TWO BEAM PROTON ACCELERATOR FOR ELECTRONUCLEAR INDUSTRY (PLUTONIUM CONVERSION)

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A concept of a linear proton accelerator with excited by electron beam RF cavities is discussed. This accelerator with parameters of a second proton beam equaled to 1 GeV, 10-30 mA can be used for the new type of electronuclear installations and weapon plutonium conversion.

1. INTRODUCTION

In electronuclear installations a flux of neutrons generated by the ~1 GeV proton beam keeps up a reaction of a heavy nucleus fission [1]. An energy produced by the protons is increased in some ten times and the electronuclear reactor represents itself as an energy amplifier [2]. From energy point of view a proton accelerator is an energy converter from a power line to RF oscillations and then to an accelerated proton beam. An efficiency of the each conversion is a very important parameter. At present a superconducting proton accelerator looks up most perspective one for the electronuclear installations [3]. In such the accelerator the conversion efficiency of the RF energy into the proton energy is practically equal to 1, and the total efficiency is about to 60%, which depends on the efficiency of RF stations converting a kinetic energy of electrons to the RF energy.

Electron beams can be used for an excitation of superconducting cavities of the accelerator directly, without their using in amplifiers of the RF stations. Herewith, if a reacceleration of the electrons by external fields is used, the efficiency of the conversion of their kinetic energy into the proton energy can be close to 1.

The excitation of an accelerating structure by the electron beam (the two beam method of the acceleration) can be used in "room temperature" accelerators. However a significant growth of a ion beam load of the cavities need be increased to reduce a relative value of a energy loss in the accelerating structure cavities. Therefore "room temperature" accelerator should operate in a pulse regime.

The electrodynamic structure of the as superconducting so "room temperature" two beam accelerator fulfills two functions. It is the buncher of the primary exciting electron beam and accelerating structure of the secondary ion beam [4-7].

2. EXCITATION OF ACCELERATING FIELDS BY ELECTRON BEAM

For an effective conversion of the electron beam energy into the energy of the ion beam, the solution of 3 principal points are needed:

- longitudinal stability of the driving electron bunch;
- amplitude of the RF field excited by the electron beam;
- synchronism of the accelerated protons and excited RF fields.

2.1 LONGITUDINAL STABILITY OF THE ELECTRON BUNCHES

A bunching of the electrons in exciting the cavities of the proton accelerating structure is provided by the excited RF field similar the multi-cavity klystron buncher. The buncher frequency is slightly less than the frequency of the unloaded cavities of the accelerator and the cavities have almost pure inductive impedance, so the bunches of the driving electron beam pass the cavity at zero phase of RF field. As a result of a phase shift between the excited voltage and the electron bunches the longitudinal stability is provided (Fig. 1).

To verify the possibility of the stationary bunches existence a computer simulations have been performed. The results of the simulations of the I_e=430 A, U_e=500 kV electron beam bunching and exciting of 14 GHz cavities of the electrodynamic structure are shown on Fig. 2.

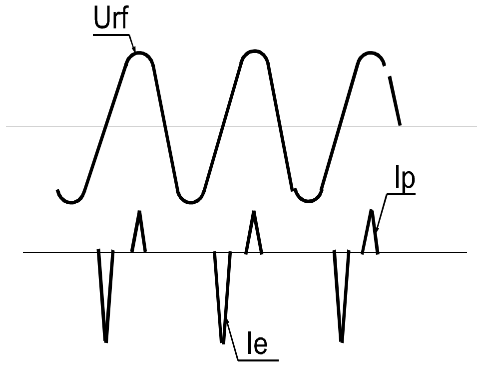

Fig. 1. *Time diagrams of the RF voltage and the electron and ion beam currents.*

The computer simulations have shown that there is the optimum matching regime when the longitudinal dimension of bunches are matched with the electrodynamic structure of the accelerator and the oscillation amplitude of the electron bunch dimensions have a minimal value. In this matching regime the 430 A, 500 keV electron beam excite the ~1 MV voltage in the cavities (Fig. 2). The average proton accelerating gradient is determined by number of the cavities per unit of length.

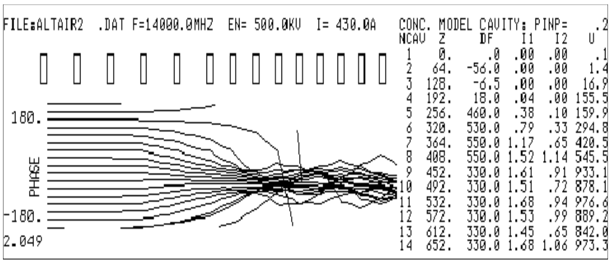

Fig. 2. *Phase trajectories of electrons. Matching of the electron bunch dimensions and electrodynamic structure parameters. RF voltage amplitudes in the cavities (kV) - right column of parameters.*

The "DISKLY v.3.5" computer program have been used for the calculation and matching of the phase trajectories. This program have been developed at the Budker Institute of Nuclear Physics (Protvino, Novosibirsk) for calculations of powerful multi-cavity klystrons.

2.2 AMPLITUDE OF RF FIELDS

From the law of conservation of energy

$$P_e = P_i + P_{loss},$$

where P_e - average power of the driving beam which is spent to excite the cavity, P_i - average power which is taken to accelerate the proton beam, P_{loss} - power lost in the cavity, it results that the magnitude of the cavity voltage excited by electron beam is equal to

$$U_i = 2R_0\left(\frac{I_e}{\sqrt{1+\xi^2}} - I_i\right).$$

Here I_e - average electron beam current, I_i - average proton beam current, $\xi = 2Q_0\frac{\Delta f}{f}$ - relative detuning of the frequencies of the cavity and bunching electron beam, R_0 and Q_0 - shunt impedance and quality factor of the unloaded cavity.

The shunt impedance of the superconducting cavities is some ten GOhm, therefore there it is not a problem to excite the very high RF voltage. Maximum accelerating gradients will be limited by critical fields of the superconducting cavities.

The use of the "room temperature" cavities requires a choice of a compromise between a wish to have the maximum accelerating gradient and maximum efficiency of the electron beam energy conversion into the energy of the ion beam.

2.3. CONDITION OF SYNCHRONISM FOR THE PROTONS AND EXCITING RF FIELDS

The condition of synchronism for the protons and exciting RF field is realized when [4-7]:

$$\frac{1}{\beta_i} \mp \frac{1}{\beta_e} = \pm k\frac{\lambda}{L},$$

L - period of the accelerating structure, λ- wave length, β_i and β_e - relative velocity of protons and electrons, k - integer. This condition is consequence of the equality:

$$\Delta\varphi_i \mp \Delta\varphi_e = \pm 2\pi k,$$

where $\Delta\varphi_{i,e}$ – a proton and electron transit phase of the accelerating structure period. Synchronism is possible when the electron and ion beams move as in the same so in the opposite directions.

3. SUPERCONDUCTING VARIANT OF TWO BEAM PROTON ACCELERATOR

There is possibility to construct some variants of the two beam accelerator:

- Variant using a reacceleration of the electron beam to recover the electron energy loss. (counter-propagating electron and ion beams), Fig. 3,a.
- Variant without a reacceleration of the electron beam. The kinetic energy of the electron beam is almost wholly used to excite the cavity (counter-propagating electron and ion beams), Fig. 3,b.
- Accelerator using a reacceleration of the electrons to provide an equality of the electron and ion velocities. In this case the excited RF fields and ions are always phased and the dependence of the structure period upon the ion velocity is absent, Fig. 3,c.

It is assumed that a remainder of the electron beam kinetic energy is recuperated.

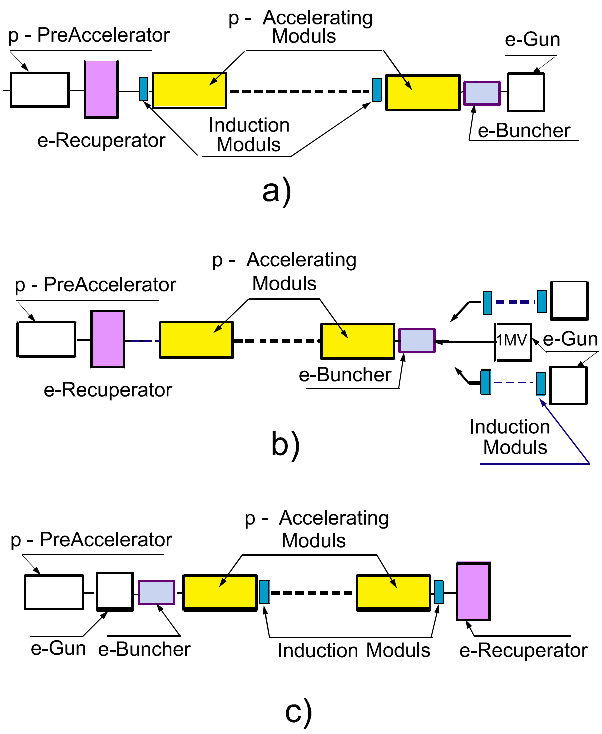

Fig. 3. *Schemes of the superconducting two beam accelerator.*

In the first variant (a), the velocity and energy electrons are close to constant. The ratio of the energies spent by the electrons and gained by the ions depends on the relative detuning magnitude of the cavities ξ. The magnitude of the relative detuning can be about to 10^3 - 10^4.

For superconducting accelerator

$$U_e = \frac{U_i}{\sqrt{1+\xi^2}},$$

$$I_e = I_i\sqrt{1+\xi^2},$$

and to accelerate the ions up to 1 GeV the total potential of induction modules should be equal to 0.1 - 1.0 MeV. At 30 mA current of the ion beam the electron beam current should be equal to 300 - 30 A. The induction modules and itself proton accelerator operate in the pulse regime. The low reaccelerating gradient and magnitude of the induction core voltage allow one to use the transistor variant of the modulators. Cheap and reliable modulator is composed of the DC voltage source and transistor bridge circuit. The output voltage of the modulator is a square wave ("meander"). The efficiency of the energy conversion from the power line to the electron beam is up to 90-95%. The total length of the induction modules depends on the used ferromagnetic material (metglas ~20 m/MV, ferrite ~50 m/MV).

The cost of induction accelerator is estimated to be 0.1-1 million USD (depend on the total energy and type of the ferromagnetic material).

In the second variant (b) the electron gun generates the direct current beam. The initial electron beam power slightly larger the final proton beam power. For the 1 GeV, 30 mA proton accelerator the parameters of the electron beam would be following: energy ~ 1 MeV, current ~ 30 A. This gun can be constructed on the base of the industrial accelerator for EB-technologies [8].

This variant allows using the lower current, 20-10 A, but higher energy, 1.5-3 MeV, beams. In this case, for a generation of the direct current beam the two induction accelerators are required. These accelerators should operate at the opposite phase regime of the square waves. After the addition of the beams the direct current would be got.

The approximate cost of the electron beam units is ~1-3 million USD. The efficiency of the energy conversion from the power line to the electron beam is ~85-95%.

In the variant (c) the protons and electrons move with the same value and direction of the velocities. It allows choosing the period of the electrodynamic structure, which is more optimum to achieve the maximum ion accelerating gradient and focusing of the electron and ion beams. The cost and efficiency of the electron part of the accelerator is the same as the variant (a).

Further analysis and experimental tests will allow one to choose the most optimum variant of the superconducting two beam accelerator.

4. "ROOM TEMPERATURE" VARIANT OF THE PROTON ACCELERATOR

There is principal possibility to use the "room temperature" cavity in the two beam accelerator of the protons. In this case, to increase the efficiency of the energy conversion from the electron beam into the proton beam it is necessary to increase the load of the cavities by the proton beam (to increase the proton beam current). Therefore the "room temperature" accelerator is the pulsed machine.

Let the energy conversion efficiency from the electrons into the ions be equal to η, then the voltage of the cavity induced by the electron beam can be written as:

$$U = 2(1-\eta)\frac{R_0 I_e}{\sqrt{1+\xi^2}}.$$

The average current of the electron and ion beams and the conversion efficiency of their energy are associated by the ratio:

$$I_i = \eta\frac{I_e}{\sqrt{1+\xi^2}}.$$

The average accelerating gradient, $E = U/L$, of the accelerating structure with cylindrical cavities and the period of the structure $L = \lambda/(\beta_i^{-1}+\beta_e^{-1})$ is equal to

$$E = \frac{1-\eta}{\sqrt{1+\xi^2}}\cdot\frac{\rho_0 I_e}{\pi\delta}\cdot\Psi,$$

where $\rho_0 = \sqrt{\mu_0/\varepsilon_0} = 120\pi$ - wave-forming resistance of free space, δ - skin-layer,

$$\Psi = \left(\frac{1}{\beta_i}+\frac{1}{\beta_e}+\frac{h}{L}\frac{2\pi}{j_0}\right)^{-1},$$

h- accelerating gap, $j_0 = 2.4$ - first root of the Bessel function J_0.

For accelerating structure based on copper cavities

$$E = 3.1\cdot 10^7\cdot\frac{1-\eta}{\sqrt{1+\xi^2}}\cdot\frac{I_e}{\sqrt{\lambda}}\cdot\Psi.$$

At energies of the electron and ion beams in regions

eU_i = 100-1000 MeV,

eU_e = 100-1000 keV,

and h/L=0.25 we have Ψ=0.2–0.35.

The average deaccelerating gradient of this structure for driving electrons is equal to

$$E_e = \frac{E}{\sqrt{1+\xi^2}}.$$

4.1 AVERAGE ACCELERATING GRADIENT

The average accelerating electric field strength of the two beam accelerator with the copper cavities and $\lambda = 0.1$ m is

$$E = (2.0-3.4)\cdot 10^7\cdot\frac{1-\eta}{\sqrt{1+\xi^2}}\cdot I_e.$$

If parameters of the electron beam is the same as the powerful klystron beam parameters:

I_e = 500 A, U_e = 500 keV,

and the ratio of the accelerating ions and deaccelerating electrons fields of the cavities is

$$U/U_e = \sqrt{1-\xi^2} = 100,$$

the average electric field strength will be equal to

E≈20 -30 MV/m.

Herewith the efficiency of the conversion of the electron kinetic energy into the energy of the accelerating protons will achieve 80% (η=0.8).

4.2 INTENSITY OF THE PROTON AND ELECTRON BEAMS

At the average electron beam current of the micropulse equaled 500 A to achieve the 80% efficiency of the beam energy conversion the average proton beam current should be increased up to

$$I_i = \eta \frac{I_e}{\sqrt{1+\xi^2}} = 4A$$

The generation of the 4 A pulsed proton beams is the rather difficult problem. Possible ways of its solution are the use of the ion beam compression technique or MV voltage proton gun.

4.3 SCHEME OF THE "ROOM TEMPERATURE" PROTON ACCELERATOR

The main part of the accelerator (0.1-1 GeV) has the 900 MeV total accelerating potential. At above regime of the two beam accelerator the total deaccelerating electron potential will be equal to ~9 MeV. Therefore, if the electron gun voltage is ~500 kV more than 20 this guns are required.

If to assume that 300 keV of the 500 keV electron kinetic energy is converted into the RF energy of the loaded cavities, then total number of the proton accelerating modules with autonomous electron guns will be 30. After passing the module the 200 keV electron beam is injected into the recuperator of the kinetic energy.

A scheme of the proton accelerator composed of the autonomous accelerating modules with the energy equaled some ten MeV is showed on Fig. 4. The voltage of the electron gun is egualed to $U=U_1+U_2$, where U_1 - deaccelerated electrons voltage of the module, U_2 - voltage of the recuperator.

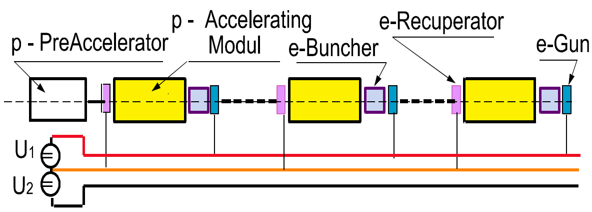

Fig. 4. *Scheme of the "room temperature" proton accelerator with the excited by electron beam cavities. U_1 - deaccelerated electrons voltage of the module, U_2 - voltage of the recuperator. Cathodes of the electron guns have a hole on the axis to pass the proton beam.*

The cost of the "room temperature" variant of the two beam accelerator of protons is significantly lower because the superconducting cavities, cryogenic system and RF station are absent. The "room temperature" accelerator is more reliable and its maintenance is cheaper. In this variant the requirement on the electron loss value is significantly lower because a water-cooling of accelerator systems is used.

To make the electron guns simpler and cheaper it is assumed the use of the high voltage sources developed by V.E. Balakin team for the VLEPP klystron. DC voltage (1MV [9]) is used in this variant of the electron source. A pulsed regime of an operation is realized by means of an employment of the electron gun with a grid control [9]. Analogously VLEPP the high voltage coaxial feeder is laid along the proton accelerator and the electron guns of the autonomous modules is connected to a branch of this feeder (Fig. 4).

The powerful klystron technique of the beam focusing can be used to focus the electron beam of the two beam accelerator. In our opinion, most preferable focusing system is the system based on a permanent magnets, which is developed by V. Balakin team (Budker INP, Protvino, Novosibirsk) for the VLEPP linear collider klystron [9,10].

The problem of the recuperation is less worked up. The rough estimations of the recuperation efficiency give the value ≥ 0.9, and the total accelerator efficiency is ~70%. If the recuperation is absent the total efficiency from the power line is ~50%.

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