A DEUTERON LINAC FOR SUBCRITICAL ASSEMBLY DRIVING

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A scheme of a deuteron linac for driving a thermal neutron source based on a subcritical uranium assembly is presented. The accelerator is based on *RFQ* and *H*-cavities. Beam stability as the beam moves along an accelerating channel is provided by *RF* electric fields. Beam phase characteristics are matching with sections and a neutron target parameters by transport lines between: an injector-*RFQ* sectio*n*, the *RFQ* section-an initial *H*-section, adjacent *H*-sections, and an accelerator output-the target.

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INTRODUCTION

Investigations into construction of a neutron source based on a subcritical uranium assembly are in progress at the *NSC KIPT* in collaboration with *ANL (USA)* [1]. Primary neutrons, driving the subcritical assembly, are assumed to be generated in deuteron-neutron producing target of beryllium or electron interactions with a tungsten or uranium target.

Paper [2] presents a conceptual scheme and main parameters for a thermal neutron source based on the subcritical uranium assembly driven by the deuteron linac with output energy $W=23$ MeV and an average current $I=1$ mA.

Specialists of the *NSC KIPT* have gained a lot of experience in designing of the effective ion accelerating structures for low-energy region: we have elaborated the methods and computer codes for accelerating channel calculations and charged particle dynamics simulation; a series of accelerators has been designed, constructed and tested [3].

DEUTERON LINAC AND BEAM-TARGET TRANSPORT LINE

The key criteria for an accelerator choice were: construction simplicity of the accelerator, operational reliability, radiation purity, and the possibility to use the available production facilities which have been already built [4].

The deuteron linac for production of medical radioisotope-generator ^{99}Mo-^{99m}Tc [5] was a basis for a new design. Its accelerating channel meets the requirements for radiation purity [6]. The output energy of the accelerator-driver was increased up to 23 MeV to obtain a higher neutron yield from the converting target.

The main parameters of the driving accelerator are listed in the Table 1, and Fig. 1 depicts a structure layout.

The accelerator consists of a deuteron injector *DI*; an injected beam transport line *LEBT* and an accelerating channel built on a conventional scheme for powerful ion accelerators. It has initial part (*IPA*) based on a *H*-cavity with radio-frequency quadrupole focusing (*RFQ*) and main part (*MPA*) on a basis of *H*-cavities in which drift tubes are alternately connected with two conducting plates fastened to the opposite sides of the resonators. Beam movement stability in *MPA* resonators is provided by modified alternating phase focusing (*MAPF*) [5]. Beam matching lines *MEBT* with magnetic quadrupole lenses, Fig. 1, are located between the accelerating sections that are installed in separate vacuum tanks. At the accelerator outlet there is a high energy beam line *HEBT* to transport deuteron to the neutron-producing target. Provided is also a bend magnet lead-out (*BM*) for an accelerated beam with energy of 15 MeV for medicine radioisotope production.

Table 1. *The main accelerator characteristics*

Particle type	d^+
Pulsed current, mA	50.0
Duty factor, %	2
Operating frequency, MHz	152.0
Injection energy, MeV	0.1
Output energy, MeV	23.,0
Accelerator length, m	~ 30

The injector is consists of a plasma ion source and three-electrodes ion-optical system for beam formation with pulsed current up to $I\cong100$ mA and energy of $W_i=100$ keV. Two types of plasma ion sources were considered: (i) duoplasmatron with hollow cold cathode, and (ii) ion source based on an electron-cyclotron resonance discharge. The energy spread does not exceed ±0.25%, while normalized emittance varies in the range of 0.1…0.2 π·mm·mrad.

To provide matching of injected divergent beam with *RFQ* section acceptance, the *LEBT* transport line with two focusing solenoids is implemented similar to a paper [8]. *LEBT* parameters are calculated with *TRACE-3D* code [9] by computing beam enveloping and phase space ellipses in transverse and longitudinal planes for a given transport system. The optimal beam parameters, such as radius $R=2.1$ mm, convergence angle $\theta=52.5°$, beam transmission efficiency more than 90%, are the result of numerical simulation for various solenoids loca-

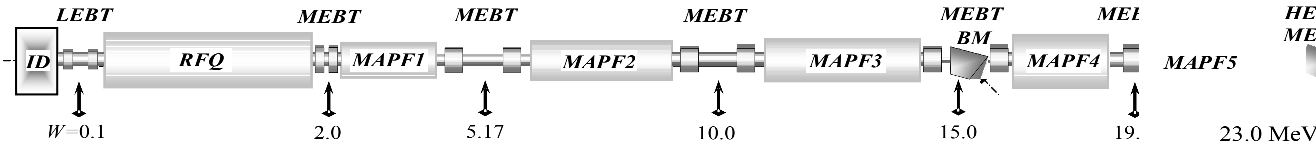

Fig.1 Deuteron linac layout: ID is deuteron injector; RFQ is section with RF quadrupole focusing, MAPF1…MAPF5 are sections with modified alternative phase focusing; LEBT, MEBT, HEBT are beam transport lines, BM is a bending magnet

tions, magnetic field intensities, and distances for beam drift. Fig.2 presents beam enveloping in horizontal and vertical planes together with the phase space portraits at the inlet and outlet of the transportation system.

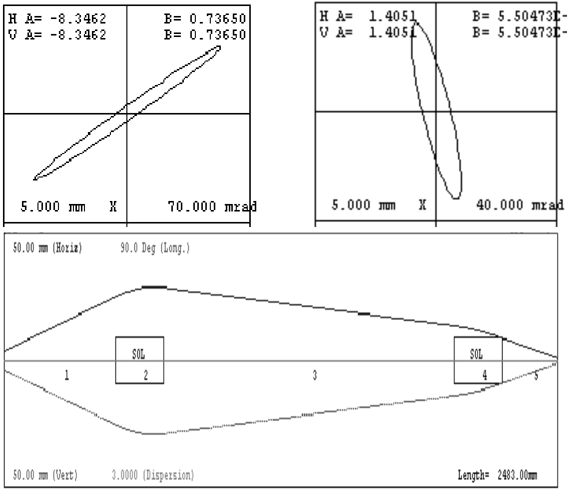

Fig.2. Beam phase-space and enveloping in LEBT

Total length of the transport line is 2.48 m, a drift gap between the injector and the first solenoid is 0.5 m, the distance between solenoids is 1.3 m, and the distance from the second solenoid to the *RFQ* input equals 0.25 m. Magnetic fields in the solenoids are 0.35 Tesla and 0.45 Tesla, correspondingly. Each solenoid has a length of 216 mm and an aperture of 100 mm.

The accelerating channel calculations and numerical simulation for the deuteron beam dynamics was performed by macroparticles technique using the original codes elaborated in the *NSC KIPT*.

The accelerating channel of the linac was calculated that way to provide the main particle losses in the low energy *RFQ* section. Note that the *RFQ* output energy of 2 MeV is chosen to be less than a deuteron nuclear binding energy of 2.2 MeV.

The initial *RFQ* section is based on the *H*-cavity and provides bunching and preliminary acceleration of the deuterons from 100 keV to 2 MeV with the beam current up to 100 mA. This section is a four vane resonator of 4.7 m length. Modulation depth of the electrodes increases monotonically from 1.0 mm at the inlet up to 1.56 mm at the outlet. The vanes have non-modulated parts at the input and output of the section. At the parts of *RFQ* where strong longitudinal beam compression occurs, the synchronous particle phase was taken a positive one [5]. This way increases the beam focusing without considerable drop of an acceleration rate. The maximal electric field at the electrode surfaces is about 225 kV/cm.

Without a beam space charge, the transition ratio is 0.92. The transition ratio drops down to ~0.87, if the beam load is increasing up to 60 mA.

For optimal beam matching between *RFQ* and *MAPF1* sections, Fig.1, a medium energy beam line *MEBT* is applied. The beam at the *RFQ* outlet is converging in longitudinal direction and diverging in transverse one. While drifting through the *MEBT* the beam after crossover becomes divergent longitudinally but its phase width is the optimal ones for longitudinal matching to the *MAPF1* section. The transverse matching is provided by quadrupole lenses of *MEBT*: a beam radius of R=6 mm and convergence angle of θ=25 mrad. The optimal length for *MEBT* is 63.5 cm.

The main part of the linac (*MPA*) consists of five drift tube *H*-cavities with the *MAPF*. Their main characteristics are listed in the Table 2. The electric field at the electrode surface does not exceed 240 kV/cm.

The parameters of the first (*MAPF1*) section of the *MPA* determine quality of the whole accelerating channel substantially. Therefore, much attention was given to the beam dynamics simulation in *MAPF1*. Studies have shown that *MAPF1* can accelerate a beam with the current up to 100 mA without losses. Any of 1000 modeling macrparticles does not lose on the drift tubes. Thus, the particle losses in the accelerating channel is less than 0.1%. The increase in injection current up to 150 mA results in particle losses increase about to 0.5%. If the injection current is higher than 150mA, the particle losses rise drastically.

***Table. 2.** The main characteristic of MPA sections*

MAPF section number	Energy, MeV		Length, m	*RF* power supply, MW
	Input	Output		
1	2.0	5.17	2.2	0,55
2	5.17	10.03	3.3	1,25
3	10.03	15.0	3.5	1,4
4	15.0	19.0	2.1	1,2
5	19.0	23.0	2.0	1,0

The beam matching between the next *MPA* sections is similar to one between the *RFQ* and *MAPF1*. Beam drift along the correspondent *MEBT* provides 6-dimension matching to adjacent *MAPF* section. Using above number of macroparticles for simulation, the *MEBT* ensures the beam transmission without any particle losses to the next section and beam acceleration there. *MEBT* length between the second and third sections is 1.27 m, the length between other sections is 1.29 m. One quadrupole triplet per *MEBT* provides matching in transverse phase plane.

Beam acceleration occurs without deuteron losses within all *MAPF* sections under used macroparticles statistics.

Bunch phase width at the linac outlet is of 85°, relative energy spread is in the range of 0.1…0.25%. The beam is divergent in the transverse plane.

Including to the accelerating channel several *MEBT* units ensures the possibility to control independently the transverse and longitudinal phase space characteristics of the beam. It results in minimization of beam losses in the linac, whereas the beam acceleration and focusing in all sections are ensured by the *RF* fields only.

A high-energy beam transportation line (*HEBT*) is used to transmit deuterons from the linac output on the neutron-producing target. It serves to solve two tasks: first, to transport the beam to the target with minimal losses; second, to form the beam important for uniform distribution of the thermal power on the target due to the deuteron energy dissipation.

The *HEBT* consists of four quadrupole lenses and a bending magnet for beam deflection to an angle of 45°. The lenses placed before the magnet focus the beam in transverse plane and provide optimal beam transportation through the bending magnet ion guide. The lenses placed after the magnet serve for beam transportation to the target and formation of required distribution of beam current density on the target.

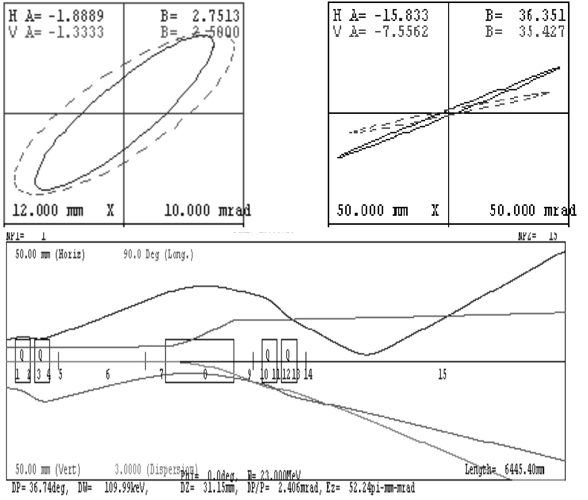

Fig.3. Beam phase space ellipses at input and output of the HEBT along with x-z and y-z plane enveloping

Numerical simulation of the *HEBT* parameters was performed with *TRACE-3D* code as well. The optimal values are calculated for magnetic field gradients in the quadrupole lenses and the bending magnet field as well as optimal dimensions and disposition all ion-optics elements along the *HEBT*. Fig.3 shows beam enveloping in x-z (horizontal) and y-z (vertical) planes and phase space ellipses at the linac output and at the input of the beryllium target. Here, Fig.3, the main ion-optics elements are shown in diagram form.

At the linac output we have a beam size of 10 mm and beam divergence of 5.8 mrad in the horizontal plane, while the beam size in the vertical plane is 12.5 mm and divergence of. 3.9 mrad, respectively. The total length of the transport line, from the linac to the neutron-producing target, is 6.38 m. The beam diameter on the target is about 8 cm.

CONCLUSION

Accelerator driven systems on the base of a subcritical assembly can be used not only as neutron sources for nuclear physics and applied researches. The hybrid installations with high current beams of protons or deuterons of low energy and respectively low fission power enable to examine dynamics, stability, safety and reliability of these systems. Low energy parts of high current ion accelerators for industry power production and radioactive wastes transmutations can be tested and optimal design of the future high power installations may be chosen.

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ЛИНЕЙНЫЙ УСКОРИТЕЛЬ ДЕЙТРОНОВ ДЛЯ УПРАВЛЕНИЯ ПОДКРИТИЧЕСКОЙ СБОРКОЙ

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Рассмотрена схема линейного ускорителя дейтронов для управления источником тепловых нейтронов на основе подкритической урановой сборки. Ускоритель базируется на *H*-резонаторах. Устойчивость движения пучка в ускоряющем канале обеспечивается высокочастотным полем. Линии транспортировки на переходах между секциями, между инжектором и ускоряющей структурой, а также между ускорителем и мишенью обеспечивают согласование характеристик пучка с параметрами секций и мишени.

ЛІНІЙНИЙ ПРИСКОРЮВАЧ ДЕЙТРОНІВ ДЛЯ КЕРУВАННЯ ПІДКРИТИЧНОЮ ЗБІРКОЮ

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Розглянуто схему лінійного прискорювача дейтронів для керування джерелом теплових нейтронів на основі підкритичної уранової збірки. Прискорювач базується на *H*-резонаторах. Стійкість руху пучка в прискорювальному каналі забезпечується високочастотним полем. Лінії транспортування між секціями, між

інжектором і першою секцією прискорювача, а також між прискорювачем і мішенню забезпечують узгодження характеристик пучка з параметрами секцій і мішені.