Linear Accelerator for Plutonium Conversion and Transmutation of NPP Wastes

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I. INTRODUCTION

The conclusion of an agreement between Russia and the USA for significantly reducing the number of nuclear warheads has made the effective peaceful use of the stockpiles of weapons-grade plutonium a very urgent problem. Another relevant problem for all advanced countries is the transmutation of long-lived high level NPP wastes. One of the most promising ecologically pure and safe methods of plutonium conversion is to use it in subcritical accelerator-driven power reactors simultaneously for two aims – energy production and waste burning, as proposed last year by A. Favale [1].

The main parameters and engineering design of such a reactor are not reliably defined at present, so we do not know the optimal value of the proton energy and beam current. Nevertheless, the preliminary estimates [2,3] show that in any scenario the energy is in the range of 0.8–1.6 GeV and the beam current is 100–300 mA [1-3]. Estimates in projects of transmutation plants [4,5] show the values in the same ranges, although from common considerations in the last case the current must be closer to the upper limit.

The very high average beam power (hundreds of megawatts) involved requires construction of an accelerator with high efficiency (near 50%). This fact and the necessity of having extremely low beam losses make it possible to suppose that both tasks may be solved by the use of a CW linac only.

II. BASIC CONSIDERATIONS FOR LINAC SCHEME CHOICE

No doubt the most important criterion is the cost of construction and operation of the linac. However, it is hardly possible to determine the dependence of cost on even basic linac parameters at the beginning stage of design. So for elaboration of linac schemes and comparison of alternative variants one may assume:

1) the possibility of minimizing particle losses at extremely low permissible levels, particularly at the most radiation-sensitive places of the machine and at energies with the largest neutron yield;

2) ensured adequate removal of RF heat from accelerating structures upon the minimum linac length;

3) ensured adequate reliability;

4) ensured maximum efficiency;

5) the possibility of increasing beam current over the nominal value.

The permissible level of integral losses in the machine can be estimated according to those in the LAMPF and INR meson factory in Troizk, where at an average beam current about 1 mA they are of order 10^{-4}. Evidently, at the current of order 100 mA this value will be about 10^{-6}.

Because of very strong limitations on the particle losses, the requirements in transporting intensive beams along the whole tract are sharply increased, especially as one approaches the space-charge limit. This points to the necessity for detailed investigation into the problem of growth in the six-dimensional phase volume of the beam and defining the conditions which provide self-matching beam motion in the focusing channel, including particle acceleration.

Analytical solution of this problem is difficult to achieve and is possible only for some specific cases under the far going simplifying suppositions, which are not realized in practice. The widely used model of bunch in the view of uniformly charged ellipsoids, as has been shown in [6], cannot be self-matching in the field of conservative forces. So the application of this model for calculating the emittance growth and estimates of current limit requires caution. At present the most accurate method for calculating beam dynamics is computer simulation of the macroparticles. However, no existing computer codes are able to calculate beam halo and particle losses at the level of 10^{-6} - 10^{-7} and do not account for all factors leading to appearance of this halo [7]. One of the physical effects influencing beam quality is the dependence of the form of matching phase

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volume on the correlation between Coulomb forces and forces of external field under non-microcanonical phase density distributions. As far as particles are accelerating this correlation is changing, that is may be regarded as adiabatic mismatching of beam with regular channel. Such mismatching may lead to production of beam halo, which is the main deliverer of losing particles. The influence of this effect under the loss level of 10^{-6} is not yet known. There exists a row of other effects, which influence under the same level of losses cannot be ignored. It is vital that the result of these effects show themselves not in the initial part of linac, but where they are most dangerous.

The above points out the necessity of calculating the linac with a sufficient reserve on beam current limit. The cost of the initial part of the accelerator structure is not large comparing with the cost of the main part of linac. So such reserve is admittable.

Construction decisions for accelerator structures essentially influence the choice of its scheme. These decisions cannot be accepted without examining such a complicated problem as heat removal from structure elements; apparently for solving this problem new original approaches will be required.

The considerations mentioned above allow us to admit as a lower limit the value of $\sim$ 100 mA which guarantees acceptable efficiency and for a conservative upper limit, the Coulomb repulsion on order of 300 mA.

III. STRUCTURAL SCHEME AND THE MAIN DATA OF THE ITEP LINAC

The proposed scheme of one-channel linac is presented in Fig.1. The initial part of the accelerator is the RFQ structure, the intermediate part is the DTL with PMQs, and the main part is the DAW structure. This scheme is the result of further development of earlier published work [4,5].

The DAW structure, invented by V.G. Andreev [8], we proposed as main part of the linac. This structure has more wide dispersion characteristics and a higher shunt-impedance in comparison with SCS and ACS structures.

It seems to us that the DTL with PMQs is the most suitable for the intermediate part of the linac. Note that the PMQs allow us to decrease the diameter of the drift tubes and thus to increase the RF frequency and decrease active RF power losses.

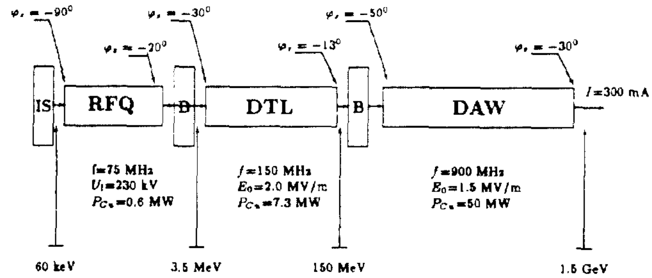

Figure 1: Block scheme of the linac.

However, the possibility of using PMQs must be confirmed by examination of their radiation resistance. The advantages of the RFQ for accelerating high current beams are well known.

The frequency of 900 MHz for the DAW structure is defined by the requirements of maximum efficiency. The frequency of 75 MHz is chosen for the RFQ in order to have a margin of the acceptance under nominal beam current 150 mA, suitable current limit (about 300 mA), and a decrease of emittance growth in the most dangerous parts of linac. The relatively low frequency of the RFQ allows us to realize a one-channel scheme for the linac. The frequency of the DTL is twice as high as that in the RFQ which simplifies the transverse matching of the beam at the input of the DTL.

To avoid particle losses between structures with frequencies 150 MHz and 900 MHz it is proposed to considerably decrease the absolute value of the synchronous phase according to the law

$$|\varphi_s| \sim W_s^{-\frac{1}{4}},$$

which must provide a more effective compression of the phase length of the bunch.

To provide adequate reliability let us set the value of the maximum RF electric field strength at the surface of the electrodes of the accelerating structures equal 160 kV/cm, that is 1.5 Kp criterion for a frequency of 75 MHz and a gap of 3 cm. In this case, for the minimum value of relative particle velocity 0.01131 the average value between adjacent electrodes is equal to 2.16 cm. With the field enhancement factor 1.47 for a four-vane RFQ structure [9,10] for defined parameters the value of the potential difference between the adjacent electrodes is equal to 230 kV/cm. Beam bunching is designed for quasi-stationary regimes. The value of the average field on the axis of DTL resonators was chosen to be 2.0 MV/m, and the aperture is 1.5 cm. The value of the synchronous phase varies along the DTL from -30^0 to -13^0. Calculations of the resonators were carried out by the RESALV code [11]. The total length of the DTL is 87 m. The value of the synchronous phase varies along the DAW structure from -50^0 to -30^0. The average field on the axis was chosen to be 1.5 MV/m [12].

A. Matching Transitions in Linacs

Because neighboring sections in the proposed scheme are operating at different frequencies of RF field and with different types of focusing it is necessary to match the beam both in the transverse and longitudinal phase planes.

The special feature of space-homogeneous quadruple focusing creates one more problem while matching the beam that we do not meet in linacs without RFQ. The problem is that the acceptance of the RFQ channel depends on time, and the parameters of normalized emittance of the beam in the regular channel are the same along the structure in any moment. The dependance of the beam emittance on the phase of RF field causes it to increase at the exit from the RFQ. And this increase will be larger the longer the phase width of the bunch. The calculations made for the ISTRA accelerator gives the value of the relation of the effective emittance at the exit from RFQ with phase length of 70^0 to the value of the current emittance of 1.70 for the focusing plane and 1.43 for the defocusing one. The computer simulation carried out in ITEP allowed us to work out the method of dynamically matching the space-homogeneous beam with the static space periodical channel [13]. (Under the dynamical matching we understand the conversion of the beam with time-dependent parameters into the beam with parameters that do not depend on time and vice verse.) If we have the beam crossover at the exit from RFQ for the synchronous particle the coordinates of the particles in the "head" and "tail" of the bunch while passing the output cross-section of the RFQ electrodes changes slightly, and the angles with longitudinal axis to a marked degree. The phase portraits for the particle in the "head" and "tail" of the bunch in this case deflects to different sides from the position of crossover on the phase plane, corresponding to the moment of passing of the synchronous particles through the output cross-sections of electrodes. The idea of the method is to create at the exit from the RFQ a short sector of sign-alternative RF field with the same frequency, the phase of which is shifted relative to the phase of oscillation of the beam envelope for the defined value in order to compensate the deflection of the phase portraits for the particles in the "head" and "tail" of the bunch to the position of crossover. The influence of matching RF field does not change the frequencies of transverse oscillations of the particles, but its compensating effect is kept over a wide range of currents.

The possibility of preserving the transverse matching of the beam in connecting the RFQ and DTL channel was studied in [14] for different multiple frequencies of the RF field in the DTL. The results of this investigation show that for specific channels with the same length of focusing period and values of phase advance it is possible to realize the matching of the beam with the large phase differences of transverse oscillations of the particles over a wide range of currents. The higher quality of matching can be achieved by using in the DTL magnetic lenses with the maximum possible length. At the connecting point of the channels with the same frequencies of RF field, the transverse matching of the beam is possible only at the minimal frequency of transverse oscillations of the particles as most critical for beam losses by use of adiabatic matching horn. In any case the necessary condition of the direct connection of the channels is the presence of the crossover of the beam for the cross-section of the beam corresponding to the synchronous particle.

Equal frequencies of particle transverse oscillation (especially of a minimal frequency) at all the passages between the different parts of the linac and adiabatic changing of beam parameters in the focusing channels of the separate parts make it possible to construct the unified focusing channel throughout the linac in which the matching of the beam with the channel has no critical dependence on the beam current. The conditions of correctness of the adiabatic approximation defined in [14] and illustrated in Fig. 2 of the proposed scheme are proved for every part of linac. Such a design of the focusing channel carries the problem of matching the beam with the channel to the entrance of the RFQ. Methods and devices of matching the beam of the electrostatic injector and RFQ structure are well known today and have been tested at the working accelerators. Now preparations for the experimental test on the ISTRA-36 accelerator of the proposed ITEP method of dynamic matching are underway. Match-

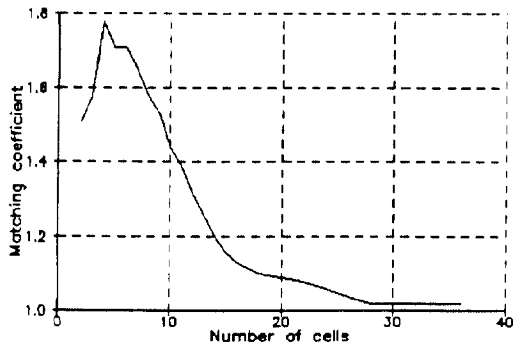

Figure 2: The dependence of matching coefficient on the number of RFQ cells for cosine law of RFQ electrodes mean radius variation in adiabatic matching horn.

ing of the RFQ with the Alvarez structure which works at the doubled frequency of RF field using the one gap buncher and the system of matching magnetic quadruple lenses at the drift space have been realized on the ISTRA-36 accelerator. Substitution of the one gap buncher for the quarter wave matching resonator on the part with RFQ with preliminary drift space [15] will let us connect both structures directly while preserving the transverse matching of the beam. The possibility of such a substitution is studied below.

To fully guarantee the absence of particle losses additional bunching of the beam between the RFQ and DTL with bunching factor 1.76 is needed. This result may be obtained by using a single-gap buncher with wavelength of 2 m or 4 m, effective voltage of 162.5 kV or 325 kV, respectively, and drift space of 80.4 cm. Between the DTL and DAW structures one may use the four-gap buncher with average field of 0.47 MV/m and wavelength of 2 meters. Use of a single-gap buncher in this case is impossible [12].

B. Current Limits and RF Power Losses in Linac Resonators

Current limits and transverse dimensions of the beam were calculated based on typical parameters of ion sources in the ITEP linac ISTRA-36: beam current = 150 mA and normalized emittance = 0.2 cm · mrad. Emittance growth along the linac was set partly taking into account of the experience with previous computer simulations for ISTRA [16] and partly analogical to values calculated in LANL. The values of current limits were calculated in smooth approximation to oscillation equations [17]. The minimum value of the current limit of 800 mA is at the end of the RFQ and it is defined by longitudinal Coulomb repulsion due to decrease of the absolute value of the synchronous phase in the RFQ. Nevertheless, the presented value is 2.5 times higher than the maximum current of the beam. The matched beam size along the whole linac is below approximately one half of the aperture. As the taken value of input emittance is of an order of magnitude higher than the value adopted at LANL there is no reason to expect significant emittance growth in separate sections of the linac than the presented values. However, it is necessary to confirm this estimate by beam dynamics simulations.

As the total length of the RFQ is equal to 8.6 m the total losses in copper of the resonator are approximately 570 kW. Power consumption for acceleration is 1.03 MW.

Analysis of the calculation results [12] shows that the parameters of the DTL resonators are quite close to optimum from the point of view of efficiency. The obtained data show also that dissipation of RF power in the drift tubes is rather high (at the end of the last resonator each drift tube dissipates about 80 kW). Total RF power losses in the DTL resonators is 7.3 MW and total needed power is 51 MW.

For estimating RF power losses in the DAW resonators we use the data of MRTI for the INR meson factory: at an energy gain of 1 MeV/m the specific losses in copper are 0.04 MW/m. At a DAW structure length of 1246 m the losses will be 50 MW. Total power consumption in the DAW resonator is 455 MW.

The efficiency of the linac structures as a whole is ~80%.

IV. BRIEF ANALYSIS OF PROPOSED STRUCTURAL SCHEMES

The structural scheme of designing a high current linac has the same features in all the projects proposed by ITEP, MRTI, LANL and JAERI [4,5,12,18-23]. However, there are serious differences in the selection of such basic parameters as frequency and type of accelerating structures, energy of the beam at the passage between structures, beam current and so on. Because of the high price of accelerators and the difficulties of optimizing their characteristics and design, which depends on a large number of factors, a detailed discussion and estimation of different structural schemes and basic parameters of accelerators becomes a necessary and important step in designing such a linac. There are enough data about the schemes of accelerators of LANL, MRTI and ITEP.

The main disadvantage of the LANL scheme is the possibility of the appearance of considerable deflection of the bunch's particles from the axis in the different parts along it after the beam convergence device. If we suppose that the deflecting field is sinusoidal, that the phase length of the bunch is 0.1 of the RF field period in the deflecting device, that it must work at a frequency of 350 MHz, that the deflecting angle in this device is 10^0, and that the wavelength of transverse oscillations is 2 m, then the amplitude of coherent oscillations of the "head" and "tail" of the bunch will reach a value of 3 mm. As a result of nonlinearity of the field inside the focusing lenses, the coherent oscillations will quickly become noncoherent and emittance will be increased because of the appearance of the halo around the bunch, which will cause the loss of particles. Additional troubles can be expected because of the possibility of excitation inside the accelerating structure of the transverse modes of RF oscillations by the beam with periodical and multiple frequency deflections of the different parts of the beam from the axis of the structure.

At the same time the LANL scheme possesses some important merits. Among them, the simplicity of longitudinal matching while the bunches pass from one part of accelerator to another (only one change of frequency and only for two times), the filling in of all separatrixes in accelerators with 700 MHz frequency, which decreases the peak current, and the ability to increase the shunt-impedance in the structure with the drift tubes at a frequency of 700 MHz due to the absence of lenses in tubes.

The scheme of the JAERI accelerator [22] for energy of 1.5 GeV and average current of 39 mA will be defined as the experience is gained while working on the prototype BTA-RFQ structures with energies of 0.1 - 2.0 MeV and the 10 MeV DTL with pulse current of 110 mA, df= 10% at a frequency of 201 MHz. Probably such a gradual approach to the development of such a large project is the most conservative.

The main disadvantage of the MRTI scheme [23] is the impossibility of correctly matching the channel with beam focusing by a longitudinal magnetic field of 7.6 Tl with the DTL; this mismatching causes large losses of particles, basically at a low energy. A problem difficult to solve is created by placing the accelerating structure with the high heat extraction inside the superconductive solenoid, which will probably reduce the reliability of the accelerator. The merit of the scheme is the high ultimate current in the initial part if the difficulties with its design can be overcome.

The main disadvantage of the ITEP scheme is the very big difference (six times) between the frequencies in the DTL and DAW that forces a reduction in the synchronous phase along the DTL to low absolute value. Today this decision is not finally studied on particle losses. Among the merits of the ITEP's scheme is its simplicity and the possibility of transverse matching of the beam along all the linac in a wide range of currents, use of the structures tested in the working systems, and a good reserve in acceptance for the increase of the nominal current value.

Now we can see that all the proposed schemes have many common features, especially in the main part of the accelerator. The choice of DAW, SCS or ACS structures can be made after a detailed comparison of RF parameters and costs for construction and use, which can be done in a short time.

A much more difficult problem is the comparison of particle loss among the various accelerator schemes. There is no such data for losses of 10^{-6} – 10^{-7} today.

Comparison of the results is difficult also because different programs for accelerator design are used in the different accelerator centers. That is why the results can be compared only after calculation of the beam dynamics for all the proposed schemes using the same software package.

V. CONCLUSION

The analysis of the proposed structural schemes of the linacs and the results of estimates of the linacs' parameters shows us how impossible it is to choose definitively the optimal structural scheme today without some additional scientific and construction research. Some of the experimental investigations can be realized on the working accelerators LAMPF and ISTRA-36. To test heat removal from the critical parts of CW accelerating structures a special experimental test stand should be constructed. Highly efficient and reliable CW power generators must be designed for this project.

To collect data about particle loss below the permissible integral level of 1.0 E^{-6} it is necessary to develop adequate programs for computing simulation of intensive beam dynamics along the whole accelerator, keeping in mind all the known factors that cause the beam's six-dimensional phase volume growth. For its minimization the investigations and solving of the problems connected with matching of the beam with the linac channel along its full length have to be done.

The parameters of the project proposed by ITEP can be corrected according to results of additional investigations and will be precise while studying the processes in the target and blanket of the accelerator.

The construction of such a large and expensive accelerator should be made step by step with the necessary corrections of design at the end of every step. It seems useful to start with the construction of a prototype of the initial part of CW linac, which will include all the elements that influence the beam quality.

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