COLLECTIVE ACCELERATOR AS AN INJECTOR OF HEAVY ION ACCELERATING COMPLEX JINR

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In many countries heavy ion accelerator complexes for all types of ions[1] at energies from a few MeV/u up to GeV/u are being designed. Also, the possibilities of colliding nuclear beams in these complexes are being considered. The scheme of such a complex that has been constructed at JINR is given in fig. 1.

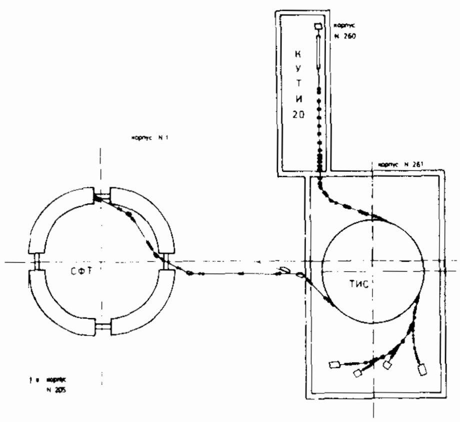

Fig. 1: The scheme of accelerating complex.

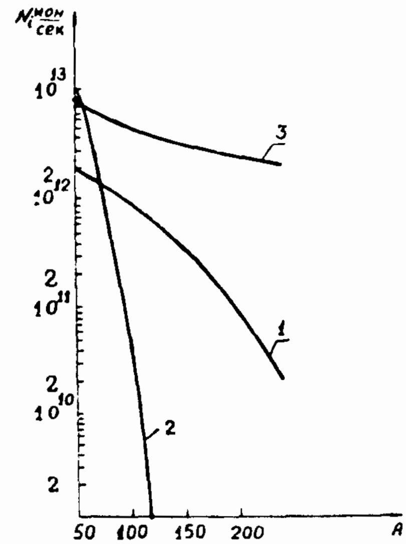

Fig. 2: The intensities of different accelerators as a function of A.
1. Linac; 2. Cyclic; 3. Collective

In the scheme, the first stage of accelerator is a collective heavy ion accelerator for the acceleration of all types of ions up to an energy of 20 MeV/u. Subsequent acceleration occurs with the heavy ion synchrotron (TIS). The energy of the ions produced in the synchrotron (450-650 MeV/u) facilitates investigations in the region of intermediate energies and provides effective injection into the existing synchrophasotron for experiments using beams of ions with energies of 3.5 - 4.5 GeV/u. The replacement of the synchrophasotron by a more effective and up-to-date ion accelerator is being considered.

The choice of a collective accelerator as an injector was stimulated by the weak dependence of the acceleration process on the type of accelerated ions. The dependence of accelerated ion intensities on their atomic number for different types of accelerators - Linac (1), cyclic (2) and collective (3) are given in fig. 2.

The advantages of collective accelerators are evident. However, the use of an accelerator as an injector involves a great number of specific requirements. To satisfy these requirements, both theoretical and experimental investigations of collective heavy ion accelerators are necessary.

I. The Principle Requirements for an Accelerator Injector

A careful examination of the heavy ion synchrotron, TIS, enables one to give an accurate formulation of the requirements on an injected beam of heavy ions.

The energy of the injected ions is mainly determined by ion losses in the residual gas, i.e. by the vacuum in the synchrotron and, in the first turn, fast impact and septum magnets demonstrate that it is inexpedient to have an average vacuum in the synchrotron of better than 10^{-9} Torr. In practice, this leads to an ion injection energy of up to 20 MeV/u.

The **energy spread** of particles is defined by the accelerating system of the synchrotron and should be < 0,6 %.

The **charge spread** in the beam of injected ions is defined by the spread after passing the stripper. For the ions of U with an energy of 20 MeV/u we obtain an equilibrium charge of 80 + 3. The examination of the motion in the synchrotron[2] indicated the possibility of acceleration of 3 charges simultaneously. The acceptance of the synchrotron entirely determines **the geometry characteristics of a beam.** The main restriction is imposed on the vertical emittance - 10 mrad.cm.

Finally, the operating frequency of the synchrotron was selected at 3 Hz which, with multiple injection of a beam, fully defines the requirements of maximum and **mean repetition pulse injector frequency.** The time scheme of injection is presented in fig. 3.

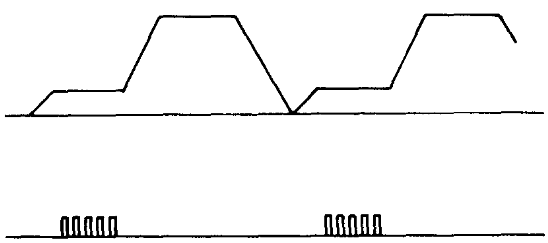

Fig. 3: Time diagram of TIS.

The main requirements on the beam for injection are summarized in table I:

The Energy of Ions - E	20 MeV/nucl.
Energy Spread $\frac{\Delta E}{E}$	0,3%, i.e. 60 keV/nucl.
Charge Spread ΔZ (for ions of U)	80 + I
Emittance YY'	10 mrad.cm.
Frequency f_{max}.	50 Hz
Average Frequency $f_{сред}$.	15 Hz

On the basis of investigations of an ion accelerator with the electron rings at the Joint Institute for Nuclear Research, let us examine the possibility of satisfying the injection requirements with a collective accelerator. It is known that the process of ion acceleration in the electron ring is given by the following:

$$\Delta E = K \frac{Z}{A} \frac{2V_e}{a_r + a_z} \frac{1-f}{1+\alpha} \text{ MeV/nucl.sm.} \quad (1)$$

here, besides the principle characteristics of an electron ring - V_e, a_r, a_z,

the ion component is of great importance:

f - coefficient of charge neutralization,
α - mass coefficient of the components,
K - polarization of the components conventionally taken to be equal to 1/4.

Since with polarization the nonlinearity of forces plays a significant role, it is necessary to study sufficiently well the functions of the distribution of the ring components at its formation.

The electron density in the ring is well described by the Gaussian distribution

$$\rho_e = \frac{1}{2\pi a^2} \exp\left(-\frac{r^2}{2a^2}\right) \quad (2)$$

The ion distribution from ionization with such an electron beam is also essentially different from that with a beam with uniform density. The r.m.s. dimensions and the effective phase volume of the ion components with an average charge Z are decreased as:

$$a_z = a_1/\sqrt{Z} \div a_1/\sqrt[4]{Z} \quad (3)$$

In fig. 4 the dependence of the charge on various ways of injecting neutrals and distributions of electrons are given.

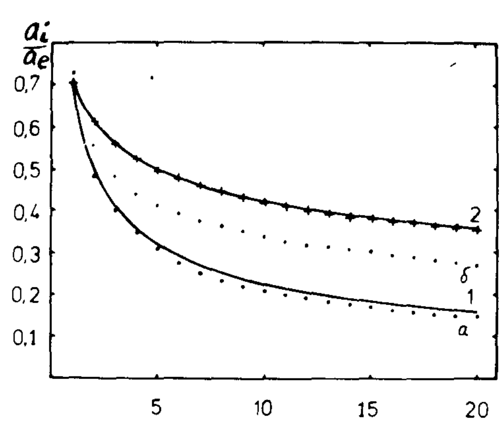

Fig. 4: Relative dimensions of the electron and ion components of the ring as a function of the ion charge for constant (1) and pulsed (2) neutral source.

For ions of U^{+25} the magnitude of the effective emittance becomes 0.4 π mrad.cm for the parameters of the electron rings obtained.

The distribution function of the ion number and their charge is entirely defined by the conditions of neutral particle injection in the "Adhezator" during the time of the ring compression. For the schemes of compression accepted at JINR, the dependence of Ni/Z (A) for various ions is presented in fig. 2. As shown in this figure, for ions with the exception of the lightest ones, the dependence on the process of acceleration is absent.

The factor of neutralization plays a significant role not only in the process of acceleration but also in changing the ion distribution function in the ring. The conditions given in fig. 4 are fulfilled up to f ~ 0.2. Hence, for the number of ions of U in a single electron ring we have 4.2 • 10^{10} assuming the neutralization factor to be equal to 0.1. Let's demand the fulfillment of summed mass equality for the same acceleration of any kind of ions in such an accelerator.

Since $\frac{NiAM}{Nem f_1}$ = Const. = 45, as for the ions of U, then:

A	H	Ar	Ge	Xe	Hg	U
Ni	$7 \cdot 10^{11}$	$2,4 \cdot 10^{11}$	$1,3 \cdot 10^{11}$	$7,4 \cdot 10^{10}$	$4,9 \cdot 10^{10}$	$4,1 \cdot 10^{10}$
Ni/s.	$3,5 \cdot 10^{13}$	$1,2 \cdot 10^{13}$	$6,5 \cdot 10^{12}$	$3,7 \cdot 10^{12}$	$2,5 \cdot 10^{12}$	$2,1 \cdot 10^{12}$

The number of accelerated ions in a single ring corresponds to the magnitude obtained in the experiments at the prototype[3]. The ion number as well as their distribution function define all the remaining characteristics of the ion beam (Δβ, ΔE, XX', Z, etc.). The calculated effective emittance for U ions is 0.4 π mrad.cm. However, to provide similar conditions for ring acceleration, it is necessary to have an accurate knowledge of the ion and electron number in the storage process. To measure the ion and electron number at the prototype, accelerator bremsstrahlung and synchrotron radiation of electrons[4/5] was used. The bremsstrahlung measurement results for Ni • Ne are indicated in fig. 5.

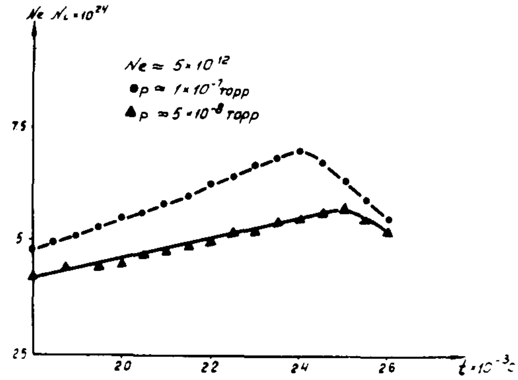

Fig. 5: The ion storage in the ring.

For the given measurements, the electron number was (6 ± 2) • 10^{12}. The maximum magnitude of the electron and ion number product reached was Ni • Ne (7,5 ± 1,8) • 10^{24}. The maximum corresponds to a charge neutralization of ~ 1. The relative accuracy of the measurements at the prototype was a few per cent and can be reduced to 1 % so that it will provide the relative accuracy of the process of acceleration for different pulses. The synchrotron light measurement of the particle number in the ring is based on the influence of betatron oscillations on the angular distribution of synchrotron radiation[6]. During storage of ions in the ring the frequency of the betatron oscillations is greatly changed. In Fig. 6 the angular distributions of synchrotron light for various electron numbers (2 • 10^{11} and 2 • 10^{12}) are given.

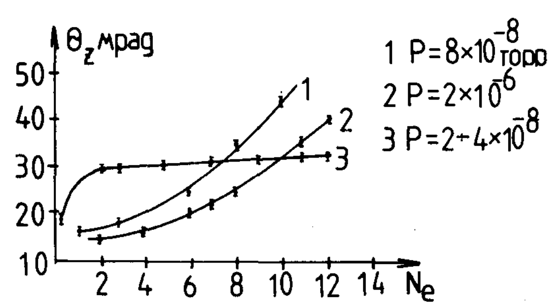

Fig. 6: The angle distribution of synchrotron light.

Thus, during formation of an annular electron-ion bunch the value of the ring mass $(\frac{N_i}{m\gamma_\perp}\frac{AM}{N_e})$ can be chosen with an accuracy of 1 % so that during acceleration it will amount to $\Delta E/E \sim 1$ %. In the collective accelerator a self-focussing two-component ring is being accelerated. The process of component separation after acceleration is important from the point of view of the changing emittance of the ion ring. The system for the separation of the ring components was tested and the characteristics of the ion beam ($\Delta\beta$, ΔE, X, X') were measured in experiments on the collective accelerator prototype. The component separation was provided by increasing the magnetic gradient, whereby the conditions of ring integrity are not satisfied, and also by losing electrons on azimuthally placed targets. The main parameters of an ion ring were measured ~ 1 m after separation. The ion velocities were $\beta_{\parallel} = 0.05 - 0.06$. In table I the experimental results and also the calculated values corresponding to the ion velocity $\beta_{\parallel} = 0.2$ (the energy 20 MeV/u) are represented.

TABLE I

The energy of ions E	1,7±0,2 MeV/nucl.	20 MeV/nucl.
Velocity $\beta_{\parallel}$	0,06	0,2
$\beta_\perp$	$1{,}5\cdot 10^{-3}$	$1{,}5\cdot 10^{-3}$
Emittance yy'	(6±1) mrad.cm	1,8π mrad.cm
Energy spread $\frac{\Delta E}{E}$	$(5\pm 1)\cdot 10^{-2}$	$1{,}5\cdot 10^{-2}$

To transform an annular phase volume of ions to an on-axis beam, a parabolic lens is installed with an azimuthal field that provids a bend of the ring components towards the axis. At a distance of 10 m from the lens a bunch with the matched dimension of 2 cm* is formed. Further transportation is realized by a standard channel. After passage through a stripper situated at the end of the channel the charge of U ions is Z ~ 80. So only the energy spread is not in accordance with the synchrotron injection conditions. To decrease the energy spread the monochromator, that section of the inductive accelerator with the linearly increasing voltage pulse, will be used. The rise time is 70 ns. Such a monochromator permits a reduction in both the spread of longitudinal velocities in a single pulse and also the spread in the mean velocities from pulse to pulse. The chosen monochromator allows us to have $\Delta\beta/\beta \le 3\cdot 10^{-3}$.

*) The effective emittance of the transformed beam is equal to 6π mrad.cm.

At injection into the synchrotron, the separation of ion charges makes it possible to select one or three charges (for U, 80 ± 1) for injection into the synchrotron. Taking into account the losses in all the beam transformation elements for the injection of a single charge, we have $1.7\cdot 10^{10}$ U ions, $4.3\cdot 10^{10}$ Xe ions or $6.5\cdot 10^{11}$ N ions captured. Recently, the ion loading experiments with various elements were done using a laser for the neutrals. In particular the load of ions of Pb, Cu, Al and N is demonstrated in relative units in fig. 7 for various electron ring intensities. The bremsstrahlung of the electrons on the ions was measured.

A	Pb	Cu	Al
Ni	$4{,}7\cdot 10^{10}$	$1{,}5\cdot 10^{11}$	$3{,}6\cdot 10^{11}$

Thus, it is feasible to utilize a collective accelerator as an effective injection into synchrotron.

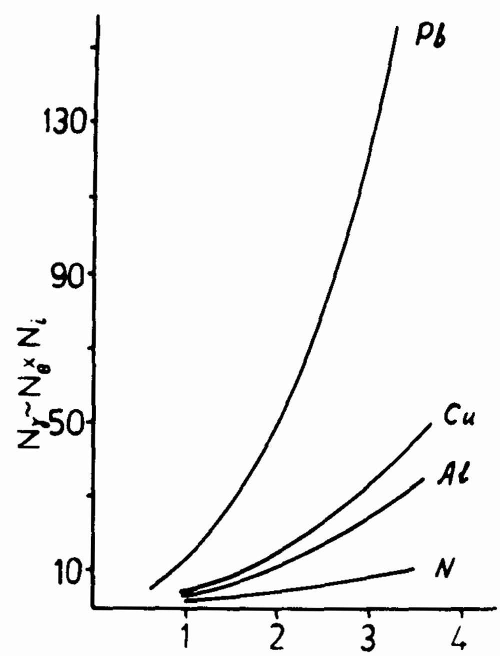

Fig. 7: The load of ions.

Collective Heavy Ion Accelerator - 20 (KUTI)

Principle Scheme of Accelerator

The schematic of the accelerator is given in fig. 8.

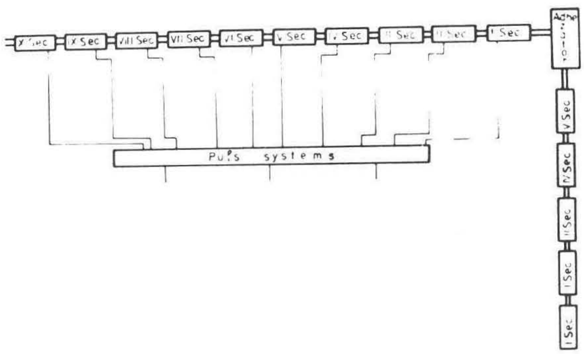

Fig. 8: The scheme of KUTI-20.

The scheme corresponds essentially to the one verified in the experiments on the prototype of the accelerator. Electrons accelerated in the inductive accelerator SILUND-20 are injected into the ADHEZATOR chamber and are trapped onto the closed orbit with a radius of 35 cm. Compression in the increasing magnetic field takes place with a coefficient of 10. Neutrals are injected into the region of an electron ring with one of the sources of neutrals (gaseous, effusion and laser). Acceleration of the two-component ring occurs in 10 inductive accelerating sections of the same type with an electric field of 10 kV/cm. After component separation of the accelerated ring, the transformation of the annular ion bunch is produced. During transportation in the channel a bunch is stretched due to the velocity spread and enters a pulsed monochromator providing the reduction of the particle spread over pulses. First, an additional ion stripping and separation of a single charge occurs. In general, all the systems have had a principle verification on the prototype of the accelerator. However, the requirements for duty cycle have brought changes in the construction of separate elements.

SILUND-20

For the construction of an inductive accelerator with higher cycling rates, greater requirements on the parameters of an electron beam defined by the method of ring formation in the collective heavy ion accelerator-20 (KUTI) have been demanded. For ring formation with an electron number of $\geq 10^{13}$ in the system with single-turn injection using the present geometry, an electron beam with a current of ~ 200 A and a pulse duration of 10 ns is required. The energy of the electrons should be in the range of 2-2.5 MeV. Taking into account the system's beam capture efficiency of 50-60 % the current should be 500 A. The design of a new inductive accelerator has become a further development of the systems of the inductive electron accelerator - SILUND (I). Transition to the higher frequencies of cycle repetition (50 Hz) has required new solutions for most systems. For the accelerator modulator, a scheme with the transformation of pulsed power has been suggested and realized. This has reduced the number of commutator elements by up to 5 for the whole accelerator (fig. 9).

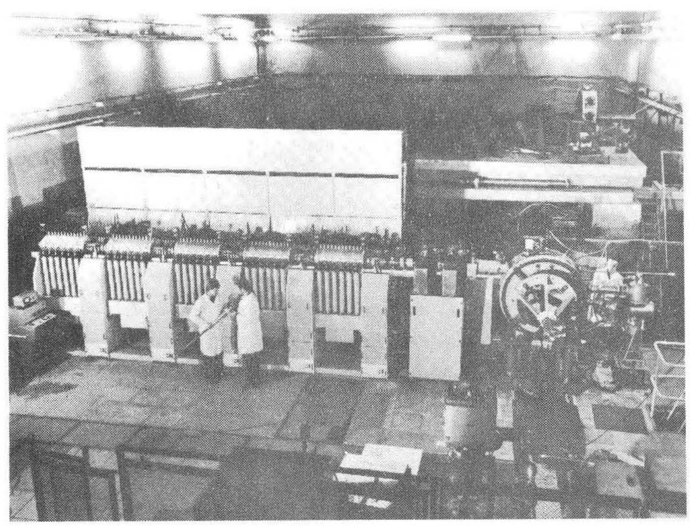

Fig. 9: SILUND-20 (a general view of the accelerator).

The plasma source for electrons is designed essentially with the aim of increasing the life time and removing of the main heat loadings at the pulse repetition frequencies of 50 Hz.

The power supply of the focussing system of the accelerator uses a pulsed current source with a pulse duration of 50 mksrc. Transition to shorter pulses of current enables us to decrease the electric power delivered to this section of the accelerator to lower than 20 kW. This can be easily removed by the cooling system.

In 1982 all the main components of the accelerator were made and constructed; the adjustment and accelerator start-up were carried out. The following beam parameters have been obtained.

Energy	– (2 + 0,15) MeV
Current	– 800 A
Emittance	– (34 + 12)π mrad.cm.
$\frac{\Delta E}{E}$	– 3%

ADHEZATOR-20

The principle concept on which the Adhezator of the prototype collective accelerator is based, namely: the necessity of the presence close to the beam of the metallic wall of the vacuum chamber and a high coefficient of the ring compression in the magnetic field were also taken as the basis of Adhezator constructions (Adhezator-20). However, the search for a more reliable construction and the use of material with small losses due to eddy currents have led to a Ti vacuum chamber (fig. 10).

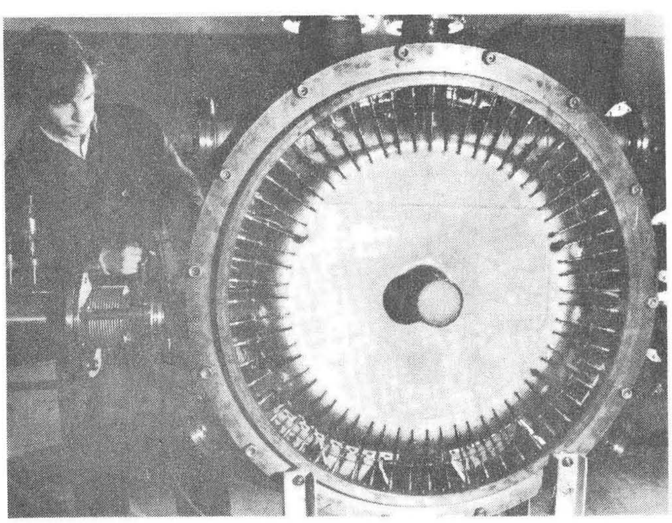

Fig. 10: Vacuum chamber.

The necessity of removing the heat loading from the Adhezator chamber and the magnetic field coils and, in the first turn, from the coils of the final compression stage required the possibility of cooling the external walls. Also, the future placement of the third stage coils in a specific cooled container was included in the design. The main systems of Adhezator were created and tested at the repetition frequency of 20 Hz.

Acceleration Sections of the Rings

As in the prototype of the collective accelerator, the initial electron ring acceleration is accomplished in the decreasing magnetic field of solenoid.

The value of the ion energy at the outlet of the solenoid was taken to be equal to 5 MeV/u. For the admissible energy gains of 3 MeV/u.m the length of the solenoid will be 1.5 m. It is known that acceleration in the decreasing magnetic field is accompanied by the increasing radius of the electron-ion ring and, therefore, the magnitude of acceleration in the solenoid is restricted. Further acceleration of the rings occurs in the pulsed electric field which is formed in the inductive section. The effective length of the section is 1.5 m, the electric field - 10 kV/cm. The scheme of such a section is shown in fig. 11.

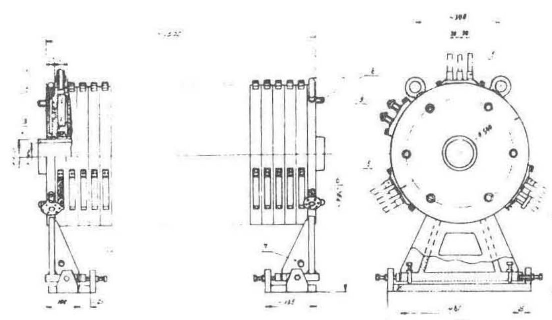

Fig. 11: Acceleration section of the rings.

The possibility of creating a section with only a travelling wave of the electric field is also being considered. This would increase the efficiency of acceleration by two. The principle of formation of the leading magnetic field in this section is the same as in the sections of the electron accelerator.

Thus, at the Joint Institute for Nuclear Research a collective heavy ion accelerator has been designed and the operation of a collective heavy ion accelerator capable of accelerating any type of ions up to U has been started. The accelerator can be effectively utilized as an injector in a heavy ion synchrotron.

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