронного излучения в магнитном поле с показателем спада $n \lesssim 1$ и их последующего удержания в медленно убывающем магнитном поле в течение 0,1 с. Источник ионов с электронными кольцами может давать в секунду 10^{10} ионов X_e^{54+} и $3\cdot 10^9$ ионов U^{90+}.

Работа выполнена в Отделе новых методов ускорения ОИЯИ.

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Perelstein E.A., Shirkov G.D. E9-85-4
Electron-Ion Ring Phenomena and the Problem
of Highly-Charged Ion Production

The phenomena in the electron rings at the collective accelerator with a long confinement time are examined. The main factors limiting the lifetime of the electron-ion ring and possibilities of highly charged ion production are: relativistic electron loses energy due to the synchrotron radiation; the small electron ring dimensions increase provided by electron scattering on trapped ions; neutralization of the electron charge due to the ionization of the background gas in the accelerator chamber; ion charge decreasing as a result of electron capture in the background gas. This examination shows that the lifetime of the electron-ion rings at the collective accelerator can be increased up to ~ 0.1 s. A possibility of production of highly charged ions on the base of the collective accelerator is examined. A supplementary synchrotron radiation decreasing of the electron ring dimensions takes place in the magnetic field with index $n \lesssim 1$. Then the rings are kept in a slowly decreasing magnetic field during 0.1 s. Ion source with electron rings can give 10^{10} ions of Xe^{54+} and $3\cdot 10^9$ U^{90+} ions per second.

The investigation has been performed at the Department of New Acceleration Methods, JINR.

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