COLLECTIVE METHOD OF PROTON ACCELERATION

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I. General Problems of Collective Methods of Acceleration

Great development of high energy physics has resulted in a number of discoveries of significant value. However the most fundamental regularities of elementary particle world and of the structure of the matter will be established and understood only after putting into life accelerators with the beam energy of hundreds and thousands billions of electronvolts.

As it was shown in a number of the designs in different countries, the accelerators for such energies would represent a system of a giant size. The weight of the electromagnets,sizes and the cost of such constructions will go beyond any reasonable measures and become comparable with the budget of intire states. The increase of particle energy causing such a growth of the size and the cost of accelerators is easily explained mainly by the following reasons:

In linear accelerators the intensity of the field affecting the particles is rather small so this fact requires a tremendous length of a system for an energy of about 10 GeV and higher.

Nowadays in cyclic accelerators producing presently the highest energies (Accelerators with Alternating Gradient - AGS) it is possible to reach higher and ever higher energies due to increasing radius of the particle trajectory,because the maximum intensity of the magnetic field used to hold a particle on an orbit is not higher than I2-I5kG.Consequently the sizes of the electromagnet power and the cost of the whole system increase too.Hence it is evident that the construction of the accelerators for superhigh energies of ~ 1000 GeV requires principally new methods of acceleration to be worked out. According to these new methods the effective fields affecting the particles (accelerating or trapping) must be much larger than the affecting fields used in the modern autophasing accelerators.

In 1956 Veksler V.J./1/ suggested new methods of acceleration, based on collective interactions and coherent effects. Following it the field accelerating the particles is created not by external sources but due to interactions between a number of accelerated particles with some other group of charged particles, an electron beam, plasma stream or electromagnetic radiation.

Coherent methods of acceleration (at first all new ideas of Veksler V.J. were combined under this term) are based on proportionallity of the field intensity affecting a separate particle under certain conditions to the number of accelerated particles.

In the collective methods the accelerating field is created by another group of charges(bunch) and it is proportional to their number. Therefore the number of accelerated particles can be arbitrary in some ranges.

Collective acceleration method and the assumed structure of acceleration are given in the report at the Sixth International Conference on Accelerators in the USA in 1967.

Nevertheless we had better refresh the idea of this method in short. Let us imagine a compact electron bunch in which there is a certain rather small amount of ions,let it be protons. We shall make this bunch move in an external electric field accelerating electrons. Then, under certain conditions ions will stay in the bunch captured by a Coulomb field, and will be accelerated together with the electrons. If the effective mass of an electron taking into account finite transverse motion in the bunch is $m_\perp$ and ion mass M, then the energy of the ion with the same velocity as that of the electron bunch appears to be in $\frac{M}{m_\perp}$ times more, than the energy of the electron in the bunch. However the fact that the external field cannot be arbitrarily large must be considered otherwise ions will be lost from the bunch. It is evident that the larger are the Coulomb forces holding ions, the larger external fields can be used and the larger ion energy will be obtained at the given length.

While being accelerated the bunch is polarized,the center of the ion bunch is placed a little behind the center of the electron bunch, and the average accelerating force affecting the ions coincides with the Coulomb force affecting the central ion directed from the electron bunch.

So the bunch must possess the following properties:the number of electrons must be essentially larger than the number of ions,electron density must be as high as possible.

2. Electron-Ion Bunch, its Extraction and Focussing.

An electron bunch is formed in a system called "ADGEZATOR"(adiabatic generator of charged toroids). It is based on the adiabatic changes of parameters of the electron ring in a rising magnetic field /2/. Considering this method of electron bunch creation in a form of a ring, one can prove that the Coulomb field at its boundary for given dimensions will be of an order of

$$\varepsilon_{Coul} = \frac{e N_e}{2 \pi R a}$$

where N_e is the total number of electrons in a ring. Hence,with the reasonable values of N_e ,injection currents and phase space accentance of the adgezator the field intensity $10^6 \div 10^7$ v/cm can be obtained.

The question of pumping the ions captured in the ring to accelerate them by the given field has to be considered.

At the end of the electron ring compression with the help of the pulsed gas valve the portion of neutral gas (H_2) is brought into the adgezator. Collisions of relativistic electrons with hydrogen molecules result in the production of the molecular ions mainly. (Ionisation cross-section is of $\sigma = 10^{-19} cm^2$). At the subsequent collisions with electrons they dissociate into a hydrogen and a proton.

The characteristic ionization time is

$$t_1 = \frac{2 \pi R a}{N_e c \sigma} \approx (50 - 5)\ \mu sec ,$$

where $N_e = 10^{13} \div 10^{14}$

For the given number of protons (in our case this value is chosen to be 10^{-2}) the gas pressure in the region of a ring can be determined.

Instead of hydrogen other gasses can be used and hence different kinds of ions in a ring can be obtained.

The probability of obtaining multiply charged ions of heavy elements /3,4/ has been studied.

The multiply charged ion accumulation occurs while passing electrons at the end of the ring compression through a stream of neutral atoms of the matter.

While colliding with electrons atoms are ionised and mainly trapped by an electron ring. Successive collisions of ions with electrons lead to the accumulation of ions with various ionization degrees. This process of successive ionization (without taking into account the shell rearrangements)can be discribed approximately by a well-known equation for density changing of K-fold ionized atoms n_k in the time unit $(k \equiv Z_{eff})$

$$\frac{dn_k}{dt} = \frac{n_{k-1}}{\tau_{k-1}} - \frac{n_k}{\tau_k}$$

where $\tau_k(n_e c\, \sigma_k)^{-1}$ time ionization, n_e ,σ_k -density and ionization cross-section.

If the density of neutral atoms n_a is the same outside and inside the ring,then for the time interval larger than the ionization time the ion density in the ring is

$$n_k = n_a \frac{\sigma_0}{\sigma_k}.$$

The ionization cross-section may be approximately counted

$$\sigma = \pi r_0^2 \frac{m_0 c^2}{J_k} \ln \frac{E}{J_k},$$

where J_k ionization potential K-fold of an ionized atoms and $r_0 = \frac{e^2}{m c^2}$.

Here is an example of accumulation of ions Hg in a ring.

We shall get that ionization time of a 5 fold ionized atom Hg is equal to 3o μsec.So we see that even in the adgezator , working in our Institute it is possible to get Io-fold ionized atoms. The time of the ring staying in a final state in fact can be grown in IO times.

The exepted method of bunch making is not unique. However, the analysis made for some other variants, showed that compression on the radius gives probability to obtain the largest densities of particles in a ring.Two methods of bunch making similar in the physics process seem to be worth examining. One of these methods uses tubular beam of electrons passing with relativistic velocities. At the hitting of such a beam on a "magnetic field hill" the beam is bunched and turns into a ring.

By variating electron energy and the length of cylindrical formation together with the gradients of the magnetic field you can obtain very high coefficients of compression. The mentioned method of obtaining a bunch seems to be perspective for making bunches with large numbers of particles($IO^{I5}$and higher), if not to ask very high requirements on the dimension of the cross-section in the formation.

Such a bunch can be used for so called "impact acceleration".

The question of accelerating the tubular beam is not still sufficiently clear. Finally there is one more probability of obtaining ring bunches, i.e. by using the pulsed magnetic mirror field. We mention this method here because of two reasons. Firstly, such a probability has been already examined by us as the very first variant of the adgezator, and then because at present the experiments have been made to carry this variant into practice/5/. This method has got some weak points, namely while injecting many turns of the electron current into the magnetic mirror field there appeared difficulties to obtain small dimensions of the cross section at the final state, but injection of only one turn makes it difficult to get a large number of particles into a ring. It is necessary to solve separately the problem of ring extraction, not trivial in this system. Apart from that here are some words about obtaining a relativistically stable beam of the Budker type /6/. It is estimated that obtaining such a ring in the system of the adgezator type is impossible due to high requirement of vacuum (10^{-12} mm Hg) and the difficulties concerning compensation of the losses of electron energies on radiation. It follows that obtaining the stationary state of a ring requires large time (≈ 1 sec). Difficulties can possibly be avoided if to extract the ring from the adgezator into a special trap. Formation of a stable ring in such a system occurs at its continious motion between the mirrors, so the mentioned above difficulties can be simply and totally overcome in such a system and vacuum demand will be reduced up to 10^{-7} mm Hg. Questions of stability in such a system must be examined specially.

Some words about the place of the stable ring in the perspectives of the ion acceleration by collective methods should be said. As it was shown above the limiting value of the field due to the small sizes of the cross section(10^{-3}-10^{-4}cm) grows in a thousand times. This effect makes it possible to use such a bunch in an impact acceleration.

Combined with the possibility of obtaining a heavy bunch from the tubular beam this effect increases the acceleration efficiency and reduces the cost of the accelerator compared with the usual collective accelerators by one or two orders.

The magnetic field of the adgezator is formed by the turn system, located symmetrically to the plane, in which compression of the electron ring occurs. The sceme of the turn location and the character of the magnetic field distribution produced by those turns are shown in Fig.I. As is seen in Fig.I for the extraction of the electron ring from the adgezator along its axis it is necessary to overcome the barriar made by the rising magnetic field.

As it is known from the examination of the particle motion in the space alternating fields, the ring formation like ours begins to move towards the decreasing field, nevertheless its velocity will grow respectively with the decrease of the azimuthal velocity. It is evident that for the extraction of the electron ring it is necessary to make the magnetic field decreasing along the axis. But the fact that the gradients of this field must not be higher than accepted due to which the loss of the ions starts, must be considered. This limitation can be written in the following way:

$$\frac{\partial B_z}{\partial z} = \frac{2\gamma_{\parallel 0}\, m_\perp}{R\gamma_{\parallel}^2 M}\left(1+\frac{N_i}{N_e}\,\frac{M}{m_\perp}\right).$$

For taking off the potential barriar and extracting the electron ring we add 3 disconnected turns ,short-circuited at a certain period of time. This moment is chosen so that the field in the main turns is still rising, this growth in the place of the maximum barriar due to the induced field of the added turns is reduced and the barriar dissappears. Calculations for the whole system of the turns have been carried and the results of the figure integrating of the particle motion equations show that the particles remove from the potential well at the distance of IO cm from the axis with the low speed($\beta_z = IO^{-4}$).

In Fig. 2 the distribution of the magnetic field in different periods of time at the extraction is shown. Crosses show velocity and coordinates of the particles in the different moments of time.

Experimental dimensions have shown certain discrapences with the calculations mainly on the question of the choice of the moment when to switch on the additional turns. The distribution of the magnetic field agrees with the calculation. Discrapences can be explained by the fact that the resistance of the commutatative element of the turns has not been considered but it appears to be substantial. Further motion of the ring occurs in the falling field with the given acceleration. Calculations show that the velocity of the extracted ring can be considerably high and approach 0,3C.

This estimation shows the possibility of obtaining the multicharged ions in the electron ring. In most cases with the multicharged ion accelerators the required energies are 5-IO MeV/nucl. The possibility of obtaining these energies at the extraction from the adgezator has been estimated. The specification of electron ring motion with the multicharged heavy ions is the following: the ring mass is placed mainly into the ion component and the allowed accelerations and effective accelerating field for such a ring will differ from the given above

$$\epsilon_{ex} = \frac{m_\perp Z_{eff}}{MA} \frac{1 + \frac{N_i}{N_e}\frac{AM}{m_\perp}}{1 + \frac{Z_{eff}\, m}{AM}} \epsilon_{Coul} .$$

If the total ion mass is large as compared with the electron mass then approximately

$$\epsilon_{ex} = \frac{N_i}{N_e} Z_{eff} \epsilon_{Coul} .$$

For the approximate estimation it is possible to consider that ϵ_{Coul} is still changing in the process of acceleration and is equal to

$$\epsilon_{Coul} = 2,4 \sqrt{\frac{N_e}{10^{13}}} \frac{MV}{cm} .$$

The formula is obtained for the definite dimensions of the ring.

Let us look at an example. Let the atoms accelerate with A=200.
As it has been shown above for the adgezator Z_{eff} can be addmitted equal to IO. Growth of kinetic energy of IOMeV/nucl. is required. Choose $\frac{N_i}{N_e} = IO^{-3}$ and $N_e = IO^{I4}$.

At the chosen parameters the allowed field intensity of 40kv/cm can be taken, that approximately fits 50G/ cm for the acceleration in the decreasing magnetic field. The total length of the acceleration will be equal to 50cm.
The multicharged intensity of ions will depend on a number of cycles of the systems, necessary for getting the electron rings.

Relying on the working electron accelerators we can say that a number of cycles at the modern level of the technical development can contain 10^3 sendings per sec. Then the ion intensity will be of 10^{14} sec^{-1}.

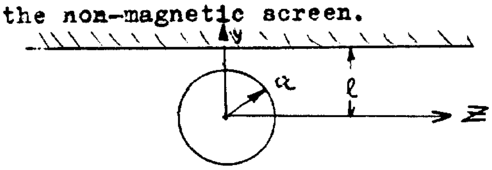
This very system of preliminary acceleration can be used for creating proton accelerators. There proton energy will be of 200-400 MeV, obtained intensity will be one order higher than the intensity of multicharged ions, i.e. for protons the relation $\frac{N_i}{N_e}$ ought to be chosen 10^{-2}. By using known betatron conditions (2:1) for the acceleration the energy range of protons in such a system can be expanded up to 1-2GeV.

All the given estimation has been made supposing that a Coulomb field of the ring effecting the ion remains constant. It can be done only in the case when cross-section dimensions of the electron rings are hold constant. The large radius of the ring and its radial dimensions are hold by the magnetic field in which the motion of the ring occurs. Later, where we shall discuss holding of the ring cross section dimensions, we shall mean always the dimension along the motion (Z dimension).

Several ways of holding the dimension have been examined by us, - autophasing on the running wave, H_ϕ focussing and focussing on the meeting waves.

All these methods have limited regions of application/7/. So, autophasing can be used only at small energies of the ring due to falling of the focussing field gradients in the ring coordinate system, as $\frac{1}{\gamma^2}$

So, at the field amplitude of 100kv/cm and $\lambda \leq 10$cm focussing is possible up to $\gamma_z = 4$. On the other hand focussing on the meeting waves is effective only at large γ_z. H_ϕ-focussing has also limits from large γ_z. Besides these methods require creation of highly powerful sources in the short wave range or creation of complicated slowing structures. For focussing the possibility of using the forces of image in the screen has been discovered by us. To explain this we shall examine the cylindrical charged beam passing near the non-magnetic screen.



Forces affecting the electron travelling inside the charged beam with some degree of accuracy can be written in the following way:

$$\frac{F_E}{m} = \frac{2 \nu z c^2}{a^2} \left(\frac{1}{\gamma^2} - \frac{a^2}{4\ell_\perp^2} \right),$$

where $\frac{a}{2\ell} > \frac{1}{\gamma_\perp}$

The stability condition of the particle deflecting from the equilibrium position towards $\frac{a}{2\ell} > \frac{1}{\gamma_\perp}$ can be obtained. However the examined case does not agree with the reality. To make such a correspondence it is necessary to consider the beam motion as a whole along the axis. But in this case the electrical field of the beam in the laboratory system of coordinates becomes dependent on the time and then because of it there appears the screened magnetic field reducing image forces in $\gamma_\perp^2$ times. The examination of the ring motion screened by the cylinder shows that the curve appears to be sufficient as it enters the self-fields and induced fields differently.

Consequently in direction Z there is a focussing force. However for practical application this effect must be increased. Calculations for the cut screen have shown that this method provides the efficient focussing force. Necessary tolerances kept while the ring is moving along the cylinder axis, have been examined. The cylinder possesses centric behaviors and this makes it possible to simplify these tolerances.

Thus, the application of this cut screen gives the ability to keep constant dimensions required for the effective acceleration of the ions in a bunch.

3.Bunch Acceleration

As it has already been mentioned above the system of preliminary acceleration does not allow to obtain very high energies of ions.

Let us examine the system using the peculiarities of falling and rising magnetic field together with the system of accelerating cavities. In the region between the cavities the longitudinal field falls according to the linear law and the ring inside it is accelerated using the energy of the rotating motion. Inside the cavity the rising longitudinal magnetic field is created in such a way that the energy is mainly transfered into the rotating motion. Only a part of it adequate to the addmitted acceleration, turns into the axial motion.

The longitudinal magnetic field is the same at the ejection of the ring from all the cavities. Hence the azimuthal impulse remains the same too /8,9/.

The motion of the particles in such a system has been studied and the motion inside the cavity and outside it has been examined separately. Then the results obtained have been joined.

The solution describing the orbit and conditions for the gradients of the magnetic field have been received.

The requirements are substantially different for various parts of the accelerating system. At the initial part of acceleration when the time of flight of the cavity is compared with the period of ion oscillations in their system,it is necessary to provide the following conditions:

$$\epsilon_{ex} = -\frac{1}{2} r_0 \beta_{\theta 0} \gamma_{\|0} \gamma_{\|} \frac{\partial B_z}{\partial z} + \epsilon_A f \cos \Omega^+ ,$$

f - function showing configuration,

z - component of the electrical field,

Ω - frequency of the cavity,

ϵ_A - amplitude of the electrical field intensity.

At $\gamma_{\|}$ =5+IO period of ion oscillation is of the order of the structure period and the conditions on the gradients can be fulfilled at average on the period.

At $\gamma_{\|}$ = 50+IOO there is no need to modulate the magnetic field as the oscillation period of ions is rather longer than the time of the structure period and the averaging occurs automatically in many periods. Noise swinging due to discretence will be very small.

At the final state of acceleration the energy stored in the rotating motion can be used and transfered in the falling field into z motion.

As estimated this period of acceleration can give an increase in 2-3 times.In this period it is useful (on purpose of better usage of rotating energy and supplying the normal focussing) to accelerate the bunch in the falling field with the constant ring radius. It becomes possible when providing conditions 2+I (betatrone condition) in the field. For the collective accelerator it can be done as it was suggested in /3/.

Besides the system of coils creating the holding field, inside the ring along the total length of the section a solenoid supplying the necessary requirements on the field is placed. Falling of the field is made simultaneously in the both systems forming the field of current variations or the number of turns on the length.

While creating the accelerator at high energies the following must be considered: the main part of its cost will consist in the cost of the accelerating system, therefore the choice of the system must be very careful and thorough. To illustrate this I shall give you some notes made for the cavity system. In the table the data for two extreme cases of cooling are given, i.e. liquid nitrogen and liquid helium.

Q	$P_{gen.}$	$\bar{P}_{gen.}$	P_{heat}	N_{ε}	appr. cost	cryog. cost
10^5	5900 kW/m	19000W/m	16000 W/m	3.10^{13}	50000 roub/m	100000 roub/m
10^{10}	3000 W/m	3000 W/m	32W/m	3.10^{13}	6500 roub/m	30000 roub/m

As it is shown in the table these systems differ in cost about 4 times. The system of creating the magnetic field for the both variants is the same and its cost is about 8-10 thousand roubles per meter.

Choosing the value ε_{Coul} according to the formula given in 2, we can come to the preliminary costs of acceleration system for the whole accelerator of the chosen energy.

As to the intensity of the ions in such an accelerator it is naturally defined by two factors, i.e. intensity of one cycle and frequency of cycle repetition. Intensity of a cycle is defined by ability of the accelerating system and it contains 5.10^{11} protons. Frequency of repetition in the superconductivity variant of the system, as it follows from the table, can be increased up to 500 without substantial increase of the cost. The same estimation can be obtained due to the technical capacity of the adgezator. Such a frequency of repetition allows to get $2-3.10^{14}$ protons per sec. It is important to consider the fact that the cavity system of acceleration is not unique.

The usage of radial lines for acceleration system is undoubtedly of a great interest.

In such a system the condensator represents the main accumulator of energy, but as it is known the cost of one joule of energy accumulated in the condensator and in the cavity differs in about 100 times. However complications in the structure and especially in the system of electrical switching lead to keeping order only in the questions concerning costs, the coefficient of accumulated energy remains high. To use this effect in the system of radial lines it is nesessary to create the comutatetive elements of the accuracy of IO^{-IO}sec. This disadvantage reduces the advantages of this system to zero , but the requirements on the accuracy can be substantially decreased, if to deal with this system in the combination of the variation of the magnetic field, the same as it was done in the cavity system. Researches in this direction will be continued.

I have not observed yet the problem of the stability of the ring bunch. The basic results of this study have been reported at the All-Union Congress on Accelerators /IO/ and I shall restrict my report here to the most general notes. The problem of stability can be apparently devided into two parts: I)stability in the adgezator in the process of compression and 2)stability of the ring with the ions in the process of its extraction and the motion in the accelerating system.

As to the first part, at present this question is considered to be sufficiently clear. Definite criteria on the density of the particles, their number, spread on the energy etc. at which some instabilities appear, have been obtained. Confidence of the truth of these criteria is confirmed by the facts which cannot be neglected, by the experimental test.

For better understanding of all these questions occuring at compression it seems necessary to scrutinize the influence of resonances in the process of compression.

In the second group of questions two are of the greatest importance.

The first - influence of so called "radiation instability" on the ring motion. This problem must be considered together with the cut screen and the changing magnetic field.
The second question, i.e. radiation of the charged beam at the interval of the cavity system.

While examining radiation in such a system it is necessary to distinguish exactly the tasks about the bunch radiation at the input membrane flight of the first cavity and the radiation at the flight of the cavity system (periodical structure).

Radiation at the input membrane must be examined at small energies of the bunch and the dependence on energies is negligible.

Radiation in the periodical structure as it is expected on the base of the papers/I,4/ at least does not increase from γ_z .

I am not going to touch here the engeneering problems of creating the collective accelerator, as they generally go out of the construction of the basic elements of the device, which I have mentioned earlier.

At present works on the collective accelerator are of a great importance. Now all these works are carried out in the USA,Italy, England,FGR.

Efforts of all the physicists will lead to my mind even in 1969 to the invention of the first accelerator working on the collective method of acceleration.

R E F E R E N C E S

I. V.I.Veksler.
Atomnaya Energiya, 5 (1957).

2. I.N.Ivanov et al.
Preprint JINR P9-4132, Dubna(1968)

3. Symposium on ERA, Berkeley,
California (1968).

4. M.L.Iovnovich et al.
Preprint JINR P9-4257,Dubna(1969).

5. A.W.Trievelpiece et al.
Phys.Rev.Let., vol.2I, 20 (1968).

6. G.I.Budker.
Atomnaya Energiya, 5 (1956).

7. A.G.Bonch-Osmolovsky et al.
Preprint JINR P9-4135,Dubna(1968).

8. V.I.Veksler et al.
Proceedings on Sixth Intern.Conf.
on Accel.,Cambridge,USA (1967).

9. A.G.Bonch-Osmolovsky et al.
Preprint JINR P9-4I7I. Dubna(1968).

I0.A.G.Bonch-Osmolovsky et al.
Preprint JINR P9-4I38, Dubna(1968).

II.B.M.Bolotovsky et al.
Uspekhi Fys. Nauk, 94, 377(1968).

I2.I.A.Gilinsky.
DAN, USSR, I50, 767 (1963).

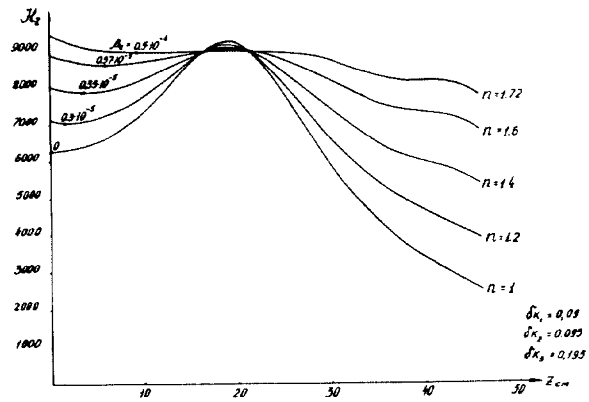


Figure 2

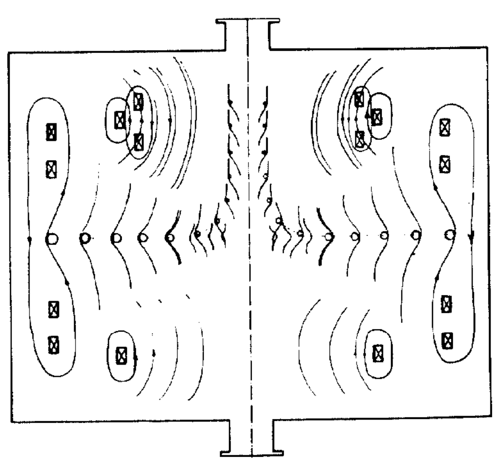


Figure 1

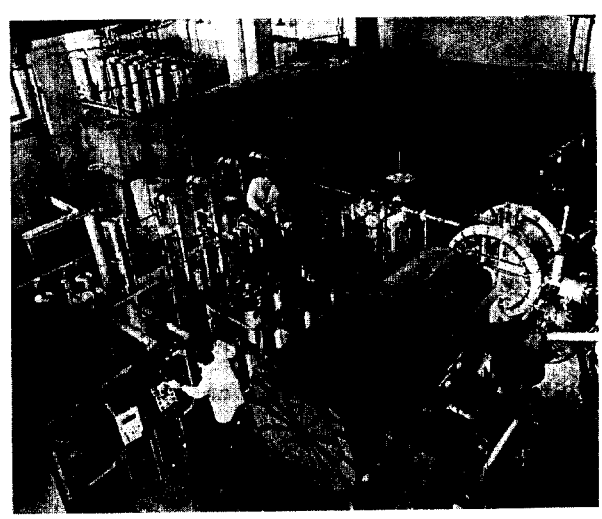


Figure 3