HEAVY ION INJECTION INTO SYNCHROTRONS, BASED ON ELECTRON STRING ION SOURCES

E. E. Donets, E.D. Donets, E.M. Syresin
Joint Institute for Nuclear Research, Dubna, 141980, Russia

Abstract

A possibility of heavy ions injection into synchrotrons is discussed on the base of two novel ion sources, which are under development JINR during last decade: 1) the electron string ion source (ESIS), which is a modified version of a conventional electron beam ion source (EBIS), working in a reflex mode of operation, and 2) the tubular electron string ion source (TESIS). The Electron String Ion Source “Krion-2” (VBLHE, JINR, Dubna) with an applied confining magnetic field of 3 T was used for injection into the superconducting JINR synchrotron – Nuclotron and during this runs the source provided a high pulse intensity of the highly charged ion beams: Ar\(^{16+}\) - 200 \(\mu\)A, Fe\(^{24+}\) - 150 \(\mu\)A in 8 \(\mu\)s pulses. It is expected, that an increase of the source magnetic field from 3 T up to 5 T should lead to increase of the intensity of Ar\(^{16+}\) and Fe\(^{24+}\) ion beams up to 1 mA at a pulse duration of 10 \(\mu\)s. It is expected also, a tubular electron string ion source should allow to produce 10 emA current per same pulse for ions like Ar\(^{16+}\), Fe\(^{24+}\) and Pb\(^{27+}\). The number of ions, extracted from the source per pulse is estimated as 2\(\cdot\)10\(^{10}\) particles. The possibilities and advantages of using ESIS and TESIS sources for heavy ions injections into the HIMAC (Chiba) and LEIR (CERN) facilities are considered.

ELECTRON STRING ION SOURCE

The so-called reflex mode of Electron Beam Ion Source operation is under intense studies both experimentally and theoretically during the last decade in the JINR [1-3]. Typically these ion sources are used in a “direct beam” mode of operation in order to produce highly charged ions.

The reflex mode of EBIS operation is realized due to using of the specially designed electron gun and electron reflector that allows multiple use of beam electrons [1-3]. The electrons do not reach electron collector after one pass through the drift space of the source; instead they are reflected backwards to the emitter side and then are reflected again in a vicinity of the emitter and so on. The electrons after few hundred reflections – electron string can be used for highly charged ions production similarly to the beam electrons.

Electron string is a stationary state of a one component pure electron plasma. The injected electrons are transformed to the plasma electrons due to some collective interactions and multiple reflections.

The processes of electron accumulation and string formation have been performed under the vacuum pressure of 10\(^{-12}\) Torr.

The interest to the reflex mode of EBIS operation was motivated first by the attractive possibility to decrease in hundred times a power of the electron beam preserving simultaneously the same ion yield. Indeed, the power of the electron beam in a direct mode can reach many hundreds of kW.

Table 1: Parameters of electron string ion sources.

<table>
<thead>
<tr>
<th>Set up</th>
<th>Krion-2</th>
<th>ESIS</th>
<th>TESIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy, keV</td>
<td>3-5</td>
<td>5-7</td>
<td>5-7</td>
</tr>
<tr>
<td>Number of electrons</td>
<td>(5\cdot10^3)</td>
<td>(2\cdot10^{11})</td>
<td>(2\cdot10^{12})</td>
</tr>
<tr>
<td>Magnetic field, T</td>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Ion current, emA</td>
<td>0.15</td>
<td>0.8</td>
<td>10</td>
</tr>
<tr>
<td>Pulse duration, (\mu)s</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Number of extracted ions</td>
<td>(3\cdot10^8)</td>
<td>(1.5\cdot10^9)</td>
<td>(2\cdot10^{10})</td>
</tr>
<tr>
<td>Injection repetition time, s</td>
<td>1</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The ions charge state spectra are narrow enough and can consist on the single line if the electron injection energy is fine tuned according to the binding energy of the electron on the corresponding atomic shell (Fig.1).

The emittances of extracted ion beams are almost negligible since the extracted ions get sufficient axial velocities still being confined in a focusing electron string space charge electric field; this focusing electric field allows to realize a fast (during a few \(\mu\)s) ions extraction from the Electron String Ion Source (ESIS).

The “Krion-2” ion source in the string mode of operation (Table 1) successfully has been used in the JINR relativistic synchrotron “Nuclotron” and the high ionization efficiency as well as the reliability and stability of “Krion-2” ESIS in an automatic regime of it’s work have been demonstrated [3]. “Krion-2” has provided a high pulse intensity of the highly charged ion beams during these runs: Ar\(^{16+}\) - 200 \(\mu\)A, Fe\(^{24+}\) - 150 \(\mu\)A in 8 \(\mu\)s pulses. In this runs the ion beams of Ar\(^{16+}\) and Fe\(^{24+}\) were accelerated on the “Nuclotron” up to the relativistic energies and used for the physics researches [3].
Fig. 1: Charge state distribution of Iron ions after 1.1 s confinement in an electron string of “Krion-2” source.

It was found experimentally [1-3] in set ups “Krion-2” and “Krion 3” that the maximum total number of the electrons accumulated in the strings grows as third power of the applied confining magnetic field \( B \) in the range of 2-3.5 T (Fig. 2):

\[ Q^{-} = a B^3. \]

The total number of stored electrons in “Krion-2” corresponds to \( N_e = 5 \times 10^{10} \) particles per pulse at confinement magnetic field of 3 T (Fig. 2, Table 1).

![Graph of electron string versus magnetic field](image)

Fig. 2: A total number of accumulated electrons in the electron string versus a guiding magnetic field; points are the experimental “Krion-2” – “Krion-3” dates.

The ESIS with the magnetic field of 5 T (Fig. 2, Table 1) permits to increase by 5 times the number of stored electrons and to reach level of \( 2 \times 10^{11} \) e\(^-\).

The proposed current of Fe\(^{24+}\) and Pb\(^{27+}\) ions in 5 T-ESIS is estimated as 0.8 emA at pulse duration of 8 \( \mu \)s (Table 1). The increase of the total number of stored electrons at 5 T magnetic field gives a reduction of ion confinement time \( \tau_{con} \propto N_e^{-1} \), which determines the injection repetition time \( \tau_{inj} \). The ion confinement time required for ionization of Fe\(^{54+}\) ions corresponds to 1 s in “Krion-2” at a magnetic field of 3 T [3]. An increase of magnetic field up 5 T permits to reach the injection repetition frequency of 5 Hz (Table 1).

In the JINR the works are in progress at present time on a generation of a tubular electron string [4]. The tubular electron string source will allow to increase the currents of the produced in ESIS ions in hundreds times in both pulse and DC modes (Table 1).

of Fe\(^{24+}\) and Pb\(^{27+}\) in 5 T-TESIS is estimated as 10 emA at pulse duration of 8 \( \mu \)s and total number of extracted ions Fe\(^{24+}\) is \( 2 \times 10^{10} \) ppp (Table 1). The first experimental work on tubular electron string formation is in progress now in JINR.

### POSSIBILITIES OF LEAD ION INJECTION IN LEIR BASED ON ESIS

It is expected that ESIS with 5 T guiding magnetic field (Table 1), installed in the CERN injection complex [5-7] should produce Pb\(^{27+}\) ion beam with intensity of \( 1.5 \times 10^9 \) ppp at pulse duration of 8 \( \mu \)s. The stripping efficiency corresponds to 12.5\% at the transformation from Pb\(^{54+}\) ions into Pb\(^{24+}\) [5]. The number of Pb\(^{54+}\) ions per one injection cycle for four-turn injection (the LEIR revolution time is of 2 \( \mu \)s) is

\[ N_i = \frac{1}{Z_e} \frac{\tau_{inj}}{t_{st}} \epsilon_{cool} \approx 2 \times 10^8 \text{ ppp}, \]

where \( \tau_{inj} \approx 8 \) \( \mu \)s is the injection time and \( I_i = 800 \) emA is the Pb\(^{27+}\) ion peak current. After four-turn injection the ion beam emittance corresponds to \( \epsilon_{mol} \approx 30/7 \pi \text{mm-mrad} \) at injected ion beam emittance of \( \epsilon_{inj} \approx 7 \pi \text{mm-mrad} \). The emittance after multi turn injection is cooled down to emittance of \( \epsilon_{cool} \approx 4 \pi \text{mm-mrad} \) during 0.2 s [6].

The lead ion Pb\(^{27+}\) production time is estimated as 0.2 s in the 5T-ESIS (Table 1). This time corresponds to the LINAC3 project repetition injection time [6]. The ESIS cooling-stacking injection can be repeated 10 times during injection time of 2 s. The storage gain for cooling stacking injection is equal to

\[ G_{st} = \frac{1 - \exp(-K t_{st} / \tau_{life})}{1 - \exp(-t_{st} / \tau_{life})} \approx 8,5, \]

where \( K = 10 \) is the number of stacking cycles, \( t_{st} = 0.2 \) s is the injection repetition time, \( \tau_{life} \approx 6 \) s is the Pb\(^{54+}\) ion lifetime. The simulated number of the stored Pb\(^{54+}\) ions in the LEIR corresponds to \( N_{st} = G_{st} \cdot N_i = 1.7 \times 10^6 \) particles during 2 s at the proposed ESIS injection. The simulated number of stored ions is closed to a LEIR project value, which is estimated as of \( 1.2 \times 10^7 \) particles [5].

In the case of using tubular electron string source (TESIS) it is expected to get ion current \( I_i \approx 10 \) emA at a pulse duration of 8 \( \mu \)s (Table 1). The number of Pb\(^{27+}\) ions, extracted form TESIS is estimated as \( N_i = 2 \times 10^{10} \) ppp (Table 1). The number of Pb\(^{54+}\) ions injected into the LEIR per one cycle is of \( N_i \approx 2.5 \times 10^9 \) ppp. After four turn injection the ion beam emittance corresponds to \( \epsilon_{mol} \approx 30/7 \pi \text{mm-mrad} \). As a result, use of TESIS should allow to reach the number of Pb\(^{54+}\) ions by 2 times higher than the existing LEIR project [5] with out cooling-staking injection. The beam emittance after four turn injection is cooled down to the \( \epsilon_{cool} \approx 4 \pi \text{mm-mrad} \) during 0.2 s. The total time of injection-cooling cycle is reduced from 2 s to 0.4 s.

A short Pb\(^{27+}\) lead ion confinement time of 0.2 s (Table 1) should permit to repeat the cooling-stacking injection from TESIS 10 times during 2 s. It is
estimated that the realization of TESIS cooling-stacking injection should allow to store in the LEIR Pb$^{24+}$ ion beam with intensity of $1.7 \times 10^{10}$ ppp. This intensity is by 14 times higher than the project one [5].

POSSIBILITIES OF MULTITURN INJECTION IN HIMAC BASED ON ESIS

The application of ESIS like “Krion-2” in the HIMAC injection complex [8,9] permits to reach Fe$^{24+}$-ion intensity of $N_{ij}=I_{ij} \tau_{ij}/Z_e \approx 3 \times 10^8$ ppp for two turns injection (the HIMAC revolution time is of 3.95s) at injection time of $\tau_{ij}=8 \mu$s and the Fe$^{24+}$ ion peak current of $I_{ij}=150 \mu$A. The small emittance of injected beam of $\epsilon_{ij} \approx 7 \pi \text{ mm-mrad}$ permits to repeat the two turn injection by 5 times at a variation of horizontal injection orbit at a final ion beam emittance of $\epsilon \approx 70/7 \pi \text{ mm-mrad}$. The storage gain is equal to $G_{inj} \approx 2.5$ at the injection repetition time of 1s and Fe$^{24+}$-ion lifetime of 2.2 s [8].

The simulated number of stored Fe$^{24+}$ ions corresponds to $N_{st}=N_{ij} G \cdot \eta_{st} \approx 8 \times 10^8$ ppp [9]. This number is comparable with one of $4 \times 10^8$ ppp obtained in the HIMAC at routine NIRS-HEC injection [8].

The ESIS with a guiding magnetic field of 5 T (Fig. 2, Table 1) permits to increase the project number of extracted Fe$^{24+}$ ions up $N_{i}=1.5 \times 10^9$ ppp and to reduce the repetition injection time to 0.3 s. This time corresponds to minimum one available at maximum HIMAC injection repetition frequency of 3 Hz. The storage gain corresponds to $G=6$ at the HIMAC injection repetition time of 3 Hz and the number of injection cycles of $K=10$. The number of stored Fe$^{24+}$ ions for a project 5T-ESIS is estimated as $N_{st}=8 \times 10^9$ ppp. This intensity is 20 times higher than it is available in the HIMAC now [8].

The project number of Fe$^{24+}$ ions extracted from TESIS is estimated as $N_{st}=2 \times 10^{10}$ ppp (Table 1). The realization of TESIS permits to store in the HIMAC the Fe$^{24+}$-ion intensity of $N_{st}=10^{11}$ ppp at storage gain of $G=5$ and the horizontal beam emittance of $\epsilon_{st}=200/10 \pi \text{ mm-mrad}$ after $K=10$ injection cycles. This intensity of coasting Fe$^{24+}$ ion beam is close to the limit related to the transverse instability [9].

COOLING-STACKING INJECTION IN HIMAC BASED ON ESIS

We consider two turns cooling-stacking injection from ESIS at the emittance after multi turn injection of $15/7 \pi \text{ mm-mrad}$. The emittance of cooled ion beam is of $10 \pi \text{ mm-mrad}$ at a number of cooled particles of $10^{10}$ ppp. The cooling time for Fe$^{24+}$ ion beam, produced by ESIS corresponds to 0.3 s [9]. The number of injected ions per cycle for “Krion-2” (Table 1) is equal to $N_{iij} \approx 3 \times 10^8$ ppp. The storage gain corresponds to $G=2.5$ at a number of injection cycles of $K=5$, an injection repetition time of 1 s and an ion lifetime of 2.2 s. The injection repetition time is related to time required for a deep ionization of highly charged ions. The ion confinement time of 1 s is required to produce Fe$^{24+}$ ions in the “Krion-2”. The total number of cooled ions stored in the HIMAC corresponds to $N_{st}=G \cdot N_{iij} \approx 8 \times 10^9$ ppp at a proposed “Krion -2” injection (Table 1). The numbers of simulated stored ions in the HIMAC at “Krion-2” injection is comparable with one at routine NIRS-HEC injection.

An increase of the magnetic field in ESIS from 3 T up 5 T permits to increase by 5 times the number of injected ions and by 2.5 times the storage gain caused by realization of 3 Hz HIMAC injection. It gives an opportunity to increase by one order magnitude the intensity of cooled ion beam $N_{st}=10^{10}$ ppp. This value is by 20 times higher than intensity, which is available now in the HIMAC [8]. This intensity is close to a limit determined by the incoherent tune shift of Fe$^{24+}$ coating beam at the emittance of $10 \pi \text{ mm-mrad}$. The stability of so intensive cooled ion beam is under investigation now.

A proposed tabular electron string ion source-TESIS with Fe$^{24+}$-ion pulse current of $I_{ij} \approx 10 \mu$A should permit to realize single turn injection and let us to store in the HIMAC the number of $N_{st}=2 \times 10^{10}$ ppp at beam emittance of $10 \pi \text{ mm-mrad}$ without electron cooling.

The high intensive beams after acceleration up the energy of 250-500 MeV/u at a small emittance of $1 \pi \text{ mm-mrad}$ are attractive for fast extraction from one HIMAC ring.

ACKNOWLEDGMENTS

The work was supported in part by INTAS (Grant No 01-2354) and CRDF (Grant No RP1-2417-DU-02).

REFERENCES