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EXPERIMENTAL RF PROTON ACCELERATOR WITH SUPERCONDUCTING SOLENOID BEAM FOCUSING

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ABSTRACT

Theoretical and applied aspects of a beam current increase in ion linacs by using superconducting solenoid focusing are considered.Results of the SIU-1 experimental RF proton accelerator development and testing are presented.The main accelerator parameter are : the 1.5 MeV energy, the 1.75 MeV/m accelerating rate, the 200 MHz operating frequency.

I.INTRODUCTION

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

Development of an accelerating structure 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 limit by 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.

Use of the the strong magnetic fields for beam focusing requires solution 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 affected by the above mentioned magnetic field.

The main results of these investigations with application to the SIU-1 linac design are briefly described below.

II. BEAM DYNAMICS ASPECTS

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

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

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

where $\delta = (\pi/2-|\varphi_{so}|) \ll 1$, $\xi = qE_{mo}z/2W_{so}$, q is the particle charge, z is the longitudinal coordinate, W_s is the synchronous particle energy. The variables with indexes "o" and "f" correspond to the buncher beginning and the buncher end accordingly.

The buncher length L_b relates to the limiting capture efficiency k_c by the following equation

$$L_b = -\frac{2\ W_{so}}{q\ E_{mo}}\,[\ 1 - \pi(1-k_c)^2]\ \ln[\pi(1-k_c)^2 tg\varphi_{sf} tg(\varphi_{sf}/2)].$$

The large buncher length is necessary to achieve a high value of the capture efficiency in the adiabatic buncher with the bunch quasi-stationary conditions exact carrying out. For example, 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 from continuous conservation of the bunch quasi-stationary invariants along the buncher axis to shorten the buncher length. An approximate satisfiability of the bunch quasi-stationary conditions is possible for the buncher with linear change of the accelerating wave amplitude and the synchronous phase. In this adiabatic buncher it is possible to use $|\ \varphi_{so}\ | = 90^\circ$. The buncher length and the accelerating wave amplitude rising are calculated on basis of the equality conditions of particles small phase oscillations frequencies and the separatrixes geometric length for the buncher input and the buncher output :

$$L_b = \frac{5.6\ W_{so}}{q\ E_{mo}},\quad \frac{E_{mf}}{E_{mo}} = \frac{\beta_{sf}}{\beta_{so}\sin|\varphi_{sf}|},$$

where β_s is the normalized velocity of a synchronous particle.

In general, the RF accelerating channel contains the adiabatic buncher and the acceleration section, where the accelerating wave amplitude and the synchronous phase remain constant. Supposing that the beam current limit is 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 is the beam radius, λ is the operating wavelength, $\omega = 2\pi c/\lambda$, Ω is the cyclic frequency of the longitudinal oscillations, I_o is the characteristic beam current, c is the speed of light.

In the SIU-1 experimental proton accelerator the adiabatic bunching has been used in the accelerating field with linear rising and the bunch quasi-stationary conditions approximate carrying out. The channel characteristics are the following : the low injection energy (100 keV), the high accelerating rate (1.75 MeV/m). The main channel parameters are : $E_{mo} = 1$ MV/m, $E_{mf} = 3.7$ MV/m, $\varphi_{so} = -90^\circ$, $\varphi_{sf} = -45^\circ$, $R_b = 5$ mm. For these parameters we have $L_b = 0.56$ m, $W_{sf} = 0.7$ MeV, $I'' = 2.5$ A when $\lambda = 1.5$ m. The bunch quasi-stationary conditions disturbance is order 25 % in the SIU-1 buncher. The gap coefficient is constant along the accelerating channel axis and is equal to 2/3, the field nonuniformity parameter along a channel aperture $2\pi a/\beta_{so}\lambda = 2.1$, that corresponds to the aperture radius a = 7.5 mm.

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.

To estimate a matching magnetic field the following relation can be used

$$B = \frac{2\ m_o}{q} \sqrt{\frac{\Omega^2}{2} + \frac{2\ c^2\ I}{\beta_s R_b^2\ I_o} + \left(\frac{c\ V_b}{R_b^2}\right)^2},$$

where m_o is the ion mass, I is the peak beam current, V_b is the beam normalized emittance.

The magnetic field value has also to provide a small value of the beam Coulomb parameter

$$h = Ic/\omega^o_{rs}\beta_s I_o V_b\ ,\ \text{where}\ \omega^o_{rs} = \left[(eB/2m_o)^2 - \Omega^2/2\right]^{1/2}.$$

The estimations and numerical simulations of a beam dynamics indicate that 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 $\lambda = 1.5$ m.

During the beam injection into the magnetic field the particles longitudinal energy decreases in accordance with the relation

$$\Delta W = - \frac{(q B r)^2}{8 m_o} ,$$

where r is the distance to the solenoid axis.

For Brillouin beam the energy reduction is defined by

$$\Delta W/W = - 2I/\beta_s^3 I_o .$$

In addition to the energy reduction, the non-Brillouin beam has also an energy spread.

In practice, to reduce these effects it is necessary to use an 20-30 % injection energy increase in comparison with a calculating value.

III. ACCELERATING STRUCTURE

Combination of small transverse sizes, low sensitivity to strong beam loading, capability of 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).

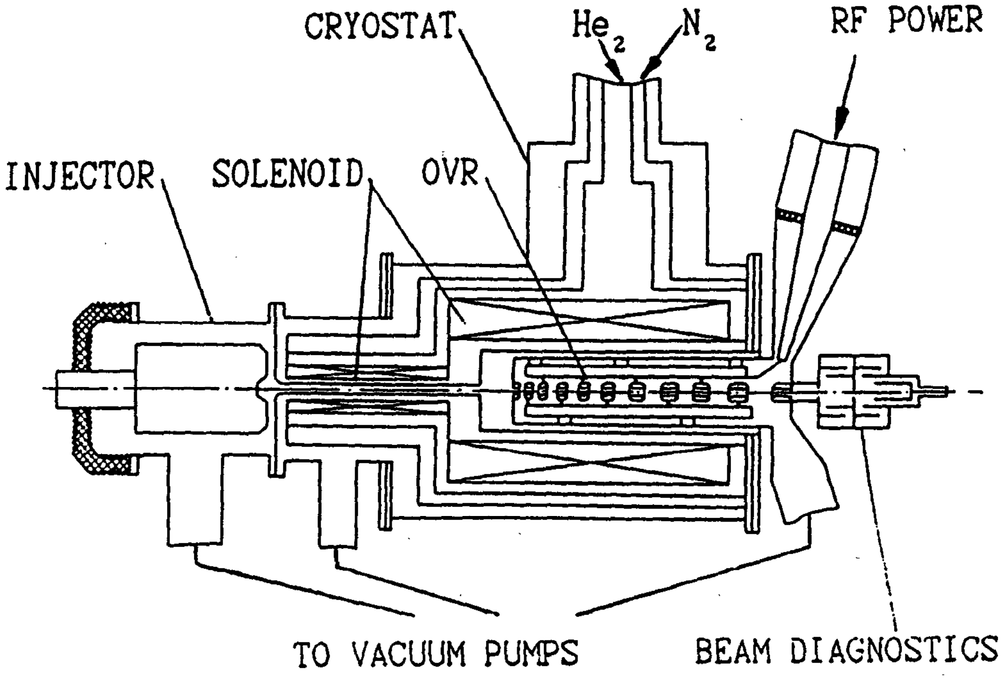

Fig.1.

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

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 is the wave number in free space, φ is the normal wave phase advance per the l length structure section. Here α and β are the distributed and lumped coupling coefficients, $\varkappa$ is the capacitance loading coefficient.

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

The resonant wavelength of the OVR operating mode is equal to

$$\lambda = \frac{2\mathcal{L}_r}{N}\left[1 + \frac{1}{\mathcal{L}_r}\int_0^{\mathcal{L}_r}\sqrt{1 + \varkappa}\,dz\right]\left[1 + \frac{2}{\pi N}\sum_{i=1}^{N}(\alpha_i + \beta_i)\right],$$

where $\mathcal{L}_r$ is the resonator length.

The OVR resonant frequency is determined by longitudinal sizes and capacitance loading of the resonator, rather than its diameter. The OVR diameter is mainly determined by electrical insulation requirement of the structure.

A high value of the accelerating wave can be achieved in the OVR. At the channel axis the accelerating wave amplitude is related to the maximum electric field at the drift tubes surfaces E_s as follows [2] :

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

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

The maximum accelerating gradient can be achieved with $k_g = 0.6\ldots0.7$. The accelerating wave amplitude should increase along the channel axis for $\pi a/h > 0.5$. E_m can achieve the value of about 5...10 MV/m for $E_s = 20\ldots30$ MV/m. Thus, at the SIU-1 accelerating resonator the accelerating wave amplitude of about

8 MV/m has been achieved without an external magnetic field.

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

IV. THE PROVE OF PRINCIPLE EXPERIMENTS

The ion acceleration with superconducting solenoid focusing has been realized at the SIU-1 RF experimental proton accelerator. The accelerator scheme is presented at Fig.1.

The SIU-1 injector contains a proton source placed inside a magnetic shield, an electrostatic preaccelerator of the diode type and a beam transport channel.

The SIU-1 accelerating structure is the compact OVR placed inside the superconducting solenoid. The OVR has a length of 0.85 m and a diameter of 0.18 m.

The NbTi superconducting solenoid produces the axial magnetic field up to 7.5 T with a stored energy of about 1 MJ.

RF power supply of the accelerator is based on the RF generator which is similar that used in the first part of the Moscow Meson Factory.

The SIU-1 accelerator design, construction 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 were obtained.
2. The test of the accelerating resonator with focusing solenoid. The test showed the resonator electrical insulation decrease in the presence of a strong magnetic field. The achieved amplitude is 4 MV/m.
3. The injector tests with the focusing solenoid. The tests indicated the magnetic field influence on plasma in the proton 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. Typical forms of voltage on measuring loop in the resonator and 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 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
Beam pulse duration (μs)	30...70
Repetition rate (puls/s)	1

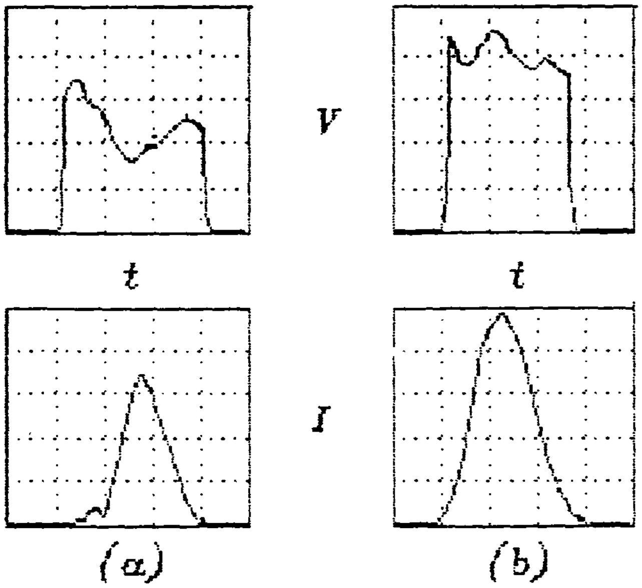

Fig.2.

V. DEVELOPMENT AND APPLICATION

The limiting calculated beam current possibilities of the SIU-1 accelerating-focusing system has not been achieved. The main reason of this 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 beam current value is not a limit to this accelerator type. Physical simulations of a beam dynamic by using an electron probe indicates that a beam with the current up to 5 A can be accelerated at the frequency of about 200 MHz [3]. Further beam current increase can be achieved using the lower operating frequency. The beam dynamic calculations indicate that at the operating frequency of about 20 MHz the beam current can rise up to 15 A [3].

The accelerator with the superconducting solenoid focusing can be used as an initial part of an accelerator for the burner-reactor [4]. Beam with the average current of about 0.3 A can be accelerated in the accelerator with the injection energy of about 100 keV and the accelerating wave amplitude of about 1.5...2 MV/m.

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