HIGH-CURRENT, LOW-ENERGY RF ION ACCELERATOR

B.P.Murin, V.M.Pirozhenko, O.V.Plink
Moscow Radiotechnical Institute USSR Academy of Sciences,
113519 Moscow,USSR

Abstract

Theoretical and applied aspects of a beam current increase in ion linacs with superconducting solenoid focusing are considered.

Introduction

The main restriction of a beam current in low-energy RF ion accelerators is the coulomb particle repulsion. The simultaneous achievement of the accelerating and focusing fields high values is necessary to compensate for the high-current beam coulomb fields. That can be realized in the accelerating- focusing system with the resonator placed inside the focusing solenoid [1]. According to estimations, the beam current limit by the transverse coulomb repulsion may be increased up to several amperes and higher by using the superconducting solenoid with the induction of 7...8 T [1].

The accelerating system development with minimum transverse dimensions is necessary to achieve a high value of a beam current. The RF accelerating channel has to provide high values of the beam current limits by the longitudinal coulomb repulsion and the capture efficiency.It is necessary to realize the required accelerating field distribution along the accelerator axis under high resonator beam loading conditions.

The strong magnetic fields use for the beam focusing requires the solution of a number of specific problems. First one needs to solve the beam injection problem into the strong magnetic field. The resonator electrical insulation and the ion injector operation are influenced by the above mentioned magnetic field.

The main results of these investigations are briefly described below.

Beam Dynamics

In the accelerating structure of this type accelerator one should use the adiabatic beam bunching with carrying out of the bunch quasi-stationary conditions during the bunching. The bunch quasi-stationary conditions allow to safe the space-charge density distribution in the bunch and to simplify the beam matching with the accelerating-focusing system.

It can be shown that the expressions for the amplitude E_m of the accelerating wave and synchronous phase φ, providing the bunch quasi-stationary conditions, are the following

$$\cos\varphi_s = [1+\delta^{-1}\exp(-\xi)]^{-1};\quad E_m/E_{mo} = 1+\delta(\exp\xi-1);$$

where $\delta = (\pi/2-|\varphi_{so}|) \ll 1$, $\xi = qE_{mo}z/2W_{so}$, q - the particle charge, z - the longitudinal coordinate, W_s - the synchronous particle energy. The variables with indexes "o" and "f" correspond to the bunch beginning and end accordingly. The large buncher length is necessary to achieve a high value of the capture efficiency k_c in the adiabatic buncher with the bunch quasi-stationary conditions correct carrying out. So, the buncher length is equal to 1.15 m for k_c = 95 %, when W_{so} = 100 keV, E_{mo} = 1 MV/m, $|\varphi_{sf}| = 45^\circ$. It is necessary to refuse the bunch quasi-stationary invariants safe along the buncher axis to shorten the buncher length. The bunch quasi-stationary conditions approximate carrying out is possible for the buncher with the linear change of the wave amplitude and synchronous phase. The buncher length and the accelerating wave amplitude rising are calculated on the basis of the equality conditions of the small phase oscillations frequencies and the separatrixes geometric length for the buncher input and output :

$$\mathcal{L}_b = \frac{5.6\ W_{so}}{q\ E_{mo}},\quad \frac{E_{mf}}{E_{mo}} = \frac{\beta_{sf}}{\beta_{so}\sin|\varphi_s|}$$

where β_s - the reduced velocity of a synchronous particle.In general, the RF accelerating channel contains the adiabatic buncher and the acceleration section, where the amplitude of the accelerating wave and synchronous phase are constant. On the supposition of the beam current limit defined by the adiabatic buncher end and the bunch phase length is equal to $2|\varphi_{sf}|$, we have that the beam current limit by the longitudinal coulomb repulsion is equal to

$$I^* = 1.5\ (\beta_{sf}\ \varphi_{sf})^2 \frac{R_b}{\lambda}\left[\frac{\Omega_f}{\omega}\right]^2 I_o,$$

where R_b - the beam radius, λ - the operating wave length, $\omega = 2\pi c/\lambda$, Ω - the cyclic frequency of the longitudinal oscillations, I_o - the characteristic beam current , c - the velocity of light.

In the SIU-1 experimental proton accelerator the adiabatic beam bunching has been used in the accelerating field with linear rising and the bunch quasi-stationary conditions approximate carrying out. The channel characteristics are following : the low injection energy (100 keV), the high accelerating rate (1.75 MeV/m). The channel general parameters are : E_{mo} = 1 MV/m, E_{mf}=3.7 MV/m, $\varphi_{so}=-90°$, $\varphi_{sf}=-45°$, R_b = 5 mm. For the above mentioned parameters it is found that $\mathcal{L}_b$ = 0.56 m, W_{sf} = 0.7 MeV, I'' = 2.5 A for λ =1.5 m. The bunch quasi-stationary conditions disturbance is order 25 % in the SIU-1 buncher. Numerical simulations of a beam longitudinal dynamics indicate that the beam current limit is equal to 2.75 A, the capture efficiency achieves 96 % for the beam current of 1 A.

Magnetic fields of 5...7 T are necessary to focus the beam with the current density of about 1 A/cm^2 and the phase density of several A/cm mrad for λ = 1.5 m. During the beam injection into the magnetic field the particles longitudinal energy is decreased. For compensation that it is necessary to increase an injection energy up to 20 ÷ 30 %.

Accelerating structure

The combination of the small transverse sizes, the low sensitivity to the strong beam loading, capability of the uniting the large number of accelerating gaps and high value of an accelerating field can be reached in the opposed vibrator resonator (OVR) (see Fig.1.)

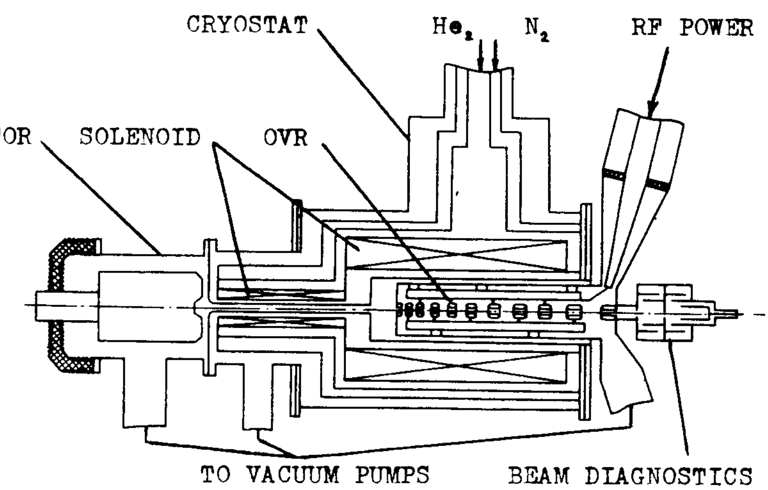

Fig.1.

The OVR can be considered as a system of the coupled lines loaded by the lumped elements [2].

One can show that the structure dispersion equation is of the form

$$kl(1 + \sqrt{1 + \varkappa})/2 = \pi/2 + \alpha\cos\varphi - \beta\cos^2\varphi,$$

where k - the wave number in the free space, φ - the normal wave phase shift in the l length structure section. Here α and β are the distributed and lumped coupling coefficients, ϰ is the capacitive load coefficient.

In the lowest passband the resonance condition of the OVR, consisting of N sections, is φ = πm/N, m = 0,1,...,N. Together with the large bandwidth , the small number of the modes for the resonator, consisting of the large number of the accelerating cells, defines good modes separation in the OVR, and, hence, the low sensitivity to the strong beam loading. By means of the resonator section detuning , the various accelerating wave amplitude distributions are possible in the OVR, in particular, the increasing law, which is needed to realize adiabatic beam bunching and to achieve the accelerating channel equal electric insulation.

The high value of the accelerating wave can be achieved in the OVR. At the channel axis the accelerating wave amplitude is coupled with the maximum electric field at the drift tubes surfaces E_s by the relation [3] :

$$E_m = \frac{E_s k_g \cos(\lambda k_g/2)}{I_o\left[\pi a/h + \pi(1 - k_g)/2\right]},$$

where h - the accelerating cell length; k_g -the gap coefficient; I_o - the modified Bessel function.

The maximum accelerating gradient can be achieved with k_g = 0.6...0.7.The accelerating wave amplitude should increase along the channel axis for πa/h > 0.5. E_m can achieve the value of about 5...10 MV/m with E_s = 20...30 MV/m. Thus, at the SIU-1 accelerator resonator the accelerating wave amplitude of about 8 MV/m has been achieved.

The OVR has a high value of the shunt impedance in the low-energy region. The SIU-1 accelerator resonator has the shunt impedance of about 30 MOhm/m.

The Prove of Principle Experiments

The RF ion acceleration has been realized at the SIU-1 RF experimental proton accelerator. The accelerator is described in short at [4] and in details at [2]. The accelerator scheme is presented at Fig.1. The SIU-1 accelerator design and investigation were carried out as follows :

1. The autonomous tests of the injector, the accelerating resonator and the focusing solenoid. All the calculating parameters have been obtained.
2. The test of the accelerating resonator with focusing solenoid. The test showed the resonator electric insulation decreases at the presence of a strong magnetic field.
3. The injector tests with the focusing solenoid. The tests indicated the magnetic field influence on plasma in the source. To decrease this influence the compensating coil has been installed in the discharge chamber section. The beam current at the resonator input has been risen up to 0.6 A.
4. The beam acceleration experiments. The typical forms of the voltage on measuring loop in the resonator and the beam current from the Faraday-cylinder are presented at the Fig.2a. It is obvious, that the strong RF voltage decrease takes place up to about the half of its value. A number of experiments were carried out using the automating amplitude tuning system to compensate this decrease. The beam current and the RF voltage pulses obtained with the operating automatic amplitude tuning system are presented at the Fig.2b. Experimental data are presented in Table I.

TABLE I
SIU-1 Experimental Accelerator Performances

Maximum particle energy (MeV)	1.5
Injection energy (keV)	100...130
Maximum accelerated beam current (A)	0.4
Operating frequency (MHz)	196.8
Beam pulse duration (μs)	30...70
Repetition rate (puls/s)	1

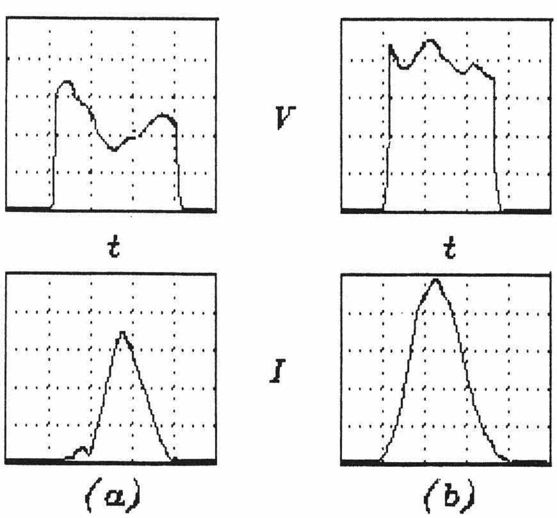

Fig.2.

Development and Application

The limiting calculated beam current possibilities of the SIU-1 accelerating-focusing system has not been achieved. The main reason of it is that the magnetic field distribution was not optimal because of the solenoid design. At present the SIU-1 accelerator is under development to increase the accelerated beam current. In the SIU-2 accelerator with the injection energy rise up to 200 keV and the simultaneous accelerating wave amplitude decrease to about 1.5 MV/m it is planned to get the proton beam with the energy of about 1.5 Mev and current up to 1.5 A.

This current value is not a limit to this type of the accelerator. Physical simulations of a beam dynamic using an electron probe indicate that the beam with the current up to 5 A may be accelerated at the frequency of about 200 MHz [5]. The further beam current increase can be achieved using the lower operation frequency. The beam dynamic calculations indicate that at the operating frequency of about 20 MHz the beam current may rise up to 15 A [4].

The accelerator with the superconducting solenoid focusing can be used as the initial part of the accelerator for the burner-reactor [6]. The beam with the average current of about 0.3 A can be accelerated using the accelerating wave amplitude of about 1.5...2 MV/m in the accelerator with the injection energy of about 100 keV.

References

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