# POWER LINEAR PROTON AND HEAVY ION ACCELERATORS FOR SOLVING SCIENTIFIC AND PRACTICAL PROBLEMS

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A scope of the important problems which solving requires the availability of powerful proton and heavy ions beams is presented. The most important among them are creation of effective and safe nuclear energetics with inexhaustible fuel resources based on a complex of a proton linear accelerator and a subcritical reactor on fast neutrons; creation of intensity neutron generators for investigation of the structure and dynamics of condensed matter; the use of intense proton beams of high energy for creation of μ-meson and neutrino factories for application in physics of weak interactions. Information about investigations on radionuclide and heavy ion beams accelerated for high energy is presented.

## 1. INTRODUCTION

Presently, the progress in development of charged particle accelerators achieves such a high level that the reasonable question can be set about application of powerful accelerator installations to solve a series of global problems. From the viewpoint of science it is a very important problem of the completion of the Grand Unified Theory of matter, from the defining the properties and functions of its fundamental bricks to the structure and dynamics of bodies in the Universe.

Practically, a possibility is discussed to solve the problem of effective and safe energetics on the eve of the nearing energetic starvation.

To solve the problems accelerating science and technology move in two lines:

1. Continual growth of the energy of accelerated particles.
2. Increase in the beam power for required kinds of particles.

As to the first, quick growth in proton and electron energies takes place. The energy region of several GeV was achieved long ago. With modern colliders on the beam-beam collision, the region of TeV is successfully mastered. In the future, the colliders of protons and heavy ions with energies of tens of TeV will exist. As yet, one cannot see the limit of the "long distance race". Modern physics sets up new tasks which solution is possible only with giant accelerators.

The second avenue of development sets the problem of the acceleration of powerful proton beams with energies of tens MW. Proton linear accelerators fit best for acceleration of such beams. These accelerators are used widely for scientific and applied purposes. The main lines of application of powerful proton beams and the most important problems on the way to their implementing are discussed below.

## 2. DEVELOPMENT OF THE ACCELERATOR DRIVEN ENERGETICS

The problem of the creation of new energetics designed to replace the existing nuclear energetics based on the reactors on thermal neutrons arose in the connection with a series of disadvantages of the latter:

1. Thermal reactors operate in the subcritical mode, and to control the chain reaction of nuclei fission complicated engineering systems are used. The reliability of these systems is rather high; however, a probability of a nuclear incident still remains despite tough operating conditions.
2. Radionuclides (the products of uranium fission) bring the threat of environment pollution. Their geological disposal is costly. Radioactive transuranics – products of nuclear reactions in reactors – worsen the long-term radiation situation.
3. A store of fissile $^{235}$U in natural uranium (0.7%) is not that high to solve the long-term problems in energetics. Energetic systems in which it is possible to use $^{238}$U, $^{232}$Th and transuranic actinides for energy production are required to ensure inexhaustible energy supplies and incineration of radioactive waste.

The new type of nuclear energetics called to replace the existing one should be completely safe, economical, and effective with practically inexhaustible supplies of low-cost nuclear fuel.

Such is energetics where a subcritical reactor on fast neutrons operates together with a proton linear accelerator. The deficiency of neutrons in the reactor operating in subcritical mode is compensated on the account of the neutrons borne in the process of the spallation-reaction of protons under irradiation of the target made of a material with heavy nuclei (lead, bismuth, depleted uranium). A mixture of thorium or depleted $^{238}$U with fissile isotopes $^{233}$U, $^{235}$U, $^{239}$Pu and other transuranics is produced in large amounts in thermal reactors.

Fast neutrons allow splitting all transuranics and producing the fissile isotope $^{233}$U of $^{232}$Th more effectively than thermal neutrons. In the course of the spallation-reaction on lead one neutron borne 10…20 neutrons depending on the proton energy.

The optimum energy of a proton beam compensating the deficiency of the neutron flux in the subcritical reactor is 1…2 GeV. Together with the reactor rated for thermal power of 1.5 GW the linear accelerator should produce the proton beam with the intensity of 20…30 mA.

A large number of science teams deals with this problem. Russian researchers work very hard, where this type of energetics is called electronuclear energetic systems (ENES) [1-3]; in the USA it is called Accelerator Driven Transmutation, ADT. It is also being developed in Japan and Korea [4-6]. But the most developed and close to implementation is a project, which is called "Energy Amplifier" proposed by CERN team supervised by C. Rubbia [7-9]. The basis for the project is a complex of a linear accelerator and subcritical reactor on fast neutrons. Its power is 1.5 GW. Very rigid requirements are imposed upon the accelerator, which will be discussed later.

## 3. ACCELERATORS AS GENERATORS OF INTENSE NEUTRON BEAMS

Presently, there are two types of neutron generators. These are: nuclear reactors and spallation-reactions in the course of which neutron fluxes are produced on a target made of heavy elements irradiated with protons accelerated to GeV energy. The reactor works in the continuous mode. The operating mode of accelerators is more flexible. There are several research reactors meant for generation of intense neutron fluxes. Usually these fluxes of thermal neutrons are about $10^{14}$n/cm$^2$·s. In excusive cases (ILL, Grenoble) the flux achieves $10^{15}$ n/cm$^2$s. In practice, this is a technical limit achieved in the reactor variant. At the same time, an accelerator-based spallation - source has a significant potential for increasing the intensity of the neutron flux. Besides that, in this case there is an additional advantage lying in the possibility of the pulsed mode of operation. The neutrons can be compressed in short time pulses. Thus, it is possible to increase the pulse intensity by two orders. This will give us a possibility to operate in the TOF (time of flight) mode and this would also allow significant decreasing the thermal load on the target which is especially important, for instance, for such a delicate material as biological objects.

During last two decades pulsed neutron sources were designed in Argon, Los Alamos], KEK, Rutherford Laboratory (RAL) where the most powerful neutron source (ISIS) was developed. Recently, a neutron source operating in the continuous mode was put into operation on the cyclotron PSI [10] where the power of the neutron beam achieved 600 kW.

During last four years the experimental base (SING) [11] was created – a research neutron source in the range of fluxes of moderate intensities. It is an alternative and equivalent for reactor neutron beams in the thermal and cold ranges. It is supposed to use them also for development of targets and for investigations in material engineering for Accelerator Driven Transmutation.

In KEK [4] and Oak-Ridge [12] accelerators rated for proton beams with power of 1 MW and possibility to increase the power to 5 MW are under construction. In Europe the joint project "European Spallation Source" (ESS) [13] is being developed. For implementation of the project an association of 7 countries was established.

The characteristic feature of the listed projects is a complex approach to their application. Beside the tasks of neutron technologies each of them includes investigations on the development of liquid lead and lead-bismuth spallation targets and their operation with the proton beam power of 1 MW.

The most general variant a pulsed neutron source is a linear accelerator in combination with a storage ring of a synchrotron type. A possibility of obtaining the required time structure with the peak duration of less than 1 μs and repetition rate of 20…50 MHz is expected.

The most effective spallation targets are the targets from depleted $^{238}$U. However, currently the targets of unfissile material are preferred which is less efficient in the quantity of produced neutrons, but they have considerably higher life and less affect the surrounding materials.

The most important task in the development of powerful neutron generators of $10^{15}$n/cm$^2$·s is the investigation of the structure and dynamics of the condensed matter. Obtaining the information on the structure is possible on lengths $10^{-6}…10^{3}$ nm. This corresponds to the wavefunctions of hydrogen and macromolecules. In this range it is necessary to study the dynamics of the processes in the form of molecular and crystal oscillations at the level of neV and eV. Distinctive properties of neutrons make them ideal instruments for investigations of condensed matter [14]:

1. The absence of the charge, the small cross-section of interaction allow investigating bulk materials in the form of thick targets.
2. Scattering on nuclei allows hydrogen "imaging" and identifying isotopes.
3. Neutron's magnetic moment allows to discover magnetic parameters at the micro-level.
4. The wavelength of thermal neutrons at inter-atomic distances allows us to determine the crystalline structure and the arrangement of atoms in the lattice.
5. Kinetic energy of elementary interactions allows determining dynamic properties and the excitation energy.
6. Coherent and non-coherent scattering allow investigating collective phenomena and diffusion of individual atoms.

## 4. MESON AND NEUTRINO FACTORIES

In recent years, serious evidences follow from the experiments on neutrino that was carried out in Gransasso (Italy) [15] and Kamioke (Japan) [16] about the existence of physics that does not fit the frames of the Standard Model. The question whether neutrino has or has not the mass became the decisive for justification of principles of the theory of weak interactions, and, on the other hand, it is decisive for solving problem in astrophysics. The experiments with electron neutrino $\nu_e$ from the Sun, and also with $\nu_e$ and $\nu_\mu$ from the space rays in the atmosphere showed that it is well possible that neutrino oscillates between the $\nu_e$, $\nu_\mu$ and $\nu_\tau$ states.

At least two of these neutrinos have the mass different from zero.

Neutrino beams of high energies can be obtained with the decay of $\pi$-mesons when they pass a long channel. With that, $\mu^+$-mesons and anti $\mu^-$-mesons are generated. Accumulated beams of $\mu^+$-mesons are the sources of $\nu_e$ and anti-$\nu_{\mu,}$ neutrino, and beams of $\mu^-$-mesons generate anti-$\nu_e$ and $\nu_\mu$.

This approach to neutrino production in storage rings forms the basis for circular $\mu$-colliders where energy up to 10 GeV can be achieved in the mass center. In the initial part intense beams of accelerated protons are used. Such is the CERN project – the pulsed linear accelerator for the energy of 2.2 GeV, 13 mA with a duty factor of 14% and the average proton beam power of 4 MW [17].

Projects of factories of intense fluxes of $\mu$-mesons and neutrino are extremely sophisticated complexes; that indicates great importance of the problems being solved. Such complexes are being developed in Fermilab (USA) [18] and CERN [19]. The initial part is a linear accelerator – an injector to the synchrotron ring. At the output of the ring, protons with the energy of 16 GeV fall on the target (solid graphite or mercury). Generated $\pi$-mesons pass 50 m and decay generating beams of $\mu$-mesons and $+\nu_e$. After preliminary acceleration in the induction accelerator $\mu$-mesons are bunched, cooled down and accelerated in the linear accelerator to 1.6 GeV, and then to 3 GeV. Two following recirculation linacs accelerate the $\mu$-beam and direct it to a storage ring. On extended linear sections of the storage ring $\mu$-mesons decay forming directed fluxes of $\nu_\mu$-neutrino.

## 5. BEAMS OF RADIOACTIVE IONS

Recently, nuclear physics is focused on investigation of structure of the nuclear matter under extreme conditions, which can be created in the most powerful accelerator laboratories. The scope of these works and prospects of the advance of technical background is given in [20].

After the century since radioactivity has been discovered, there were produced about 3 000 proton and neutron combinations; some of them are studied in details while others were only described. At the same time, according to theoretical predictions still more nuclei are waiting for their hour, particularly, neutron-exceeding and neutron-deficient nuclei. The problems in nuclear multiplicity and dynamics of the highly excited nuclear matter is associated with nuclear fusion in astrophysical objects, and therefore will give a possibility to establish the starting point of the process of element formation in our Universe.

In this connection, in many laboratories over the world a great activity is seen in development and creation of the systems, which allow obtaining and accelerating beams of radioactive ions. Two methods of radionuclide beams are known. One of them is the method of Isotopic Separation On Line (ISOL), the other is the In-Flight method.

Historically, for the first time the ISOL method was developed in CERN (ISOLDE). In this case, radioisotopes arise on the rather thick resting target, trap or in the gas bulk that is bombarded with the initial beam of particles accelerated at an accelerator. After their ionization in the ion source of isotopic separation secondary beams of radionuclides are accelerated again to the required energy in post-accelerators.

In the in-flight method heavy ion beams with high energy are generated with initial beam passes a thin target through fragmentation or fission of atoms of the target. After the separation in masses, charges and pulses these ions are directed to the second target for study. In this case no post-accelerator is required as the reaction products are generated in-flight. With the use of powerful initial proton beams it is possible to obtain heavy ion beams of high intensity. For the first time the in-flight “fragment-separators” concept was applied for heavy ion beam in Berkley, USA and GANIL, France ]. Further, this method was widely used in many laboratories all over the world.

The most universal project of the complex for production and application of radioactive ion beams is the Pan-European project EURISOL. It is being built on the basis of the proton linear accelerator on the energy of 1 GeV, beam power of 5 MW in the continuous mode, with a possibility to raise the proton energy to 2 GeV [21].

In the EURISOL project, beside the mentioned powerful linear accelerator it is assumed to use the electron beam of 50 MeV, which provides fission fragments as a result of the photoreaction on the uranium target. In this way it is possible to achieve $10^{15}$ fission/s. To this end, the electron beam of 1 to 2 MW (50…70 MeV and 30 mA in the continuous mode) is necessary. It is believed that this alternative is the cheapest and easiest for realization. Photonuclear reactions are also under consideration in Dubna where together with ISOL + post-accelerator based on two cyclotrons (DRIBS) it is assumed to use electron microtron on 25 MeV, 20 $\mu$A [22].

Proton beams with energy up to tens MW are necessary for obtaining very high neutron fluxes and other secondary particles. The field of their application ranges from accelerator driven energetics and spallation-neutron generators to factories of radioactive ion beams, neutrino and meson colliders. In the Table 2 [23] typical beam parameters meant for solving various problems are listed.

*Beam parameters for solving various problems*

| Application | Beam power | Energy | Average current |
|---|---|---|---|
| Condensed matter | 5 MW | 1.3 GeV | 3.75 mA |
| Radioactive ions | > 10 MW | ~ 1 GeV | ~ 10 mA |
| Hybrid Systems | ~ 50 MW | ~ 1 GeV | ~ 50 mA |
| Irradiation tool | 10-40 MW | ~ 1 GeV | 10-40 mA |
| Tritium production | 10-100 MW | ~ 1 GeV | 100 mA |
| Muons-neutrinos | 4 MW | 2 GeV | 2 mA |

As one can see, the proton energy of 1…2 GeV is the same for all variants. The average beam currents differ essentially depending on their purposes. The operational mode is continuous or pulsed with a high duty factor. Modern accelerating technologies and experience in development and running proton accelerators show that these accelerators can be created for relatively low cost of building. At the same time, significant increase (10…100 times) in beam power as compared with that existing now will demand solving a series of new tasks.

1. Radiation situation in the immediate proximity from the accelerator systems should be such that it would allow fulfilling works on control, fixing and replacement of failed elements and should not exceed 1 W (30 mrad/hour). To do this, the beam losses should not exceed 1 nA/m or $10^{-8}$ from the total amount of particles being accelerated. This poses strict requirements on stability of all systems, accuracy of fabrication and assembling, accurate procedures of beam dynamics calculation, elimination of the causes for radial and phase beam instability and halos which are the main source of beam losses. Specialists of many accelerator centers work on this problem as applied to each of accelerators being developed. Achieved success ensures the problem will be settled.
2. The nature of the works being carried out with powerful proton beams poses special requirements on reliability of the accelerator as a whole. In the Table 3 a list of accelerator systems is given and their contribution to the total time of beam failures for the well-known and presently the most powerful proton linac on the energy of 800 MeV (Los Alamos meson factory). Despite the fact that it is manufactured at the technological level of early 70-s and though its parameters are rather high they do not fit new tasks.

During last 30 years accelerating technology has significantly advanced and also in resolution of the problem of reliability. That concerns all accelerator systems showed in the Table 3. Presently, the most of systems are designed which in their parameters are close to required ones. For instance, in Los Alamos a variant of the initial section of the linac called LEDA is created [24] which is a proton source system, injector system, transportation line, and RFQ structure on the energy of 6.7 MeV operating in the continuous mode. In CEA, France, an injector system SILHI is created using an ECR proton source operating in the continuous mode of rather high stability and reliability. A proton beam with a current of 75 mA was accelerated during 104 hours with the only breakdown of 2.5 minutes.

The similar situation exists in the development of other systems. Application of superconductive accelerating structures allowed solving several tasks at a time, among them to provide high reliability. Such structures operated for a long time on LEP in CERN and KEK, Japan. With that reliability was brought up to 99.3% and 99.5%, respectively.

The estimation indicates [25] that modern accelerators of powerful proton beam would provide exclusively high level of reliability. This concerns especially the most proton beams operating in accelerator driven energetic complexes. Evidence are given that during a year of commercial operation only of no less than 10 unforeseen breakdowns are acceptable with duration of no longer than 100 ms. These fantastic requirements could be only met with active and passive reservation and doubling weak links of accelerators. This inevitably causes the rise in costs of their construction and maintenance; however, “the game's worth the candle” when we have to do with solving the most important problems of modernity.

## 6. RESEARCH FACILITY WITH ION AND ANTIPROTON BEAMS (FAIR)

In the recent years in GSI (Darmstadt) the plans for creation of the International research complex with ion and antiproton beams (FAIR) are under way [26]. The scientific goals concern a large number of the most important aspects of the structure of matter, from the quark-gluon structure of hadrons to structure of hadrons to dynamics of the macroscopic objects in the universe and, related to the various hierarchical levels of matter a number of key aspects of the evolution of the universe.

The FAIR complex will produce the following accelerated beams:

Beam of $^{238}U^{28+}$ ions with the intensity of $10^{12}$ /s and the energy of 1…2 GeV/u.

Beam of protons with the intensity of $4\cdot10^{13}$ /s up to the energy of 30 GeV generating antiprotons.

Beam of relativistic $^{238}U^{73+}$ ions with the intensity of $10^{10}$/s up to the energy of 35 GeV/u.

Beams of radioactive nuclei.

Beam antiprotons with intensity $10^{11}$ /s and energy 3 …15 GeV.

Both primary and secondary beams may be injected into the system rings where they will be cooled, stored and impinge internal and external targets. The rings may be used in the mode of simultaneous distribution of different beams.

With that, the following tasks are proposed:

1. Investigations concerning the nuclei generation which are far from stability; areas of astrophysical processes of nucleosynthesis in supernovaes and other stellar processes and tests of fundamental symmetries.

2. Study of hadron matter at the subnuclear level with antiproton beams in the two main aspects: quark creation and generation of hadron masses. They concern the problem existence (and spontaneous breaking) of chiral symmetry, a fundamental property of the strong interaction.

3. Studying the properties of dense compressed hadron matter in the process of nucleous-nucleous collisions at high energies.

4. Studying of the matter in the state of high-density plasma which is of interest for the process for inertial confinement fusion and astrophysical settings

5. Investigations in quantum electrodynamics in extremely strong (electromagnetic) fields.

The programme of the investigations with beams of heavy ions and antiprotons in the FAIR complex is developed in which evolution of matter in the Universe is followed stage by stage from the moment of the singular explosion, formation of quark-gluon plasma and symmetry violation the formation of dark matter, synthesis of light elements, formation of neutron stars and strange matter, synthesis of nuclear matter in novas and supernovas.

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## МОЩНЫЕ ЛИНЕЙНЫЕ УСКОРИТЕЛИ ПРОТОНОВ И ТЯЖЕЛЫХ ИОНОВ ДЛЯ РЕШЕНИЯ НАУЧНЫХ И ПРИКЛАДНЫХ ЗАДАЧ

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Представлен обзор актуальных проблем, решение которых требует мощных ускорителей протонов и тяжелых ионов. Среди них наиболее важными являются создание эффективной и безопасной ядерной энергетики с неисчерпаемыми ресурсами топлива на базе комплекса линейного ускорителя протонов и подкритического реактора на быстрых нейтронах; создание интенсивных нейтронных генераторов для изучения структуры и динамики конденсированной материи; использование интенсивных пучков протонов для создания фабрик μ-мезонов и нейтрино для физики слабых взаимодействий. Представлен обзор материалов по исследованиям на пучках радионуклидов и тяжелых ионов, ускореных до высоких энергий.

## ПОТУЖНІ ЛІНІЙНІ ПРИСКОРЮВАЧІ ПРОТОНІВ І ВАЖКИХ ІОНІВ ДЛЯ ВИРІШЕННЯ НАУКОВИХ ТА ПРИКЛАДНИХ ЗАДАЧ

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Представлено огляд актуальних проблем, вирішення яких вимагає потужних прискорювачів протонів і важких іонів. Серед них найбільш важливими є створення ефективної і безпечної ядерної енергетики з невичерними ресурсами палива на базі комплексу лінійного прискорювача протонів і підкритичного реактора на швидких нейтронах; створення інтенсивних нейтронних генераторів для вивчення структури і динаміки конденсованої матерії; використання інтенсивних пучків протонів для створення фабрик μ-мезонів та нейтрино для фізики слабких взаємодій. Представлено огляд матеріалів, що відносяться до досліджень на пучках радіонуклідів та важких іонів, прискорених до високих енергій.