DEVELOPMENT OF MHF CONCEPTION AT ITEP

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Abstract

The conception of Multi-purpose Hadrons Facility (MHF) began to be discussed at ITEP in the late ~2010s [1] when ITEP-TWAC facility was intensively exploited for physical and applied research with the use of accelerated proton and ion beams varied in a wide range of operating parameters. Technological developments have continued to expand the scope of beams utilizing in diverse fields of science, medicine, industry and education. The ITEP-TWAC facility was decommissioned in 2012 and continues to remain in a state of waiting for reasonable decision on its recovery and upgrade, but conception of MHF is alive and aims at reviving in ITEP a technological base of particle accelerator technique intended for generation of proton and ion beams, covering the needs of many areas of fundamental, applied and technological research and industrial applications, represents a significant scientific and practical interest for modern and future engineering community. Created MHF environment should obviously be friendly and flexible for collaboration with industry, universities, and other national and foreign labs to provide continuous intelligent and technological progress. The key components of the MHF mission and vision are presented.

INTRODUCTION

The history of accelerator science and technology in our country, spanning more than seven decades, contains many glorious pages of the extraordinary contribution of national research institutions, scientists and engineers in the development and implementation of new ideas and the creation of unique installations.

ITEP is historically related to innovative accelerator center and it has been one of the basic institutions of the accelerator industry which specialized on the technological peculiarities of proton and ion beam accelerators. The ITEP School of accelerator science and technology has a long tradition and is focused on studying, invention, construction, creation, mastering and implementation to operation of equipment, systems and installations providing proton and ion beams for usage in physical experiments and applied research works.

Main accelerator facility of ITEP until 2012 was ITEP-TWAC which decommissioning not only significantly reduced the innovative ability of the Institute in the field of accelerator technology, but also virtually terminated all experimental work with usage of accelerated beams. The creation of MHF as a new generation of accelerator facilities would help to restore and significantly expand the accelerator technological base of the Institute and to bring the possibility of physical experiments and application works in usage of hadrons beams

TRENDS IN ACCELERATOR TECHNIQUE DEVELOPMENT

The project of MHF has to be elaborated on a base of world trends in accelerator development. The main motivation for the promotion of accelerator technologies remains still high energy physics which after the discovery of the Higgs boson has charted new frontiers of research on the accelerated beams in two main ways: the study of the properties of known and search for new particles at increasingly high both energies of interaction and luminosity; precision measurements of known processes to look for possible, tiny deviations from the SM expectations which require primarily high intensity beams [2]. At a time when accelerator projects at the high-energy frontier are experiencing difficulties in gaining financial support, projects at the high-intensity frontier are flourishing worldwide [3].

Super High Energy Colliders

There is international consensus that the priority for the short and medium term future is the full exploitation of LHC, including its luminosity upgrade (project HL-LHC). Two similar projects of colliders are currently being considered: SppC in China and FCC-hh in CERN [4]. The conceptual design for both projects foresees to 100 km ring equipped with 16-20 T magnets, to reach a pp centre-of-mass energy 100 TeV. Two projects of linear colliders being considered are: ILC [5], for which Japans has expressed interest as host country; and the CLIC [6], being developed at CERN. The needed RF gradients is 31 MV/m for 500 GeV ILC and 100 MV/m for 3 TeV CLIC.

High Intensity Proton Accelerators

Proton beam intensity is one of frontiers in advance of physics research including [7]: neutrino experiments (experimental studies of neutrino oscillations and neutrino interaction physics); kaon, muon, nucleon, and neutron precision experiments (studying ultra-rare kaon decays, searching for muon-to-electron conversion and nuclear electron dipole moments, exploring neutron properties at very high precision); material science and nuclear energy applications (critical input into the design of future energy systems, including next generation fission reactors, nuclear waste transmutation systems and future thorium fuel-cycle power systems).

During the past decades, accelerator-based neutron-generating facilities like SNS [8], J-PARC [9], PSI [10] and LANSCE [11] advanced the frontier of proton beam intensity to 1 MW power level. There are a number of different types of accelerators running at 100 kW or more today (TRIUMF, ISIS, FNAL MI, AGS, SPS). Many of these involve rapid cycling synchrotrons (RCS) as part of the acceleration chain. Many of these operate, or have

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operated, as part of a higher energy collider chain. There are two accelerators that operate at the MW level: the PSI cyclotron chain and the SNS linac. Many of the existing accelerators have plans and on-going design for further power increases more than 1 MW: ESS (5 MW, 2 GeV), SPL (4 MW, 5 GeV), Project-X (3 MW, 3 GeV), MYRRHA (2.4 MW, 0.6 GeV), Daejalus (3 MW, 0.8 GeV). Visible trend of reducing the energy of powerful proton beam.

Main Some Key Technical Challenges for high power proton accelerators are: management of beam loss to very low fraction levels and improvements simulations to predict beam behavior to the level $<10^{-6}$; increase gradients in SRF linacs, development of high power coupler, high power RF sources, minimize cryogenic loads; improvement charge exchange injection techniques of ring injection; for ADS high reliability is a major consideration.

High Intensity Heavy Ion Accelerators

Extremely high energies of heavy ions (HI) is achieved in hadron colliders (LHC) in which HI are used in the experiments, a fraction of the time, for colliding with protons [12]. The only collider, specialized for HI, is RHIC operating successfully for over 10 years and continuing to improve their operational parameters [13]. RHIC's main objective is to increase its ability to study quark-gluon plasma and the rare processes associated with it. The project of HI collider NICA, which is realized in JINR, Dubna, complements RHIC in the range of extremely low for the quark-gluon plasma energies [14].

The largest HI project under construction is FAIR [15] that allows acceleration of intense beams of stable elements from protons (30 GeV) to uranium (10 GeV/u) to be used for research in several scientific areas: physics of hadrons and quarks in compressed nuclear matter (CBM experiments); atomic and plasma physics; applied sciences in the bio, medical, and materials sciences (APPA); hadron structure and spectroscopy; strange and charm physics; hypernuclear physics with antiproton beams (PANDA) and the structure of nuclei; physics of nuclear reactions and nuclear astrophysics with RIBs (NuSTAR).

The main purpose of other high intensity HI accelerators is rare isotope production using the projectile fragmentation method (RIKEN [16], FRIB [17], SPIRAL2 [18]). Deuteron beams are effectively used for neutron production (SAFAR [19], IFMIF [20], SPIRAL2). For HI, the power frontier is supposed to be advanced to 400 kW with the construction of FRIB currently underway at Michigan State University [21].

Key Technical Challenges for high intensity HI accelerators includes: High Intensity (CW) and High charge state Ion Source, Superconducting RF, Integrated Cryogenics, Loss Detection and Machine Protection, Collimation, Normal - and Superconducting RFQ, Charge Stripping, High Vacuum, RCS Technology for heavy ions, Accumulator Technology etc.

Accelerators for Applications

About 30,000 accelerators are in use in the world, but only few dozen of them are high energy and used for scientific purposes [22]. All known methods of particle acceleration are used for applied purposes:

Direct Voltage: DC voltage to accelerate either electrons or ions (Dynamitron & Cockcroft Walton generator, energies to 5 MeV and currents up to 100 mA; Van de Graaff, energies from 1 to 15 MeV at currents of a few nA to a few mA; Inductive Core Transformer (ICT), energies to 3 MeV at currents up to 50 mA)

RF Linacs: in a wide range of operating rf frequencies for any charged particles (Electron linacs., standing wave and traveling wave cavities from 0.8 to 9 GHz, energies from 1 to 16 MeV at beam powers to 50 kW.; Proton and Ion linacs, frequencies at 80 to 600 MHz, energies from 1 to 70 MeV at beam currents up to >1 mA)

Circular Accelerators (Betatrons, electron energies to 15 MeV at few kW beam power; Cyclotrons.,ion energies from 10 to 70 MeV at beam currents to several mA; Rhodotrons, electron energies from 5 to 10 MeV at beam powers up to 700 kW; Synchrotrons, electron energies to 3 GeV, proton and ion energies to 300 MeV/u).

Energy, current, and beam power of application accelerators span many orders of magnitude ($10^2 – 10^9$ V, 10^{-8}-10^2 A, 10^{-6}-10^9 W).

Well established commercial applications of accelerators are the following : Proton and C-ion therapy for cancer treatment, medical isotopes, electron microscopes, etc; Ion implantation for semiconductors and materials; Electron beam irradiators and material processing; Production of radioisotopes; Ion beam analysis; Analysis using neutron generators; Non-destructive testing & inspection; Synchrotron radiation application in many areas.

Sales of accelerators for applications in the world is >$5B/yr and growing ~10%/yr in products.

MHF: CONCEPTION

Following the trends of development and use of accelerator technologies in the world, strategic goal of MHF is aimed to revive at ITEP technological base of accelerator science and technique for fundamental and applied nuclear research and innovative development, using beams of protons and heavy ions of intermediate energies. Integration of technological base with educational process will allow to train the skilled workforce for accelerators construction and related technologies development in the future.

The key objectives of the MHF mission and vision are:

- maintenance, improvement and expanding of ITEP accelerator facility infrastructure as the basis of the scientific and technological base;
- fundamental and applied research and technological development using relativistic proton and ion beams with energy to 10 GeV for protons and to 5 GeV/u for ions;
- applied research, technological development and industrial application using proton and ion beams with energy to 1 GeV/u;

- fundamental research and technological development using high power pulsed nuclei beams with energy of <1 GeV/u;
- technological research and development in the field of generation, acceleration, accumulation, cooling, compression, extraction and sharp focusing of high intensity hadrons beams;
- expansion of scientific and educational activity in the areas of nuclear technologies.

The concept is based on the core capabilities available at ITEP and focuses on the multi-purpose use and development of accelerator facilities, highlighting priority and demanded activities, appropriate qualification of staff and infrastructure capabilities, expanding within existing constraints. The main competences required for the implementation of the accelerator projects are: Accelerator Science (beam dynamics, theory, simulation, beam experiments); Technology (proton and ion sources, linacs, RF systems, kickers, ring lattice, beam lines, injection/extraction, correction systems, high vacuum); Engineering (design, construction, integration of electrical, RF, electronics, mechanical, cooling, vacuum systems, etc.); Particle Detectors (advanced detector development, beam test pickups, devices, tools and instruments); Controls (processor control, interlock & DAQ systems, machine adjustment, etc).

MHF: IMPLEMENTATION

The first phase MHF is implemented in the existing infrastructure of the accelerator complex (Figure 1). Five upgraded accelerator facilities will determine the technological capabilities of MHF listed in Table 1.

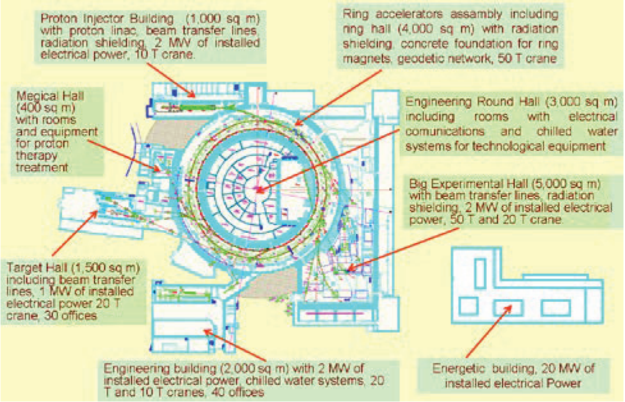

Figure 1: Existing Infrastructure of MHF.

Table 1: Expected Parameters of MHF

Accel. Type	Beam	Beam Duty	Energy MeV/u	Beam Intens., s^{-1}
I2	p	$2x10^{-5}$	25	$2x10^{14}$
I2/U10	p	$4x10^{-6}$;0.3	50-9300	$1x10^{12}$
I2/UK	p	$4x10^{-6}$;0.5	50-3000	$1x10^{12}$
I3M	Fe to U	$1x10^{-5}$	12xZ/A	$(2-8)x10^{9}$
I3M/UK	Fe to U	$5x10^{-6}$;0.5	10-1000	$(1-4)x10^{9}$
I4	d to Fe	$1x10^{-4}$	7	10^{10}-10^{12}
I4/UK	d to Fe	$5x10^{-6}$;0.5	10-1000	10^{10}-10^{11}
UK/U10	C to U	pulse, cw	100-900	to 10^{14} p/p

The MHF project can be built in two phases. The first phase includes the revival of ring accelerators with upgraded injection facility: intensity of proton injector I2 will be increased by order-of-magnitude to $1.2x10^{14}$ s^{-1}; energy of HI in injector I3 will be raised to 12xZ/A MeV (A/Z=3÷10); new injector I4 accelerating ions at A/Z≤3 to 7 MeV/u will be installed [23].

Phase two should advance MHF to the frontier of high intensity hadrons facilities providing a radical increase of the beam intensity and expansion of infrastructure for activation of a new actual scientific research and applications.

Relativistic Proton and Ion Beams

Beams of protons and ions, accelerated up to relativistic energies, can be used for generation of secondary beams on internal targets or directly at slow extraction of particles to the Big Experimental Hall (BEH) in particular, for the previously planned experiments: FLINT - Search for and study of cold dense baryonic matter; EPICURUS - Baryon spectroscopy; FRAGM - Cumulative nuclear fragments [23].

Beams for Applications

Proton and ion beam applications are performed in the energy range from 1 MeV/u up to 1GeV/u in different modes of accelerator facilities operation (Table 2).

Table 2: Use of Beams For Applications

Application	Beam	Accel. Type	Energy MeV/u	Place
Proton therapy	p	I2/UK	50-250	MB
Ion therapy	C	I4/UK	90-400	MB
Implantation	p, P, B	I2, I4	10-25	SI2, SI4
Protonography	p	I2/UK	1000	TH
Rad. effects on Comp and Sys	p, Fe, Ag, U	I2/UK I3M/UK	10-800 90-500	BEH
Radiobiology	p, C, Fe	I2/UK I4/UK	50-250 90-400	MB
Material properties	p	I2	25	SI2
Radioisotopes Production	p	I2	25	SI2

High Power Pulsed Nuclei Beams

A beam of high density nuclei of elements from C to Ni is accumulated and formed in the Ring U10 using technologies of multiple charge exchange injection, stochastic cooling and longitudinal compressing. The beam power of 10^{11}-10^{12} W can be reached at the beam energy ~1 GeV/u in pulse length of (50-100) ns.

Technological Research And Development

Ongoing technological research focuses on the development of promising projects for modernization of existing accelerators and creation of new equipment components corresponding global trends and cardinally expanding experimental and productive possibilities of MHF. The main areas of technological research are the key technical challenges for high power proton and heavy ion accelerators.

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Scientific and Educational Activity

Expanding of educational activity is one of the most important functions of MHF. On the basis of existing relations with Universities (MEPhi, MIPT, MSU) will be established practical classes, engineering and scientific training of: engineers (bachelors, masters) in many fields; physicist-experimenters; medical physicists and radiation therapists for clinics; postgraduate and doctoral students.

The infrastructure of facility allows organizing the work of interns in research groups and collaborations: participation in the creation of installations, in physics experiments, in commercial project.

Scientific and Educational Activity includes lectures, symposia, technical meetings and seminars on issues related to technical and methodological basis of engineering developments, physics experiments and implementation of physical research.

PERSPECTIVES-NEW PROPOSAL

Phase two of the concept will bring MHF to the level of the next generation of accelerator facilities with enhanced functional capabilities allowing a large variety of frontier research in physics and applied science. New 200 MeV/1 mA proton linac I2M, which will be installed instead of existing I2, will be used as the driver injector for the updated synchrotron UK to RCS UKM operated at the rep. rate of 25 Hz and delivering 1 GeV/100 kW proton beam for nuclear physics, neutron and RIB experiments.

Infrastructure

Enhanced infrastructure of MHF (Figure 2) includes the following new buildings :

Proton Injector Building (PIB), reconstructed and enlarged for installation of new proton injector I2M;

Isotope Production Building (IPB) adjacent to PIB;

Neutron Stand Building (NSB) for I2M beam;

Medical Building (MB), reconstructed and enlarged for proton and ion therapy;

Special-Purpose Building (SPB) to be used for testing of radiation effects on components and systems;

Radiation Protected Area (RPA) of BEH.

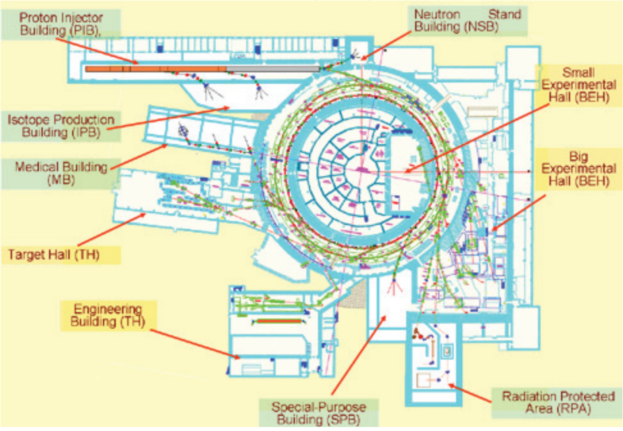


Figure 2: Enhanced Infrastructure of MHF.

High Current Proton Linac-Injector

The driver proton linac I2M (Figure 3) includes duel-beam H^+/H^- injection scheme for the 4 m long, 4-vane, 3MeV RFQ operating at 300 MHz with a high duty factor or in CW mode. The H^+ injector includes a duoplasmatron proton source delivering CW beam current of 1 mA . The H^- beam injector includes a cesiated, multicusp – field, surface – production ion source with beam current ~10 mA at 25 Hz x 500 µsec. pulse length. The MEBT line will transport and match the beam to the DTL which is ~40 m long and accelerates the beam to 80 MeV in five tanks. A FODO focusing lattice is used in DTL assumes permanent magnet quadrupoles.

The rest of the acceleration in the I2M linac will be provided by superconducting cavities. Double spoke cavities [24] can be used to accelerate the beam from 80 MeV to 200 MeV. The most prominent arguments for spoke cavity are large aperture, operational flexibility, high gradient, less real estate, lower operating costs, small wakefields, excellent vacuum, and very high efficiency.

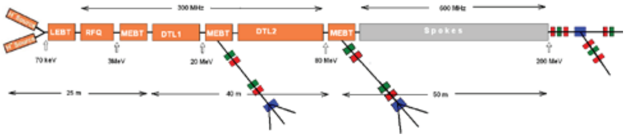
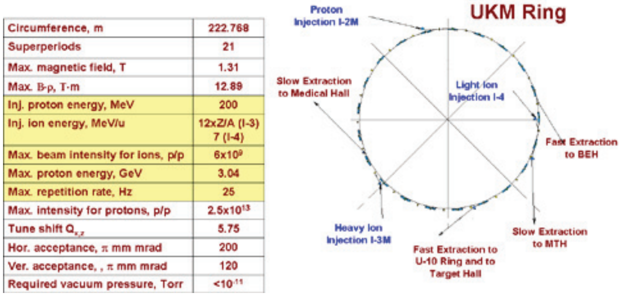


Figure 3: Scheme of proton injector-driver I2M.

The H^- beam from linac is delivered to the RCS UKM injection point, where it is multi-turn charge-exchange injected with a carbon stripper foil.

Rapid Cycling Synchrotron

The UKM (Figure 4) is upgraded synchrotron UK to 25 Hz RCS accelerating proton beam to 1 GeV with intensity 2.5×10^{13} p/p corresponding to the beam power 100 kW. Ceramic vacuum chambers will be used in the RCS dipole and quadrupole magnets, injection bumps and extraction kickers to avoid the eddy current.



Circumference, m	222.768
Superperiods	21
Max. magnetic field, T	1.31
Max. B-ρ, T·m	12.89
Inj. proton energy, MeV	200
Inj. ion energy, MeV/u	12xZ/A (I-3) 7 (I-4)
Max. beam intensity for ions, p/p	6×10^9
Max. proton energy, GeV	3.04
Max. repetition rate, Hz	25
Max. intensity for protons, p/p	2.5×10^{13}
Tune shift $Q_{x,z}$	5.75
Hor. acceptance, π mm mrad	200
Ver. acceptance, , π mm mrad	120
Required vacuum pressure, Torr	$<10^{-11}$

Figure 4: Scheme and parameters of RCS UKM.

Auxiliary Ring

The Ring U-10 will be used as Accelerator–Stretcher–Accumulator (ASA) and equipped with two injection and three extraction systems (Figure 5). The proton beam, injected from linac I2M or UKM Ring can be accelerated in ASA to relativistic energy with following throwing on the internal target or extraction (fast or slow) to BEH. The proton beam in the energy range of 50-250 MeV will delivered at slow extraction to MB. The ion beam injected from UKM Ring can be accelerated up to relativistic energy and extracted to BEH. Using multiple charge

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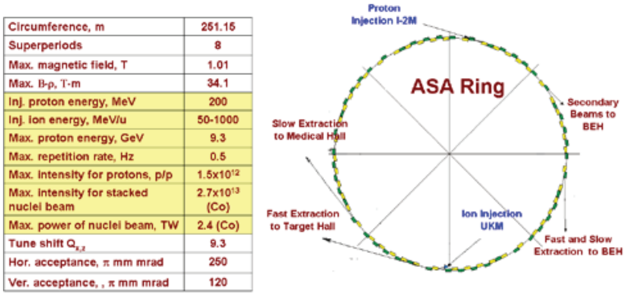
exchange injection technique, the beam of nuclei from C to Ni in the energy range <1 GeV/u can be accumulated and compressed to the extremal power level for extraction to TH. The same technique will be used for stretching of ion beam to duty factor of 1 and slow extraction to MB or TH.



Circumference, m	251.15
Superperiods	8
Max. magnetic field, T	1.01
Max. B-ρ, T-m	34.1
Inj. proton energy, MeV	200
Inj. ion energy, MeV/u	50-1000
Max. proton energy, GeV	9.3
Max. repetition rate, Hz	0.5
Max. intensity for protons, p/p	1.5×10^{12}
Max. intensity for stacked nuclei beam	2.7×10^{13} (Co)
Max. power of nuclei beam, TW	2.4 (Co)
Tune shift $Q_{x,z}$	9.3
Hor. acceptance, π mm mrad	250
Ver. acceptance, , π mm mrad	120

Figure 5: Scheme and parameters of ASA Ring.

Isotope Production

The I2M accelerator will be designed to host six beamlines to IPB for isotope production: three for 40-MeV and other three for 80-MeV beam utilization. Large variety of radio-isotopes can be produced by using the high power accelerator. Among them, F-18 for PET application, Sr-82 to monitor the blood flow in cardiac tissue and can be produced by using RbCl as a target, Cu-67 for cancer therapy and can be produced using ZnO as a target [25].

Proton and C-Ion Therapy Facility

New medical facility will have three treatment rooms and one for research. One treatment room equipped with isocentric gantry for proton therapy. The other treatment rooms for proton and ion therapy and equipped with planar irradiation systems with a dedicated pencil beam scanning nozzle.

The proton beam will be delivered to MB from ASA Ring in the energy range of 50-250 MeV for protons and 100-450 MeV/u for C-ions with high duty factor or CW mode.

Testing of Radiation Effects On Components

Radiation effects on microelectronic components and systems, including single-event upsets in microprocessors will be tested and studied with beams of proton and ions to U delivered to SPB at slow extraction from ASA Ring in the energy range up to 3 GeV for proton, and 100 (U) – 800 (C) MeV/u for ions.

Experiments with an Intense Beam

Accelerators of MHF will deliver for high intensity experiments proton beams with energy 40, 80, 200 MeV and 1 GeV.

Usage area of 40 MeV and 80 MeV proton beams is IPB, where in addition to the isotopes production will be experiments with material neutron irradiation.

The 200 MeV proton beam will be used in NSB for basic energy science and applications.

The proton beam accelerated in UKM up to 1 GeV will be delivered to RPA for experiments with rare isotope beams and study of nuclear structure, reactions and astrophysics.

High intensity beams will be used also for generation data required in applications like the transmutation of nuclear waste (ADS), design of future fission and fusion reactors, nuclear medicine (production of radio nuclei) and biology (cell irradiation), basic data for evaluated data bases.

CONCLUSION

The main goal of the presented concept is to call attention to the absolute necessity of the forced development the accelerator-technological base in the country. Disengagement of Rosatom from the management of the accelerator area in science and industry was a serious mistake that destroyed the Foundation of nuclear energetic of the future, which is impossible without solution to global problems of nuclear safety, transmutation of nuclear waste and closed cycle. The purpose of MHF is to solve these and other problems of nuclear science, and realization of this project at ITEP is a strategically optimal for this time.

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