Institute for High Energy Physics

NRC «Kurchatov Institute»

Facility for Intense Hadron Beams

Protvino, 2013

Contents

This extended Letter of Intent “Facility for Intense Hadron Beams” aims to construct a large World class multipurpose accelerator facility with megawatt power proton beams in the energy range from 100 MeV to 70 GeV.

The new facility will allow to conduct on a multi-user basis a comprehensive research program including study the fundamental properties of matter and also the investigation of substances, materials and object’s properties at nanometer and subnanometer scale.

This revised LoI has been prepared by IHEP, Protvino and collaborating Russian institutes with account for the progress made in 2011–2013.

N.E.Tyurin,

IHEP Director

Introduction

The development of the elementary particle physics was marked by a cascade of discoveries based mainly on the achievements in the accelerator physics and technologies. Discovery of the Standard Model Higgs boson at the LHC is the latest and most publicly known achievement. Today, the accelerators have become the most important tools for both the fundamental and applied studies.

One of the leading tendencies in development of the proton accelerators is increase of the beam intensities (power). There are already running facilities with beam power up to 1 MW, new accelerator facilities with the beam power up to 5 MW are under design and facilities with the beam power up to 100 MW are under consideration. The beam energy of megawatt power facilities varies from tens of MeV to hundreds of GeV. Such facilities are requested by fundamental and applied studies, they enable the development of a variety of innovative technologies during their construction phase as well as in the process of their use.

It is proposed to construct at IHEP the “Facility for Intense Hadron Beams”* yielding megawatt power beams.

The proposal is based on the following design grounds:

- Maintaining the working capacity of the existing 70 GeV accelerator U-70 and continuation of the ongoing projects at IHEP.
- Lowering the technical risks under the project realization, the use of modern but reliable and proven technologies.
- Sectioning the project flow into a few stages with the functional self-sufficiency and readiness for the practical use of each particular stage.
- Integration with the existing infrastructure of IHEP as well as with its research and technical facilities.
- Utmost use of the IHEP staff expertise.
- Consolidation of the Russian Accelerator Laboratories around this megaproject on the basis of their particular scientific and technical expertise and achievements.
- “Open architecture” and the opportunities for the development over a long-term perspective.
- The new accelerator and experimental facilities should become the ones of the common use and should provide with the possibilities to conduct the first class research on a wide spectra of applied and fundamental topics.

The core element of The OMEGA Project is a new cascade of high intensity accelerators with the top proton beam energy of 3.5 GeV. This proposed accelerator facility** will address the two major tasks:

- to provide fundamental and applied research activities with the beams of GeV energy range and the beam power above 1 MW;
- to inject the higher intensity proton beams into the U-70 accelerator to be further used for fundamental research in particle physics.

The OMEGA Project also foresees construction of the pulsed spallation neutron source utilizing the 3.5 GeV and 1.1 MW proton beam (the study of biological structures, nanostructures, substances, materials, objects). The potential of neutron studies with high intensity spallation source make The OMEGA Facility complementary to the synchrotron radiation facilities thus providing unique opportunities for a comprehensive research.

Moreover, such a proton beam can be used for investigations in the field of nuclear physics, radiation material science, to study accelerator driven subcritical systems, to produce isotopes and also to study the fundamental processes using neutrons, kaons, pions, muons and neutrinos (Figure 1).

Higher energy and higher intensity of the protons injected into the existing U-70 accelerator from the U-3.5 will result in a record intensity of the 70 GeV protons and, respectively, will create the new possibilities for the fundamental studies as well as open an opportunity for the future use of the UNK infrastructure. Construction of the new accelerator complex will allow to further optimize the existing U-70 injection chain consisting of the linac I-100 and the 1.5 GeV booster synchrotron for the operation with the light to medium nuclei.

Realization of The OMEGA Project will provide the scientific community with the unique experimental facility and the innovative technologies at every particular project stage. The proposed facility will become the largest center for the common use in Russia. It will allow the experts from various fields of science to conduct advanced research programs. The construction of such a front level facility will stimulate the development of a wide spectrum of advanced scientific investigations and technologies. Being one of the most advanced facilities (Figure 2) it should attract the experts from Russia and other countries.

** The conventional project name is “The OMEGA Project”*
*** In what follows the use is made of the conventions:*
- **Facility for Intense Hadron Beams - The OMEGA Project**, *includes «everything» (accelerators and high intensity beams and n-source)*
- **Complex of high intensity accelerators** *– includes LU-400 and U-3.5 machines*
- **U-70 Accelerator** *– 70 GeV proton synchrotron with the existing injection from the 1.5 GeV booster fed by the protons from the 30 MeV RFQ linac URAL-30*

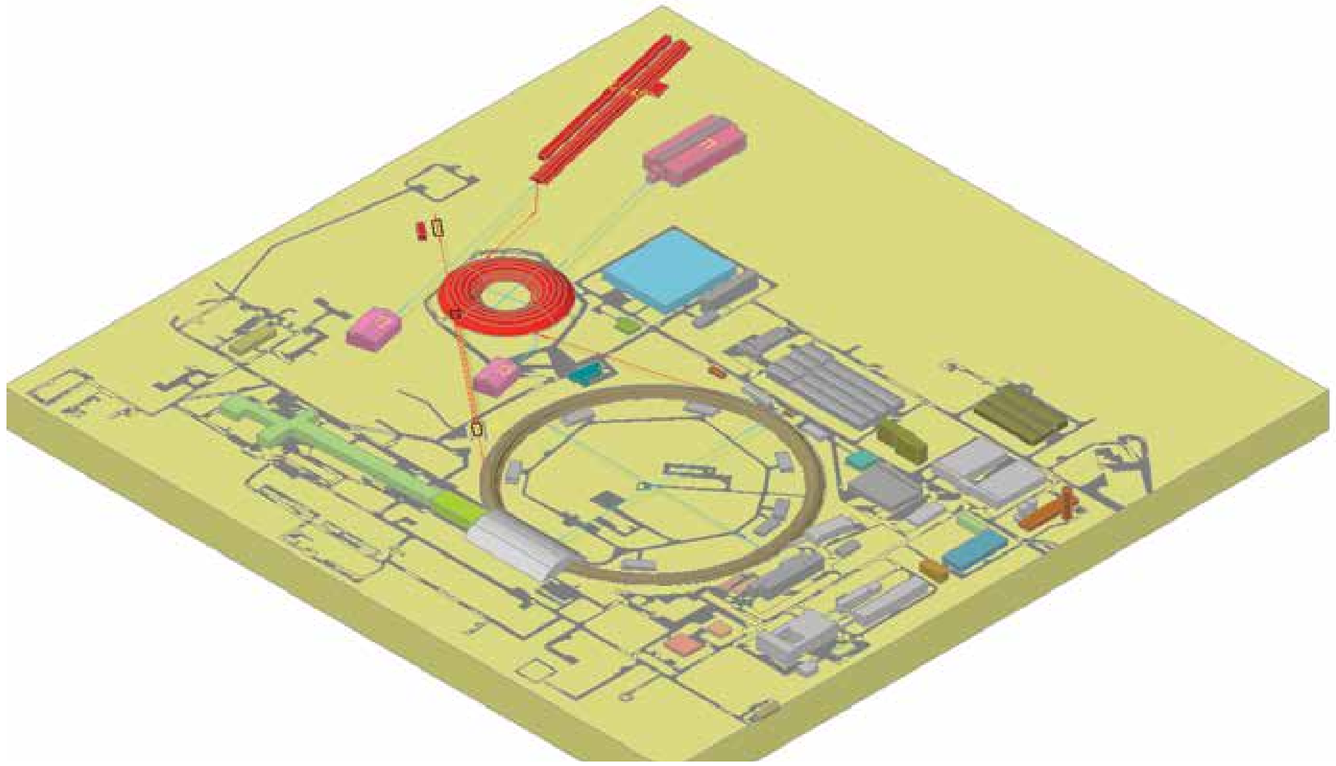


Figure 1. Location of the Facility for Intense Hadron Beams.
It is located in north-western part of the IHEP site:
1 – linear accelerator LU-400 (red color);
2 – rapid cycling synchrotron U-3.5 (red color);
3 – neutrino beam (red color);
4 – T1 – the neutron source target and experimental hall (pink color);
5-6 T2 and T3 – areas for experiments with high intensity beams (pink color);
7 – Existing building (blue color) is to be used for the technical support. Light-gray and yellow colors mark the existing infrastructure. In the center – the U-70 ring.

The IHEP territory is suggested as a construction site for the new megaproject. This particular choice is determined by the following arguments:

- IHEP staff has a significant and unique expertise in construction, operation and development of large accelerator facilities in Russia;
- IHEP has in some cases unique technological and production potential;
- IHEP has a well-developed engineering infrastructure, including the electrical power supply network;
- The IHEP location is convenient for a wide participation of Russian and foreign users;
- IHEP has a sufficient territory for accommodation of the new facility;
- IHEP has a longstanding experience in the international cooperation;
- The OMEGA Project will allow to extend the potential of the existing U-70 accelerator (synergy effect);
- The OMEGA Project opens the perspectives towards the future use of the UNK infrastructure.

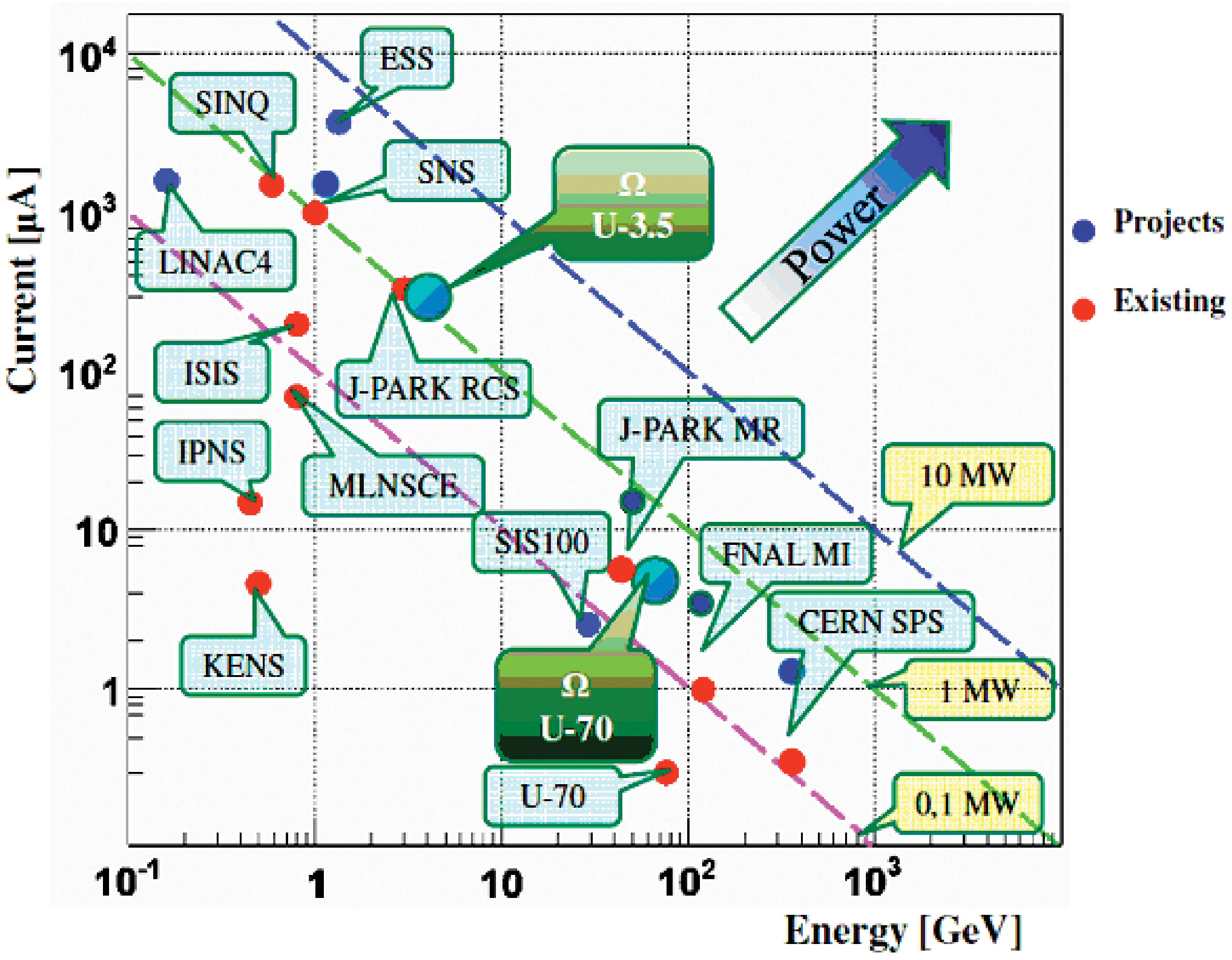


Figure 2. Parameters of high-intensity proton accelerators.
Dashed lines mark the levels of definite power. By this parameter, most important for many tasks, the proposed project (RC PS U-3.5) will surpass the existing facilities.
Two points are indicated for The OMEGA Project (Ω):
– rapid cycling synchrotron, E=3.5 GeV, I= 300 μA (W=1.1 MW)
– existing U-70 accelerator with injection from the new complex, W=0.45 MW

Owing to its immensity and complexity, the proposed project is expected to involve the major Russian accelerator laboratories, the specialized technological and manufacturing enterprises as well as foreign scientific centers interested in the project.

This document is divided in few sections. In Section 1 the main parameters of the existing IHEP accelerator complex and a number of U-70 ongoing projects are presented. In Section 2 the basic parameters of the proposed high intensity accelerator complex are specified. In Section 3 the perspectives of the experiments at U-70 accelerator with the increased intensity are presented. In Section 4 the principal fundamental and applied research directions with the intense proton beams at the energies up to 3.5 GeV are described.

Other sections of the document provide the cost estimates, preliminary schedule and further development perspectives.

In the process of subsequent detailed study certain priorities are to be adopted for the listing of possible research directions presented in Sections 3 and 4.

1. The U-70 Accelerator

In this Section, the main parameters of the existing IHEP accelerator complex are specified and an overview of the ongoing projects is presented.

1.1 Basic Parameters

At present, the accelerator complex U-70 of IHEP consists of four accelerators connected in a cascade and one linear accelerator running in a stand-alone mode. The list of the machines is presented below:

- The 30 MeV RFQ DTL proton linear accelerator (linac) URAL-30 – the regular proton injector;
- The Alvarez DTL linac I-100 – the 16.7 MeV/nucleon light-ion and/or backup 72.7 MeV proton injector;
- The rapid cycling booster synchrotron U-1.5 with a top magnetic rigidity 6.9 T·m;
- The main ring synchrotron U-70 with a top magnetic rigidity 233 T·m.

The new 30 MeV proton linac URAL-30M, the supposed successor to the URAL-30, is housed on a separate site and is operated in a pre-commissioning regime.

Layout of accelerators is shown schematically in Figure 1.1. Their parameters are listed in Tables 1.1 and 1.2. Alvarez linac I-100, the former proton-injector to the U-70 since its early days till 1985, is back on service since October 2007. It is now operated as either a light-ion or a backup proton injector feeding the intermediate booster U-1.5 ring.

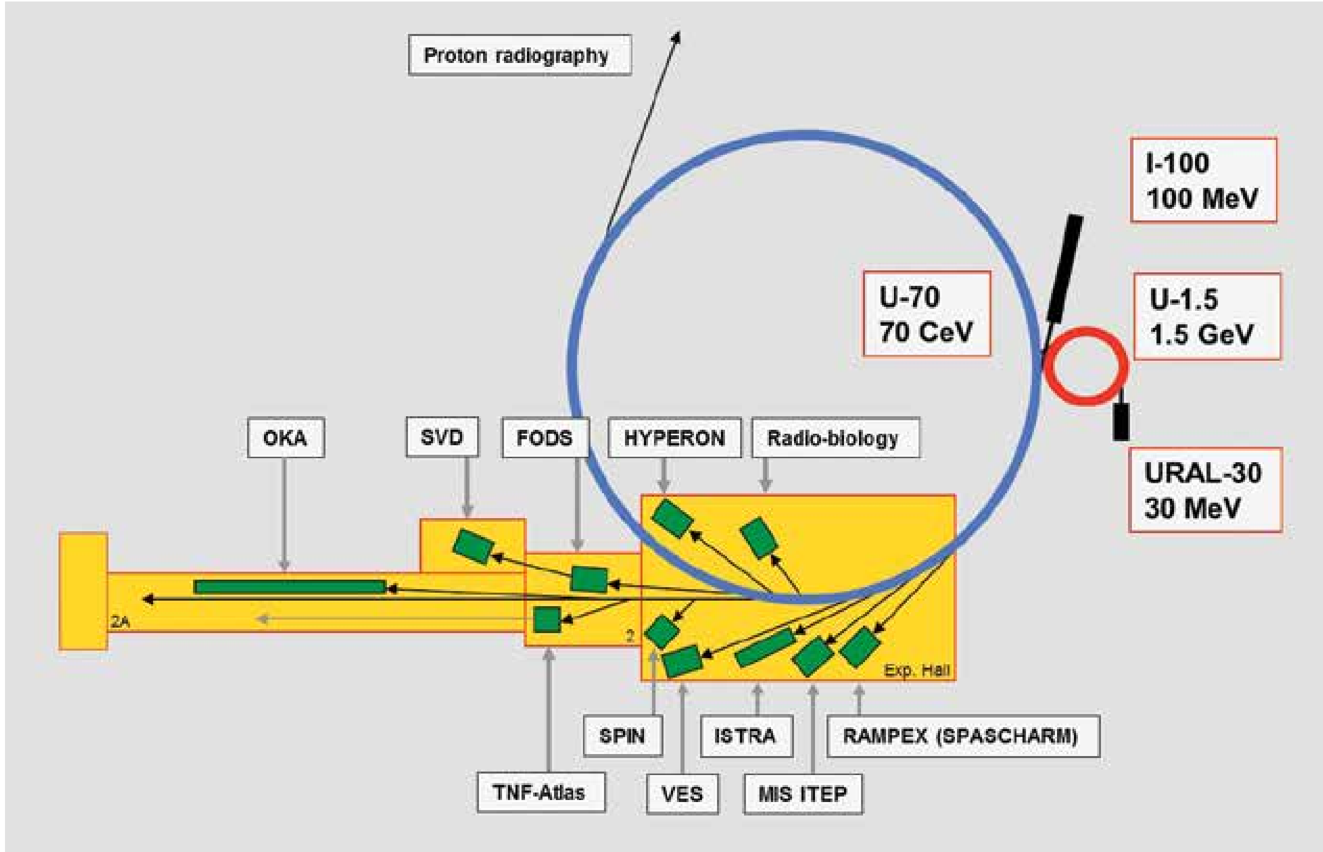


Figure 1.1. Experimental complex of IHEP: accelerators, beam transfer lines and experimental facilities

Major efforts during the accelerator operation are invested to attain the three goals:

1. To ensure stable operation and high beam availability during the regular machine runs.

2. To improve proton beam quality (by providing lower emittances and higher intensities, up to $3 \cdot 10^{13}$ protons per cycle).

3. To implement gradually a program to accelerate light ions with a charge-to-mass ratio q/A = 0.4–0.5.

Generally, the trend is to convert the largest national facility U-70 into a universal hadron accelerator for ongoing applied and fundamental fixed-target research.

Table 1.1. Proton synchrotrons specification

	U-1.5	U-70	
Energy, E (protons)	0.030–1.32	1.32–69	GeV
Orbit length, L	99.16	1483.699	m
Curvature radius, ρ	5.73	194.125	m
Magnet rigidity, $B\rho$	0.80–6.87	6.87–233	T·m
Compaction factor, α	0.07235	0.011120	
Intensity, N	$2–9 \cdot 10^{11}$	$1.7 \cdot 10^{13}$	ppp
Ramping time, t_R	0.030	2.75	s
Cycle period, T	0.060	9.77	s
RF harmonic, h	1	30	
Radio frequency, f_{RF}	0.75–2.75	5.52–6.06	MHz
RF voltage, V_{RF}	6–60	190–300	kV
Lattice period	MFDFM	FODO	
Number of periods	12	60	
Number of superperiods	12	12	
Betatron tunes (H/V)	3.85/3.80	9.9/9.8	

Table 1.2. Proton linear accelerators specification

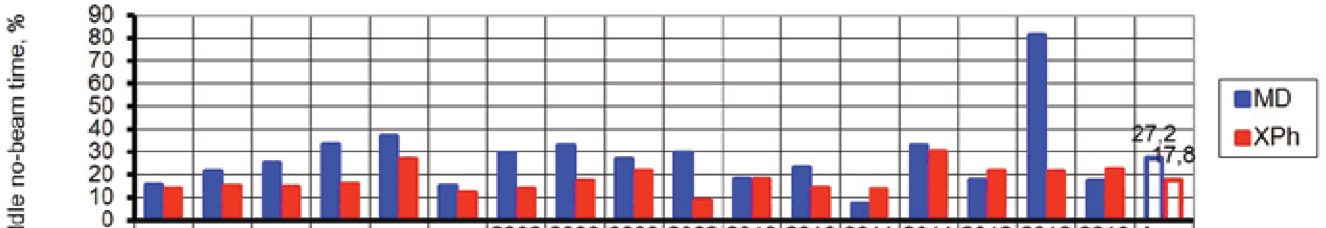
	URAL-30	I-100	
Type	RFQ DTL	Alvarez DTL	
Energy, E (protons)	0.1–30	0.7–100	MeV
Length, L	25.3	79.4	m
Radiofrequency, f_{RF}	148.5	148.5	MHz
Pulsed current, I	70	100	mA
Pulse length, t_{Pr}	1–10	12–40	µs
Cycle period, T	0.060	1–5	s
Sectioning	5	3	

The U-70 accelerator complex is used to run twice a year up to 1500 hr per run. Dedicated machine development (MD) activity takes a week prior to delivering beam to the experimental facilities.

Usually, the top energy is about 50 GeV. It is a compromised value, which is acceptable to users and noticeably minimizes electrical power consumption (–20%) thus making the runs more affordable in cost.

Figure 1.2 shows beam availability data during dedicated machine development activity (the MD columns) and runs for a fixed-target experimental program (XPh columns). The averages over 2002–2013 are also presented. Experimental facilities acquire the beam with a fractional availability of 82–83%, which corresponds to the world standards and is an outcome of an intensive routine maintenance carried out during shutdowns.

Operational parameters of the U-70 accelerator complex are getting better. The implementation of a slow stochastic extraction of protons (extraction time 2–3 s, intensity up to $1 \cdot 10^{13}$ protons per a spill) and acceleration of carbon ions to a specific kinetic energy of 23.1-34.1 GeV per nucleon constitute the latest achievements worth mentioning.



	2002	2003	2004	2005	2006	2007	2008 -1	2008 -2	2009 -1	2009 -2	2010 -1	2010 -2	2011 -1	2011 -2	2012 -1	2012 -2	2013 -1	Avrg %
MD	15,6	21,1	25,1	33,4	36,7	15	29,1	33	27	29,8	18,2	23,1	7,1	32,7	17,7	81,4	17,1	27,2
XPh	13,9	15,1	14,8	15,9	26,8	11,9	13,9	17,4	21,6	8,9	18,2	14,3	13,6	30,3	21,7	21,3	22,4	17,8

Run

Figure 1.2. Beam availability statistics

The present-day experimental program is focused on the following topics, in which the U-70 beam parameters allow to obtain valuable results of the world class:

- charged-kaon rare decays;
- hadron spectroscopy;
- physics of spin effects;
- hadron-nuclei interactions.
- high energy nuclear physics.

On top of it, an applied research is performed with the accelerator facility including proton radiography.

1.2 Upgrade Plans

RF accelerating system of the U-70 synchrotron

The development of compact and more powerful accelerating stations will allow to reduce their number by a factor of two and, therefore, to get some additional space for other equipment required for the machine development. Moreover, the upgraded system will allow accelerating the beams with a higher intensity.

Going to the up-to-date generating tubes will save the operational expenses. At the same time, it is planned to increase the equipment reliability, to switch to the modern components of low-level electronics, and to fully automate the accelerating system.

Vacuum system of the U-1.5 and U-70

In order to decrease the proton beam losses and to increase the lifetime of multi-charged ions the vacuum has to be improved down to $0.8 \cdot 10^{-8}$ Torr. For this purpose, the system of fore pumping will be equipped with oil-free turbo-molecular pumps and spiral fore-vacuum pumps. The system of vacuum diagnostics will be supplied with universal vacuum gauges operating at the pressure from $1 \cdot 10^{-3}$ to $1 \cdot 10^{-11}$ Torr. Vacuum joints will employ metal seals. The internal targets and bent-crystal deflectors will be removed from the ring vacuum volume.

Power supply systems of the ring magnets

Booster U-1.5. The main power supply system of the U-1.5 accelerator ring magnet includes the storage bank of capacitors, charging unit, re-feed rectifiers, high power switching devices, system of pulsed interference filtering, stabilization and control systems. These systems will be equipped with modern components. That will allow removal of the ecologically destructive capacitors, decrease of the power-supply ripples and optimization of the control of magnet cycle parameters.

Synchrotron U-70. The new power supply system of the U-70 is under construction now, it is to be ready for operation in the beginning of 2014. This new system should avoid the shortcomings of the old one which used the motor-generators with kinetic energy storage units (massive flywheels).

Experimental Areas Development

The beamline system of the U-70 includes the beams operating from internal targets and the extracted ones. Planned increase of the proton beam intensity requires essential reconstruction of the existing beamlines. The main trends of such reconstruction are:

- to exclude the internal targets; to develop beamline system fed exceptionally with the extracted proton beam;
- to increase the efficiency for accelerated proton beam usage by increasing number of simultaneously operating experimental setups;
- to use the existing experimental areas for construction of the new beamlines for advanced fundamental and applied researches.

Proton radiography

Protons as the probing particles can be successfully used to study material characteristics at extreme conditions and the structure of thick systems or objects.

Proton accelerator with the energy of 70 GeV and well-developed beam extraction system allowed IHEP and RFNC-VNIIEF to create jointly the unique facility to test the objects of any practically required thickness with the proton radiography technique. Priority experiments at this pilot facility allowed to justify effectiveness of the proton radiography method.

Nowadays the new full-scale facility is under construction. The planned increasing intensity and improving the U-70 proton beam parameters will open the new possibilities to increase the number of frames and exposure time. It will widen the range of proton radiography applications under the study of the fast processes and internal structure of the objects.

Ion beams for radiobiology

The radiation therapy with carbon ions having advantage of the spatial dose distribution allows maximal selectiveness of irradiation. At the same time this method has the advantages of dense ionizing radiation providing the effective treatment of the radioresistant tumors and other neoplasms insensitive to the traditional kinds of irradiation. During the last few years Institute for High Energy Physics (IHEP, Protvino, Moscow region) and The Medical Radiological Research Center (MRRC, Obninsk, Kaluga region) have developed the project of the Center for Ion Beam Therapy (CIBT).

The parameters of the IHEP accelerator complex and the abilities to form carbon ion beams are in conformity with this task.

In order to create the medical-quality ion beams as well as conditions for their usage at IHEP, Protvino the following accelerator components and the infrastructure elements are required:

- laser source of carbon ions (exists);
- linac I-100 accelerating carbon ions (exists);
- beam line for ion beam transportation from I-100 to the booster (exists);
- injection system to accommodate the ion beam into the booster (exists);
- circular accelerator-booster U-1.5 (exists);
- synchrotron U-70 operating in a storage mode (exists);
- extraction system for the beam from U-70 (exists);
- head part of the beam line (exists);
- beam lines to deliver carbon ions to treatment canyons (to be installed);
- treatment canyons for patient irradiation (to be installed);
- medical infrastructure (~3000 m^2) (to be prepared).

The majority of the above items are already parts of the accelerator complex or were commissioned in 2010–2013. This project could be realized within 3 years after getting support. It will provide:

- creation of the pilot Russian medical facility with the use of carbon beams, getting an extensive radiobiological and clinical experience and development of the carbon ions therapy technique with start of the patients treatment;
- training the radiation oncologists for the future hadron therapy centers elsevere.

2. High Intensity Accelerators to be Developed

The complex of high-intensity accele-rators comprises a linear accelerator of H-minus ions and protons with the energy of 400 MeV followed by a rapid cycling synchrotron with the energy of 3.5 GeV.

2.1. Linear Accelerators

In this Section, the general layout of linear accelerators is presented. The requirements for accelerating structures are specified and the parameters of these structures are given.

The outlook for the facilities is elaborated proceeding from analysis of existing and future high-current linacs such as MEGAN, LINAC4, ESS, LAMPF, J-PARC and others. Outcomes of the preliminary R&D followed by a few dedicated workshops attended by experts from IHEP, INR, ITEP, MEPhI, VNIIEF are taken into account as well.

The sectioning adopted for the LU-400 machine foresees use of proper accelerating structures compliant with the energy range involved.

Beam capture from the ion source, its fore-focusing and subsequent acceleration to a few MeV could be best accomplished with an RFQ section based on a spatially uniform RF quadrupole focusing concept co-invented in IHEP.

Next section to follow could be based on a spatially periodic RFQ focusing structure (RFQ DTL) which is anticipated to be more efficient than a conventional Alvarez DTL structure to 18 MeV. The Alvarez DTL itself is well applicable further, to about 100 MeV. For still higher energies, coupled-cell drift-tube structure (CC DTL) would be used.

Operational frequencies of the structures in question are different, all still being multiples of a common base frequency. To this end, the LU-400 linac comprises:

- The Initial Part of Accelerator (IPA in short) to 2 MeV and operational frequency *f*;
- The 1st main Part of Accelerator (MPA-1) to 18 MeV driven at frequency *f*;
- The 2nd main Part of Accelerator (MPA-2) to 100 MeV driven at frequency 2*f*;
- The 3rd main Part of Accelerator (MPA-3) to the ultimate 400 MeV driven at a frequency 6*f* (optionally 2f).

The selection of base frequency is dictated by a commercial availability of high-power RF generating devices operational under heavy duty factors. The most promising option if to employ THALES TH2179 klystron with the operational frequency 2*f* = 352 MHz. In this case, operation of the IPA and MPA-1 at *f* = 176 MHz could be provided by the home-made GI-54A and GI-71A tubes while operation of the MPA-3 at 1056 MHz could be ensured by the updated home-made klystron KIU-40.

Initial part of accelerator (IPA)

As an initial (front-end) part of accelerator with the energy of several MeV, the structure with spatially-homogeneous quadrupole focusing (RFQ) developed in IHEP is used. The main tasks of this structure are to capture, to bunch adiabatically and to focus the beam. The inner electrodes constitute the four-wire long transmission line with a specifically modulated distance from beam axis to electrode surface along the line (Figure 2.1a). Electrodes are mounted into the cavity with a longitudinal magnet field. The EM-fields have a quadrupole symmetric distribution in transverse plane near the axis. Figure 2.1b shows the cross-sections of cavities of 2H-type used in IHEP.

Figure 2.1a. Electrodes of accelerating structure with spatially-homogeneous quadrupole focusing (RFQ)

Figure 2.1b. 2H-cavity (IHEP)

For any feasible choice of the cavity design, the general parameters of initial part of accelerator (IPA) will have:

- Operating radiofrequency 176 MHz
- Input energy 0.1 MeV, output energy 2.0 MeV
- Maximal field strength on the surface ≤ 2 Eк (Kilpatric)
- Structure length ≤ 4 m

Main part of accelerator (MPA-1) RFQ DTL

The relevant accelerating structure period consists of accelerating and focusing gaps separated by an intermediate (spacer) electrode (Figure 2.2a).

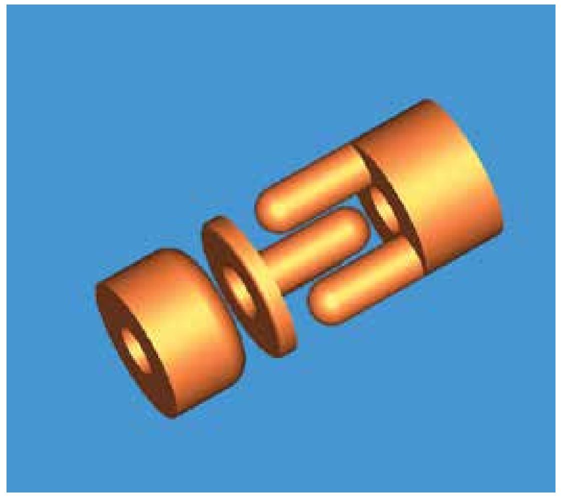


Figure 2.2a. Electrodes of accelerating period with spatially-periodic quadrupole focusing (RFQ DTL)

Figure 2.2b. 2K-cavity

As a result of the analysis of spatially-periodic quadrupole focusing, an RFQ DTL with a 2K-cavity design was chosen. Its main parameters are:

- Operating radiofrequency 176 MHz
- Input energy 2 MeV, output energy 18 MeV
- Maximum field strength ≤ 2 Eк
- Number of sections 3
- Structure length up to 13 m

MPA-2 Alvarez

For further acceleration to the energies above 18 MeV, Alvarez accelerating structure becomes more efficient (Figure 2.3).

The structure consists of a sequence of drift tubes placed onto the axis of a cylindrical cavity excited at oscillation type E_{010}. The voltages across the adjacent accelerating periods are driven in-phase, i. e. the structure operates at the 2π-mode. Focusing is accomplished by means of lenses inside the drift tubes.

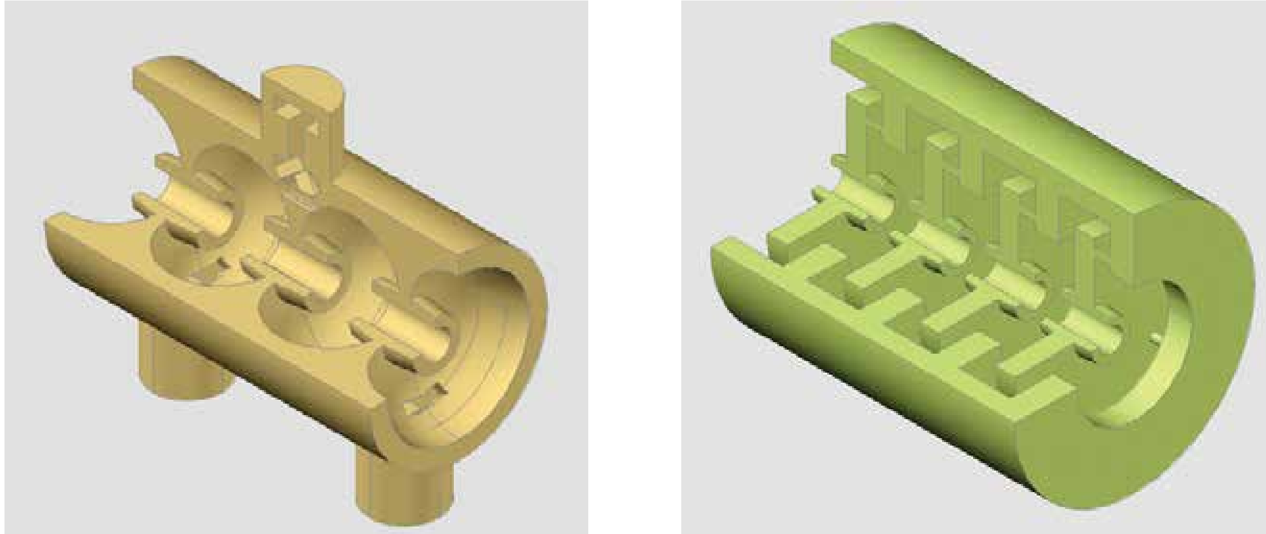
Figure 2.3. Main part of accelerator MPA-2 (Alvarez)

The basic parameters of MPA-2 Alvarez (DTL):

- Operating radiofrequency 352 MHz
- Input energy 18 MeV, output energy 100 MeV
- Maximum field strength on the surface ≤ 1.7 Eк
- Acceleration rate 2.5 MeV/m
- Structure length up to 30 m
- Number of sections 4
- Internal diameter of cavities ~ 0.6 m
- Focusing – electromagnetic or PM lenses

MPA-3 Coupled Cavity

The bi-periodic structures operating at the $\pi/2$ mode are planned for acceleration above 100 MeV. Figure 2.4 shows the geometry of such bi-periodic structures. In LINAC4 accelerator (CERN), the structure with side coupled cavities is used (Figure 2.4a). In the MEGAN accelerator, the structure with washers and diaphragms is used (Figure 2.4b). Both these structures can be employed for the accelerator in question.



a *b*

Figure 2.4. Main part of accelerator MPA-3 (CC DTL): Coupled Cavities

The basic parameters of MPA-3 (CC DTL) Coupled Cavities:

- Operating radiofrequency 1056 (176×6) MHz
- Input energy 90 MeV, output energy 400 MeV
- Maximum field strength on the surface ≤ 1.7 Eк
- Acceleration rate 1.4 MeV/m
- Structure length ~ 250 m
- Focusing – electromagnetic lenses between the sections

Structure scheme of the linear accelerator

Figure 2.5 shows the structure scheme of the linear accelerator consisting of the accelerating sectors described earlier. The accelerator will have the following design parameters:

- Average current of hydrogen ions not less than 1 mA
- Duty factor in beam current ~ 1/40
- Duty factor in RF-pulses ~ 1/10
- Output energy 400 MeV
- Normalized emittance 2–3π mm×mrad

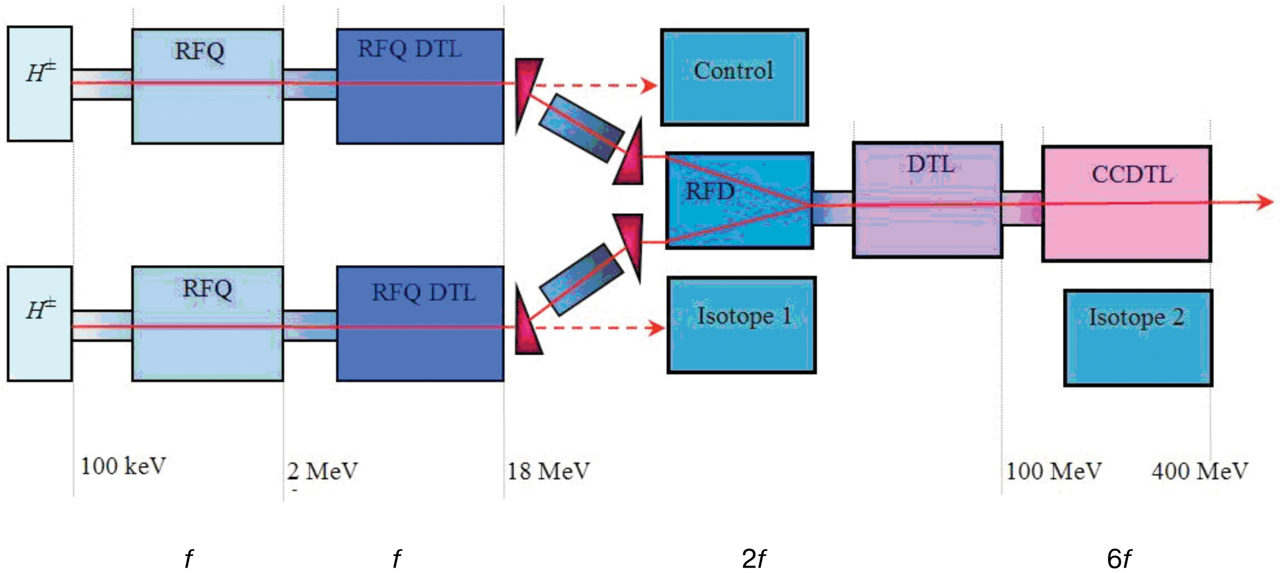


Figure 2.5.
Structure of the linear accelerator

Both IPA and MPA-1 operate at radiofrequency value of 176 MHz. Operating frequency of MPA-2 with Alvarez structure is twice higher, 352 MHz. That makes the Alvarez structure more suitable for operation under a heavy duty factor mode. In order to fill one missing (empty) period of RF oscillations during the acceleration in MPA-2, it is proposed to merge at the MPA-2 input two beams from the two identical accelerators IPA and MPA-1 operating in a counter-phase regime. In this case, both the current and power of the beam at the output of MPA-2 are doubled. The beam funneling is accomplished by means of RF cavity deflector providing parallel beam transfer. Such a scheme of beam funneling provides the minimum blow-up of beam emittance. Figure 2.6 presents radio technical model of RF deflector built on 2K-cavity operating at frequency 148.505 MHz.

Figure 2.6. “Cold” (radio technical) model of cavity deflector on a test bench

Acceleration to the energies above 100 MeV is accomplished by means of the structures with coupled cavities driven at the sixth harmonic of driving radiofrequency, at 1056 MHz. Separate sections of the accelerator are connected with the matching beam lines containing lenses, diaphragms, correctors and other elements of beam matching and diagnostics. The chopper, fast enough to affect individual bunches, is placed between IPA and MPA-1.

Source of H-minus ions

The important dedicated question is the hydrogen ion source which is able to operate in a high duty factor mode.

The preferable option for the H-minus ion source is a surface plasma source with Cesium. The R&D and operational expertise is available at INR RAS which proposed to develop such a source whose layout also incorporates:

- A subsystem to eliminate leakage of Cesium to the accelerating structure downstream,
- A vacuum pumping sub-system equipped with a fore-vacuum and high-vacuum turbo molecular pumps, say, of Scrollvac and MAG types;
- A control system,
- Electric power supply and other technological sub-systems

Estimation of power supply parameters for the linear accelerator

The estimation of power consumption parameters was carried out for the two options of the linac design taken into account. In version of the first stage A) – construction of accelerator without beam funneling — we assume the following output beam parameters: rate of current pulse repetition 25 Hz, pulse duration 300 µs, pulsed current 40 mA, average current 0.3 mA, duty factor in current 1/133, duty factor in RF pulses 1/33. In the second stage B), the scheme of beam funneling is accounted for. For this option, we have calculated the estimation for average current at the linac output 2 mA at duty factor in current 1/40 and duty factor in RF pulses 1/10.

According to this estimation power consumption of the linac is limited to an acceptable level < 10 MW. That is why it is not advisable to use superconducting structures for LU-400. Indeed, construction of superconducting linac will require more efforts for research and development and more expenses and time for the construction.

2.2. Rapid Cycling Proton Synchrotron

Basic parameters

Rapid cycling proton synchrotron U-3.5 operates as:
1. A driver for a *n*-generating target;
2. A new ring injector to the U-70.

The main parameters of the facility are specified in Table 2.1.

Table 2.1. Basic parameters of the proton synchrotron U-3.5

Accelerated particles	protons	
Orbit perimeter, Π	445.110 or 3/10	m Π of U-70
Energy of injection-extraction (kinetic), *E*	0.4–3.5	GeV
Magnetic rigidity, $B\rho$	3.183– 14.470	T·m
Period of beam rotation around orbit	2.082– 1.519	µs
RF harmonic number, *q*	9 or 3/10	*q* (U-70)
Cycle frequency, f_c	25	Hz
Form of magnetic cycle, $B(t)$	∝	$\cos(2\pi f_c t)$
Rate of magnetic field growth, max $dB(t)/dt$	58.0	T/s
Beam intensity (in 9 bunches), *N*	$7.5{\cdot}10^{13}$	protons per cycle
Average (over cycles) beam current	300	µA
Beam power on external target	> 1.0	MW

Later on, the perimeter Π might be varied by some ΔΠ in order to provide the reciprocal slippage of beams with equal energies rotating in the U-3.5 and U-70 rings to facilitate the proper beam transfer synchronization.

The large synchrotron U-70 receives up to 3 cycles of injection from the U-3.5. Beam structure in the U-70 (Figure 2.7) is:

3 × (9 filled buckets + 1 empty bucket) = 30, RF harmonic number of U-70.

From 1 to 3 trains of bunches are accelerated in the U-70. The empty buckets are used to accommodate the rise and decay fronts of pulsed injection magnet (to be developed anew). The beam gaps would also ensure the better coherent stability of intense beam in the U-70.

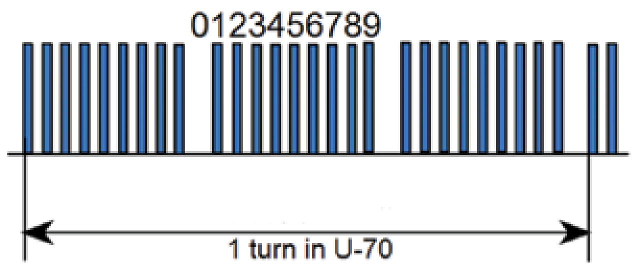


Figure 2.7. Beam structure in the U-70 with injection from the U-3.5

Injection and Coulomb tune shift

Here and in what follows, the emittance and acceptance are defined as the products of semi-axes of a phase ellipse, without factor π. The project beam parameters at exit from the linear accelerator are listed in Table 2.2.

Table 2.2. Parameters of beam at the exit from linear accelerator.

Energy (kinetic), *E*	400	MeV
Energy spread, ΔE (±3σ)	±1	MeV
Fractional momentum spread, $\Delta p/p_0$ (±3σ)	±4.9	$\cdot 10^{-3}$
Transverse normalized emittance at 1σ level, $Э_x = Э_y$	2–3	mm×mrad

Given 40 mA pulsed beam current of negative hydrogen ions H^- from the linear accelerator, the stripping multi-turn injection will take over 145 beam turns around the U-3.5 ring (0.3 ms). During injection, the controlled painting of transverse phase planes will be accomplished. After that, the normalized beam emittances (at 1σ level) will amount to:

$Э_x = 30$ mm×mrad, $Э_y = 10$ mm×mrad.

Momentum spread of the bunched beam will increase by a factor of around 2.5 to

$\Delta p/p_0 = \pm 12\times10^{-3}$ (at ±3σ level) or $\sigma p/p_0 = 4\times10^{-3}$ (at 1σ).

Coulomb tune shift of betatron oscillations is maximal vertically and is equal to

$$\Delta Q_y \cong -\frac{r_0\, N/q}{2\pi B\, \beta\gamma^2 Э_y}\,\frac{1}{\left(1+\sqrt{\dfrac{\langle\beta_x\rangle}{\langle\beta_y\rangle}\,\dfrac{Э_x^{(eff)}}{Э_y}}\right)}.$$

Here, r_0 is classical radius of a proton, *N* is number of particles in accelerator; $q = 9$ is RF harmonic number; *B* is bunching factor; β and γ are relativistic factors. $Э_x^{(eff)}$ is the effective normalized emittance (at 1σ) taking into account the addition of dispersive contribution to horizontal beam size. At the top project beam intensity $N = 7.5{\cdot}10^{13}$ protons per cycle one obtains the acceptable values of Coulomb tune shift of the betatron oscillations

$\Delta Q_y = -0.15$, $\Delta Q_x = -0.08$.

The betatron sizes of a beam are determined by its non-normalized (geometric) emittance $\varepsilon = Э/\beta\gamma$. Since at injection the product $\beta\gamma = 1.017$, with a sufficient accuracy one takes

$\varepsilon_x = 30$ mm×mrad, $\varepsilon_y = 10$ mm×mrad.

Accelerating system

The radiofrequency changes in the range of 4.322–5.925 MHz during the acceleration. This frequency range is well explored at the U-70 operation.

The magnetic guide field ramps according the sinusoidal law. The required total amplitude of the accelerating field V is then

$$\max V = 2\pi \frac{E_0}{e} f_C \frac{\Pi}{c} \frac{1}{\cos\phi_s}\left(\frac{\max\beta\gamma - \min\beta\gamma}{2}\right),$$

where E_0 is rest energy of a proton; e is elementary charge; c is velocity of light; max $\beta\gamma = 4.623$; min $\beta\gamma = 1.017$; and ϕ_s is a stable (synchronous) phase angle.

Given the acceptable value $\phi_s = 55°$, one gets max V = 687.9 kV. On taking into account the operational safety factor, the value is increased to max V = 720.0 kV per turn.

Using up-to-date and proven technologies (2-gap ferrite-loaded cavities) one can expect for the voltage V_1 = 20 kV per one RF station within an overall flange-to-flange size < 2.5 m. The project calls for 36 such accelerating stations. Their number is chosen to be an integer multiple of 6, the superperiodicity of the U-3.5 magnetic lattice.

Accomodation of the RF accelerating system requires approximately 90 m of free straight sections. The beam loading factor of a cavity is

$$k = \frac{2J_q}{V_1/R} = 3.8$$

This is a rather high value. It implies that dedicated efforts be spent to develop feedback circuits encircling the accelerating cavity in order to provide the safe stability of the closed-loop system comprising "cavity + intense beam".

Magnetic lattice

Magnetic lattice with separated functions of bending and focusing (dipoles and quadrupoles) is used. The focusing structure period type is FODO (90°).

The orbit length Π = 445.110 m, average radius R = $\Pi/2\pi$ = 70.841 m.

The accelerator consists of 6 superperiods with a length of 74.185 m each. A superperiod includes 6 FODO periods with a length of 12.364 m.

The scheme of magnetic lattice structure superperiod is shown in Figure 2.8. Superperiod obeys the reflection symmetry about its central point QD/2.

Superperiods (sextants) of the ring are identified downstream of the beam by marking the pairs of their boundary points: (a, b), (b, c), ... (f, a). The same letters label 6 bending arcs of the orbit a, b, ... f.

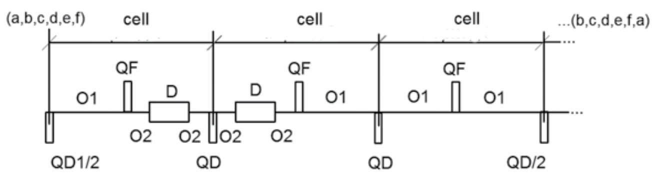


Figure 2.8. Scheme of a half superperiod of the lattice

The lattice incorporates the attractive features of the three known solutions in the magnetic optics:

1. Simplicity of a plain periodic FODO beam line.
2. Effective control over dispersion function D_x, compaction factor α and transition energy γ_t inherent in a FODO lattice with missing dipoles.
3. Long straight sections with suppressed dispersion, which are possible in the QBA scheme (quadruple bent achromat, i. e. achromatic beam bend with four dipoles).

Dipole magnets are placed only in 2 of 6 periods. Thus, the space for straight sections O1 is released (Figure 2.9).

In 3 of 6 periods, the dispersion is completely suppressed, $D_x = dD_x/ds = 0$. These periods form the long straight section 6 × O1 of each superperiod. In one period without dipoles the dispersion is not suppressed (these are the boundary half-periods on Figure 2.9).

The list of straight sections of a whole ring is presented in Table 2.3. Dispersion-free straight sections O1 occupy almost 45% of the orbit perimeter. Half of them is used to accommodate the RF accelerating system.

Table 2.3. Straight sections

Element	Type	Length, m	Total in ring	Total length, m
O1	Straight section, suppressed dispersion	5.582	36	200.952
O1	Straight section, nonzero dispersion	5.582	12	66.984
O2	Straight section	0.791	48	37.968

The 4 independent power supply circuits are used:

- For 24 dipoles D (or 25, taking into account a stand-alone reference dipole).
- For 36 regular focusing quadrupoles QF.
- For 30 regular defocusing quadrupoles QD.
- For 6 defocusing quadrupoles QD1 in the arc centers.

The three families of quadrupole lenses are necessary to ensure independent variation of betatron tunes (working point) and suppression of dispersion in the long straight sections.

The ratio of (dipole) magnet path length to orbit length is equal to

$$\frac{2\pi\rho}{\Pi} = \frac{\rho}{R} = 0.216.$$

The lattice is not the compact one. But that was not the design goal. The orbit length and top beam energy are set by other reasons.

The scheme of arrangement of the basic technological systems is presented in Table 2.4 and in Figure 2.9.

Table 2.4. Arrangement of the basic technological systems.

Secti-ons	Super-period	System	Quantity
6 × O1	(a, b)	Injection from the linear accelerator	1
6 × O1	(c, d)	Transfer to the U-70	1
6 × O1	(e, f)	Extraction to the n-generating target	1
2 × O1	in the arc center	Technological equipment, reserved	6
6 × O1	(b, c)	Accelerating stations, 2 units per O1	12
6 × O1	(d, e)	Accelerating stations, 2 units per O1	12
6 × O1	(f, a)	Accelerating stations, 2 units per O1	12
		Total number of stations	36

Tentative distribution of space along the orbit is presented in Table 2.5 (rounding up to a lattice period). It appears well balanced and should not complicate further equipment assembling solutions and does not preclude future development of the facility.

Table 2.5. Budget of space along the orbit.

System	Part
Dipole magnets	1/3
Injection/transfer/extraction	1/4
Accelerating system	1/4
Other technological systems[1] and reserve	1/6
TOTAL	1

1) Quadrupole lenses, correction of magnet field and closed orbit, vacuum pumping, beam diagnostics, actuators of feedback circuits, collimation and cleaning of halo, bellows, flanges, etc.

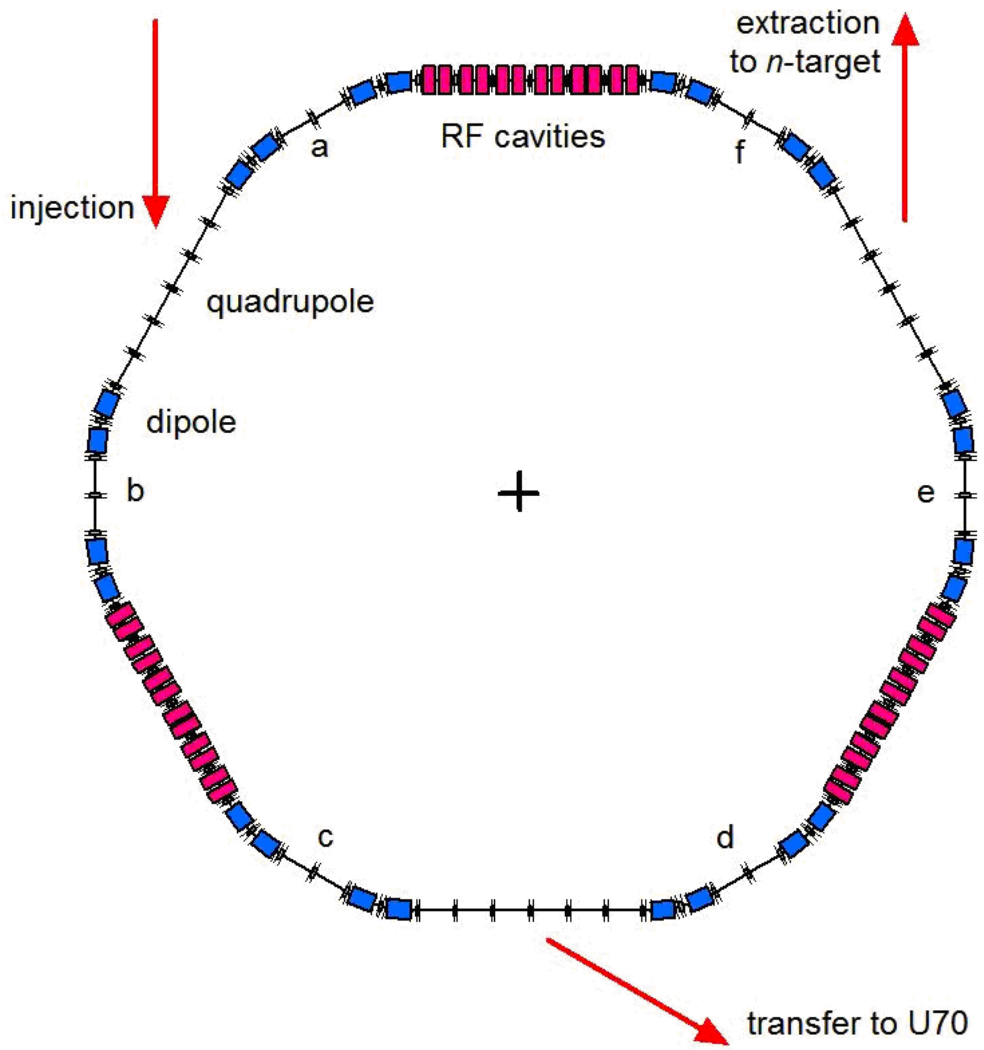


Figure 2.9. Layout of key technological systems of the U-3.5

A tentative layout of the complex on the IHEP site is shown in Figure 2.10.

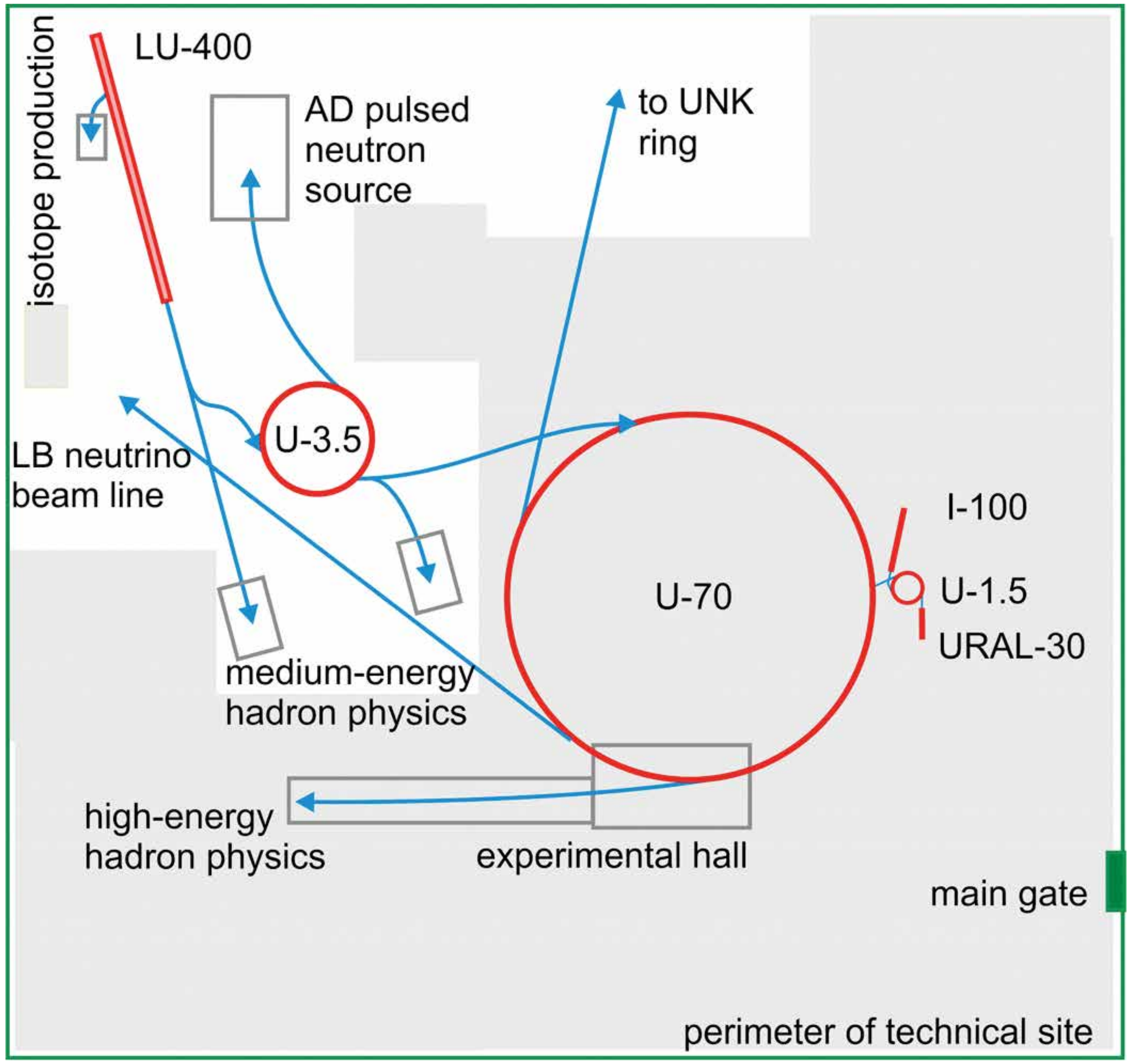


Figure 2.10. Layout of the Facility for Intense Hadron Beams on the IHEP site. Shaded (grey) area shows a zone occupied with the existing civil and engineering infrastructure.

Topology of accelerating system

The magnetic lattice of the ring has 6 × 6 = 36 FODO periods. Given RF harmonic number q = 9, the phase advance of accelerating field wave is equal to $\pi/4$ rad per 1 period (or, correspondingly, $\pi/8$ rad per a half-period).

Such phase advances, along with a symmetrical arrangement of RF stations, simplify their mutual synchronization required for coherent addition of voltages from individual stations at the beam.

The triplets of equidistant stations that have azimuths integer multiple to $2\pi/3$ form in-phase triplets. There are 12 such triplets in total. These triplets are united into 4 groups of 3 triplets with relative phase of RF field 0 (leading triplet), $\pi/4$ and $\pi/2$ rad in each group.

Relative RF phases of four groups are selected in situ according the factual azimuths of leading triplets of the group.

Dipole magnet

There are 24 dipoles D in magnetic lattice. One more, the 25th dipole, is housed outside the lattice. It is the measuring (reference) dipole.

The dipoles parameters are presented in Table 2.6.

Table 2.6. Parameters of dipole magnets.

Element	Type	Parameter	
D	Bending (dipole) magnet		
	Length along the orbit (over field)	4.00	m
	Bending angle	15	°
	Curvature radius of orbit ρ	15.280	m
	Number of packets in a block	2	
	Edge surface angle	3.75	°
	Sagitta in a block	130.7	mm
	Sagitta in a packet	32.7	mm
	Field at injection (400 MeV)	0.208	T
	Field at extraction (3500 MeV)	0.947	T

Magnet block of a dipole consists of two rectangular packets of equal length. The packets are turned by ±3.75° about the central cross-section of the dipole. Packets have common exciting coil. The incident angle of orbit at the entry/exit edges of dipole block (angle for edge focusing) is equal to 3.75°. The proven technical solution used for bending magnets of the existing booster U-1.5 is adopted.

Vacuum chamber inside the dipoles is curved with the orbit curvature radius ρ.

The bending magnet design is not strained. There is approximately 25% reserve in field (up to 1.2 T) in a bending field.

Quadrupole lens

There are 36 QF lenses, 30 QD lenses and 6 QD1 lenses in the lattice. All 72 quadrupoles are identical in their design. Their parameters are shown in Table 2.7.

Table 2.7. Parameters of quadrupole lenses

Ele-ment	Type	Parameter	
QF	Focusing quadrupole magnet		
	Length along the orbit (over gradient)	0.60	m
	Ratio of gradient to rigidity $G/B\rho$	+0.3845	m^{-2}
	Gradient at injection (400 MeV)	1.224	T/m
	Gradient at extraction (3500 MeV)	5.564	T/m
QD	Defocusing quadrupole magnet		
	Length along the orbit (over gradient)	0.60	m
	Ratio $G/B\rho$	–0.3325	m^{-2}
	Gradient at injection (400 MeV)	–1.058	T/m
	Gradient at extraction (3500 MeV)	–4.811	T/m
QD1	Defocusing quadrupole magnet		
	Length along the orbit (bover gradient)	0.60	m
	Ratio $G/B\rho$	–0.3593	m^{-2}
	Gradient at injection (400 MeV)	–1.144	T/m
	Gradient at extraction (3500 MeV)	–5.199	T/m

At an aperture radius of, for example, 100 mm, there is double reserve in field gradient. This reserve provides technical possibility for operational tuning the optics.

Optical parameters

Parameters of the synchrotron magnetic lattice are listed in Table 2.10. The plots of the amplitude and dispersion functions are shown in Figure 2.11a). The phase advance of the betatron oscillations per a lattice period is selected to be around $\pi/2$. That is a close-to-optimal tuning for a plain FODO beamline. The accelerator operates safely below transition: max $\gamma = 4.549 < \gamma_t = 7.595$.

Table 2.8. Parameters of magnetic lattice

Horizontal betatron tune	Q_x	9.150	
Horizontal amplitude β-function:	max β_x min β_x	23.939 1.995	m m
Vertical betatron tune	Q_y	7.200	
Vertical amplitude β-function:	max β_y min β_y	22.423 4.505	m m
Dispersion function	max D_x min D_x	4.105 0.0	m m
Compaction factor	α	0.01733	
Transition energy	γ_t kinetic	7.595 6.188	GeV
Natural (linear) chromaticity $\chi = p\,\partial Q/\partial p$	χ_x	–11.873	
	χ_y	–9.099	

The system for chromaticity correction is needed to obtain small negative values of χ in the range –1 ÷ –1.5. The goal is to squeeze the chromatic size of operating point on the betatron tune plot and to suppress the transverse instabilities of the "head-tail" type.

The adopted operating point (9.15; 7.20) is shown on the betatron tune plot in Figure 2.11b. This plot shows the lines of magneto-optical resonances up to the fourth order inclusive. The thick (color) lines mark the structure resonances. The Coulomb tune shift decreases both the betatron frequencies. During the motion in direction of the Coulomb shift a particle crosses sequentially the following resonances

$$Q_x - Q_y = 2,\ 2Q_y - Q_x = 5,\ 3Q_y - Q_x = 12 = 2\cdot 6.$$

The coupling resonance $Q_x - Q_y = 2$ can be corrected (skew quadrupole lenses), if required. Resonance of the 4th order (the last one in a list) is a structure resonance and requires a closer attention. This resonance and other essential magneto-optical resonances will be studied on next stages of the project.

Later on, the operating point can be corrected within sufficiently wide limits.

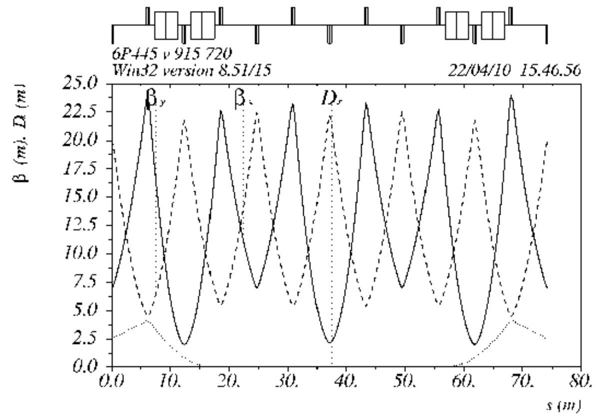


Figure 2.11a. Dynamic functions of magnetic lattice.

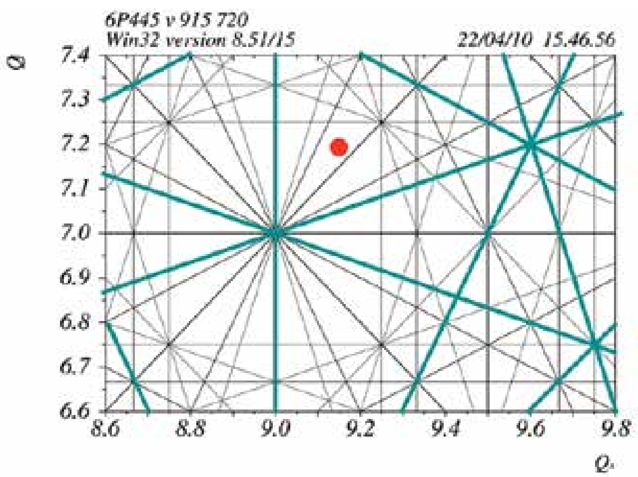


Figure 2.11b. Betatron tune plots and operating point.

Aperture of chamber and magnets

The envelope functions at 1σ level are plotted in Figure 2.12a.

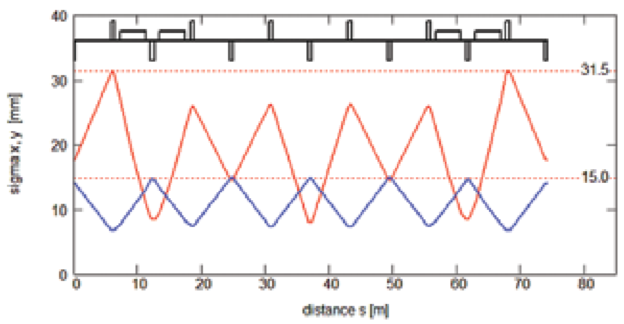


Figure 2.12a. Envelope functions of beam at 1σ level

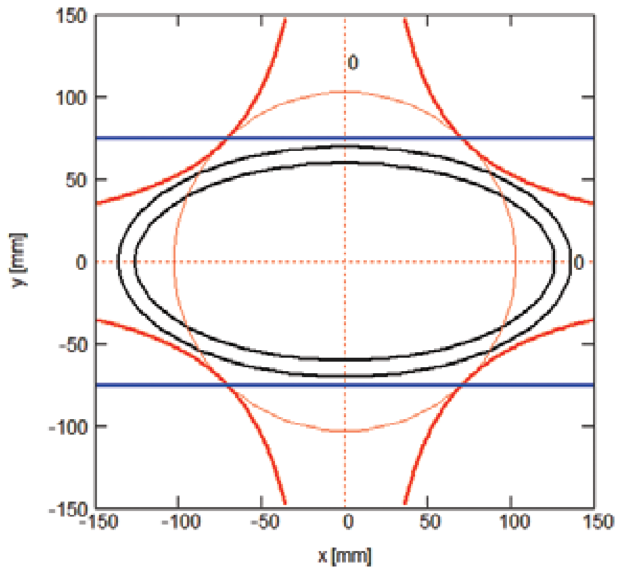


Figure 2.12b. Vacuum chamber and pole surfaces of magnets.

The aperture boundary for the vacuum chamber is set at ±4σ level of beam from the axis. The vacuum chamber is of an elliptic cross-section with internal half-axes (horizontal and vertical).

a = 126.0 mm, b = 60.0 mm

meets the demands. Betatron acceptance of such a vacuum chamber is equal to

$$A_x = \frac{a^2}{\max \beta_x} = 663.2 \text{ mm×mrad},$$

$$A_y = \frac{b^2}{\max \beta_y} = 160.5 \text{ mm×mrad}.$$

Momentum acceptance is ±3.1% (pencil beam with $\varepsilon_x = 0$) or ±1.6% (full beam).

Vacuum chamber inside the magnets is made of ceramics with a wall thickness Δ = 10 mm. The assembling clearances are set to ±5 mm. It will allow for accommodating the fittings, heating jackets for baking at the vacuum training, etc.

The dipole magnet is required to have a height and a width of the gap, respectively,

h = 150 mm, w > 272 mm (a good-field region).

Aperture radius of the quadrupole lens is

r = 102.9 mm.

The sketch of vacuum chamber inside pole surfaces of the magnets is shown in Figure 2.12 b.

2.3. Top Beam Power at Exit from the U-70

With a new injector (U-3.5) the beam power at the exit from the U-70 can be increased significantly. Here we evaluate the potential of the U-70 accelerator as high intensity machine using for guidance a long baseline neutrino experiment.

This experiment could be fed by the single-turn fast-extracted beam from the U-70 proton synchrotron. Its magnet cycles would have nearly no flat-top. Hence, average beam power at an external fixed target amounts to

$$P = \frac{N \cdot T}{\frac{n}{f} + t_U + t_D}. \qquad (2.1)$$

Here, N is the number of protons per pulse; T is kinetic energy of beam; n is the number of injection cycles required to fill the ring; f is cycling rate of the injector chain; t_U is ramping time of B-field (time of acceleration); t_D is decay time of the B-field.

Typically, $t_U = t_D$. Say, the existing power supply of the U-70 lattice yields $t_{U,D}$ = 2.8 s ca for top guide field 1.2 T (full energy 70 GeV, protons).

In case of using the RC PS U-3.5 of the OMEGA facility as a new injector to the U-70 one gets n = 3 and f = 25 Hz. The first summand in denominator of Eq. (2.1) thus turns small and could be dropped for the time being. Since both $t_{U,D} \propto T$, beam power P can be kept constant for various beam energies T manageable by the fast extraction system (estimated range is 35–70 GeV).

Geometrically, the U-70 ring can accommodate n = 3 cycles of injection from the U-3.5 each populated to $7.5 \cdot 10^{13}$ protons per pulse. With the resultant $N = 2.25 \cdot 10^{14}$ protons per pulse accumulated, the U-70 could yield beam power in the 450 kW scale.

Accomplishing The OMEGA Project is a necessary but not a sufficient condition for reaching this power frontier. Commensurable resources have to be invested to upgrade of the U-70.

Prospects for shortening cycles of the U-70

Smooth upgrade

Now, a magnetic cycle of the U-70 is nearly trapezoidal comprising four distinct segments – flat-bottom (duration t_{FB}), ramping (t_U), flattop (t_{FT}), and decay (t_D). Sum of the 4 times involved constitutes a repetition period of magnetic cycle. In such a notation Eq. (2.1) reads

$$P = \frac{N \cdot T}{t_{FB} + t_U + t_{FT} + t_D}. \qquad (2.2)$$

Shortening cycle period increases average beam power available.

Electrically, lattice of the U-70 (120 combined function magnets) is a series RL-circuit with resistance R = 1.2 Ohm and inductance L = 7 Henry.

Time data of the reference 1.3–69 GeV (trapezoidal, fully operational) cycle is listed in the 2-nd line of Table 2.9.

Table 2.9. Magnet cycle data for the U-70

cycle	flat bottom, s	ramping, s	flattop, s	decay, s	period, s
trape-zoidal, 1.3–69 GeV	2.22	2.75	2.0	2.8	9.77
trian-gular, 3.5–69 GeV	0.2	2.4	0.2	2.4	5.2

Distribution diagrams of electrical parameters for power supply convertors actuating the reference magnetic cycle are plotted in the left row of Figure 2.13. The key control points to follow and obey are:

- voltage across coils +16/–10 kV (coil and bus bar insulation sustainability),
- total power consumption +80/–50 MVA,
- active power load less than 40 MW (average 10 MW),
- range of non-active power ripple ±50 MVA.

The shortest 3.5–69 GeV (nearly triangular) cycle fitting into these safe operational constrains is specified in the 3-rd line of Table 2.9 and the right row of Figure 2.13. Current and B-field ramp and decay follow the natural law ∝ exp(–Rt/L).

In the existing layout of power supply circuitry in the U-70, its cycle repetition period (denominator in Eq. (2)) could not be set shorter than 5.2 s. Under design parameters of injection from the U-3.5, the beam power would be 460 kW. It is the top figure achievable through a smooth variation of the power supply parameters.

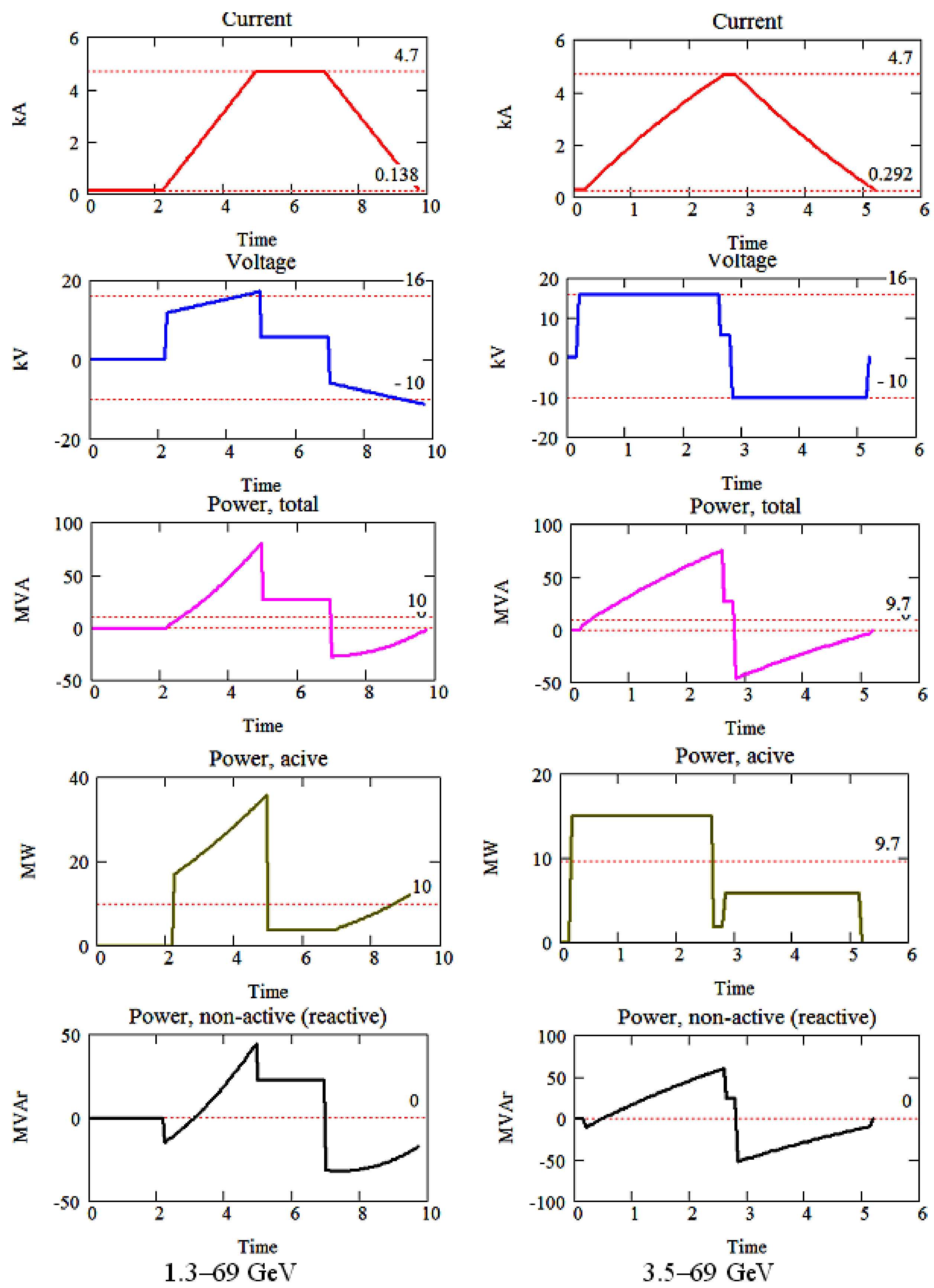


Figure 2.13: Electrical diagrams for a power supply convertor. Peak current is 4.7 kA.

Discrete upgrade, sectioning

The number of super-periods in magnetic lattice of the U-70 is 12. Tentatively, it can be split into n = 2, 3, 4, 6 or 12 identical sections. Assume the number of power convertors (feeds) be replicated by the same factor n. Scaling laws for the machine parameters would then be:

BEAM	
Cycle repetition period	× 1/n
Average power on a target	× n
LATTICE	
No of sections and power convertors	× n
Peak total power from mains (in VA)	× n ca
Average active power (in W)	1
Top current	1
Net voltage around	× n ca
Induced electromotive force in correction coils	× n
ACCELERATING SYSTEM	
RF gap voltage per turn	× n
RF power installed	× n ca

Beam energy T and intensity N are assumed unvaried. Some lines specify leading terms of the scaling laws.

Implementing even the lowest sectioning option n = 2 looks hardly affordable. To this end, one has to:

– duplicate the main power plant feeding the lattice,

– improve electrical insulation of main coils and bus bars,

– renovate the entire inventory of power supplies servicing magnetic field correction circuits (closed orbit, gradient, chromaticity) that would have to counteract a doubled external electromotive force due to inductively coupled coils,

– further double power and voltage of the RF accelerating system which already faces a challenge of handling the drastically increased design beam intensity N.

Intensity related effects

Due to:

– a conservative approach to the design of the U-3.5 relying on proven technologies,

– a commensurability of technical solutions adopted for the U-3.5 and U-70 machines, and

– smooth matching of beam parameters during transfer beams in the both rings would have nearly identical local and averaged (over orbit) peak beam currents.

To this end, designs of the U-3.5 and the high-N option of U-70 would have to address the similar issues of intense-beam dynamics (longitudinal and transverse, coherent and incoherent effects, effects of short- and long-living electromagnetic wake-fields in a non-smooth resistive-wall chamber and other beam environment, etc.). These could be solved concurrently.

Additional challenges would be faced in implementing the relevant cures in the running facility with its tight spatial constraints and ageing key technological equipment.

A closer attention would be required to transition crossing with intense beam in the U-70 that is avoided in the U-3.5 altogether.

Adequate RF accelerating system is the next to lattice and water cooling consumer of electrical power. Its performance is affected by the high-N beam loading effect. The new RF cavities with higher flange-to-flange voltage and up-to-date feedback circuitry capable of maintaining stability of the closed-loop configuration might be borrowed from the U-3.5 design.

Other matters

There is a non-vanishing list of other upgrades required for the high-N operation of the U-70:

– Fine adjustment of the magnetic lattice comprising 120 combined-function bulky (200 ton) magnets.

– Improving closed-orbit and resonance corrections.

– Smoothening vacuum chamber and removing excessive equipment with its boxes. Optionally, assembling a new vacuum pipe with TiN inner coating.

– Freeing space in the straight sections for a new equipment. This may lead to reduced diversity of the functional capabilities of the machine compared to those available now.

– Strengthening existing and mounting new beam feedback systems with their actuators to counteract coherent instabilities.

– Develop and install halo collimation and beam loss localization systems.

– Developing a new direction of fast extraction towards an external target station and/or beam abort dump.

Technical design study of the high-N option of the U-70 is expected to account for these issues.

Since some issues above are important to the current operation of the U-70 machine the ongoing upgrade program of the U-70 accelerator will resolve part of the matters related to operation of the U-70 with ultimate beam power.

3. The U-70 Intense Beams

The major tasks of the physics of fundamental interactions in the present and in the foreseeable future are the search for phenomena beyond the Standard Model and the study of processes, where the use of the Standard Model is facing problems.

A number of experiments on the given accelerator complex is aimed at searching for phenomena beyond the Standard Model. These are various experiments with neutrino, experiments on rare decays of particles, the search for anomalous properties and ultra-precise measurements of characteristics of the particles. In many cases, these experiments allow one to study physics at extremely short distances, unreachable for the existing and future colliders. Within the OMEGA Project the beams of neutrinos, muons, kaons, pions, and ultracold neutrons can achieve record parameters, this is a key factor for a wide class of experiments having world-class priority.

Among the areas that require a substantial increase of the experimental data a particular place belongs to the physics of nonperturbative strong interactions. A variety of high-intensity and high-quality hadron beams open new horizon in this field.

3.1. Research Directions

Within the proposed project the U-70 accelerator will be developed to multipurpose machine with a variety of beams:

- protons with energy up to 70 GeV and intensity up to $2.2{\cdot}10^{14}$ ppp;
- high intensity ($>10^{14}$ pps) beam of protons with energy of 3.5 GeV;
- light nuclei with energy up to 32 GeV/nucleon and intensity in a range of $10^9 \div 3{\cdot}10^{10}$ ipp;
- carbon ions ^{12}C with variable energy from 200 MeV to 450 MeV per nucleon with the beam optimized for ion therapy needs.

Such a beam set opens new possibilities for fundamental researches in a number of directions:

- neutrino physics;
- muon physics
- physics of charged and neutral kaons;
- hadron spectroscopy;
- spin physics;
- hyperon physics;
- hadron-nucleus and nucleus-nucleus interactions;
- physics of light and medium unstable nuclei.

In subsequent sections of this chapter the principal issues of researches at the U-70 accelerator with increased intensity are described. Primary attention is paid to first and foremost experiments where the high priority results can be obtained at the initial stages of the project.

3.2. Neutrino Physics

Significant rise of proton beam intensity at U-70 opens perspectives for a new generation of neutrino experiments. These experiments can be conditionally divided on several big groups:

- long baseline neutrino experiments on measurement of oscillation parameters ($\Delta m_{i,j}$, angles of mixture and phase) in the range $\Delta m^2 = 3{\cdot}10^{-3} \div 5{\cdot}10^{-5}$ eV^2;
- experiments on search for fast oscillations, for example, the search for oscillations $\nu_\mu \rightarrow \nu_e$ in the range of $\Delta m^2 = 0{,}1 \div 1$ eV^2;
- study of matter effects on neutrino propagation;
- study of earth density with neutrinos;
- precision study of low and medium energy neutrino interactions ;
- search for new neutral weakly interacting particles.

One of the central problems of the Standard Model is the origin and role of the 3 types of neutrinos.

Observation of the neutrino oscillations gives the first evidence that the neutrino masses are different from zero and very small. Their small values cannot be explained without ideas beyond the Standard Model, that is without a new physics.

For a phenomenological description of neutrino oscillations the model with three active neutrinos (ν_e, ν_μ, ν_τ) related to the massive states (ν_1, ν_2, ν_3) by the 3×3 Pontecorvo – Maki – Nakagawa – Sakata (PMNS) mixing matrix is used. PMNS matrix structure is defined by three mixing angles θ_{12}, θ_{23}, θ_{13} and CP-odd phase δ_{CP}, reflecting the nonconservation of combined parity (CP violation) for leptons.

At present most of the neutrino oscillation parameters, namely the matrix PMNS mixing angles are measured, albeit with a limited precision. The fact that all three neutrino mixing angles are not equal to zero indicates the existence of the CP-odd phase. Over the last year several independent experiments were able to measure the mixing angle θ_{13}. The large value of the mixing angle $\theta_{13} \sim 9°$, measured in the T2K, MINOS, Double Chooz, Daya Bay, RENO experiments in 2011–2012, radically changed the prospects of neutrino oscillations studies.

Now we have a unique chance to determine the neutrino mass hierarchy and to search for CP violation in neutrino oscillation experiments with a long base, about 1000 km or more, with intense neutrino beams from proton accelerators. The measured value of the angle θ_{13} allows one to plan with a high certainty the experiments that will have a high sensitivity to the δ_{CP} value.

Long base leads to the need for the most possible increase of the neutrino beam intensity and the construction of very heavy detectors.

Proposed accelerator neutrino experiments with a long base

Long baseline accelerator neutrino experiments are planned in several research centers. These experiments are LBNE (USA), HyperKamiokande (Japan), LAGUNA-LBNO (European project).

The LAGUNA-LBNO [LAGUNA-LBNO design study, http://www.laguna-science.eu/] is the most ambitious project in this field. The LAGUNA installation is designed to study a wide range of problems in astrophysics and particle physics. The proposed experimental setup consists of a complex of detectors – liquid argon time projection chamber with a mass of about 20 kt - 50 kt detector based on a liquid scintillator.

The experimental setup has to be located deeply underground to protect it against the cosmic ray background. On the set of parameters the mine in Pyhäsalmi (Finland) is the most suitable for such experiments.

One of the key elements of the LAGUNA-LBNO project is the upgrade of the accelerator complex at CERN. At present a creation of the CERN neutrino beam in the North area on the basis of a 500 kW SPS proton beam is considered. The long base of the experiment (CERN- Pyhäsalmi, ~2300 km) provides a sensitivity to the neutrino mass hierarchy at the 5σ level. CP-odd phase δ_{CP} can be measured with an accuracy of about 15°.

The accelerator complex of intense hadron beams open up possibilities to plan a high-intensity neutrino channel directed to Pyhäsalmi or to another laboratory in Western Europe from the list of LAGUNA-LBNO proposal. The experiment in a new design* with the two neutrino beams – one from CERN (the base of 2300 km), the other one from IHEP (the base of 1160 km), radically boosts the potential of the LAGUNA-LBNO project. Measurements with the two bases will double the statistics of neutrino events, significantly reduce systematic errors of the experiment by a common far detector, and provide a unique sensitivity to the CP-odd effects.

The design of the U-70 and the IHEP infrastructure allow one to create a neutrino channel in a direction of six underground laboratories from the list of the LAGUNA-LBNO project (Figure 3.1).

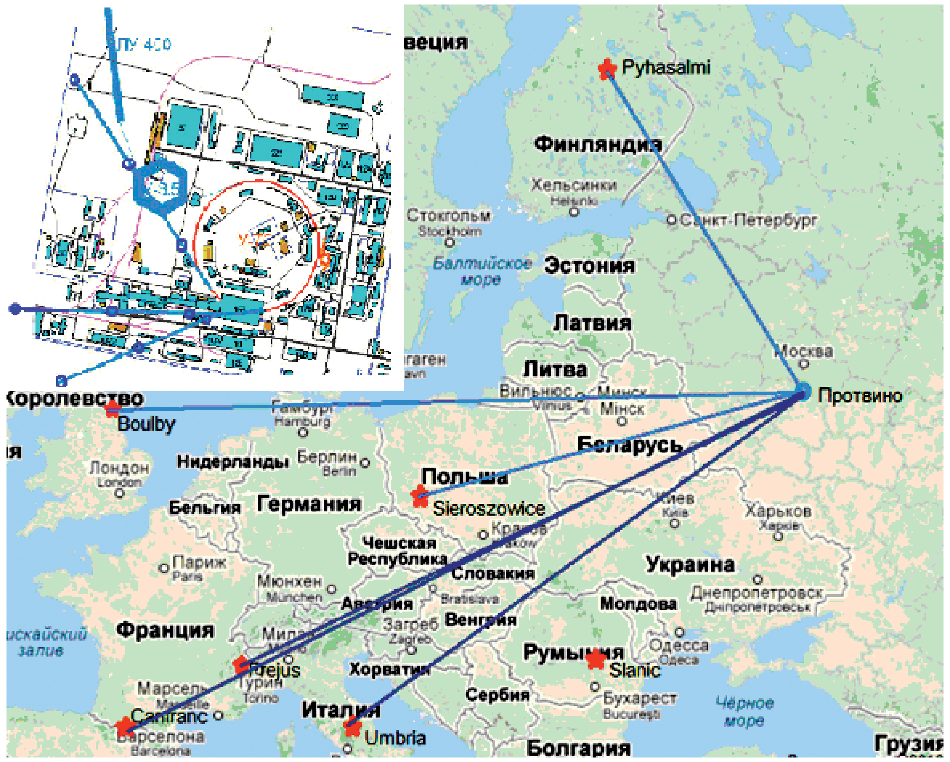


Fig. 3.1. The scheme of the IHEP neutrino beam directions to the planned location of underground laboratories in Europe (the LAGUNA-LBNO project).

*This option proposed by NRC KI and INR RAS

In the first approximation, the basic geometry of the neutrino channel for long baseline experiments at the U-70 are as follows:

- the decay pipe length – 200 m;
- the decay pipe diameter – 3 m;
- focusing system: horn and reflector;
- the energy range of neutrinos: 0.5 – 3 GeV;
- the beam angle in a vertical plane – 5.2° (Pyhäsalmi);
- the distance to the near detector – 300-700 m;
- the depth of the near detector location (depends on the channel direction and length) – from 45 to 95 m.

The distance available to allocate the neutrino beam line and the near detector in the IHEP side is ~ 700 m. Along with the channel geometry, the energy spectrum of the neutrino beam at the far detector is largely determined by parameters of the focusing system that forms a beam of secondary particles (π, K mesons) produced in the target.

For the distance of 1160 km to the far detector the required range of the neutrino beam energies is 0.5 - 3.0 GeV, which covers the 1st and 2nd peaks of $\nu_\mu \rightarrow \nu_e$ oscillations (~2.1 GeV and ~0.8 GeV, respectively). The parameters of neutrino beams has been calculated with focusing systems of the current neutrino experiments. Figure 3.2 shows the spectra at the neutrino detector in Pyhäsalmi, calculated using the following two types of focusing systems:

a) focusing system of the T2K neutrino channel at the 30 GeV proton accelerator J-PARC (Japan) [The T2K Neutrino Flux Prediction. arXiv:1211.0469v1 [hep-ex], 2 Nov 2012];

b) focusing system of the NuMI neutrino channel in the low-energy configuration of the 120 GeV proton accelerator MI (USA) [A.G.Abramov, N.A.Galyaev, V.I.Garkusha et al. Beam Optics and Target Conceptual Designs for the NuMI Project. NIM, A485 (2002) 209.].

In a calculation of the neutrino spectra a graphite target with a diameter of 10 mm and a length of 900 mm was assumed.

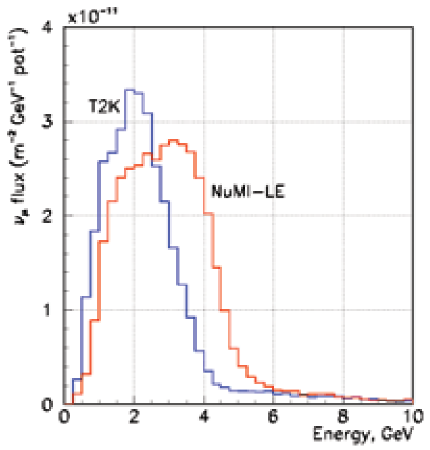


Figure 3.2. The K_l beam spectra at the far detector (1160 km) for two variants of the focusing system.

The neutrino beam generated by the T2K focusing system is nearly optimal for a study of $\nu_\mu \rightarrow \nu_e$ oscillations in the considered experiment.

The goal of this experiment is the measurement of ν_e ($\bar{\nu}_e$) neutrino appearance in the initial beam of ν_μ ($\bar{\nu}_\mu$) neutrino as a result of $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) oscillations. Therefore, it is important to form a neutrino beam with a small contamination of the initial electron neutrino (antineutrino) from the muons and Ke3-decays. For the considered neutrino beam the electron neutrino contamination is ~ 0.5% of the total neutrino flux. To obtain more intense neutrino beams at low energies the off-axis beam technique can be applied also.

The estimates show that the experiment with the detectors of the LAGUNA-LBNO project located in Pyhäsalmi, using neutrino beams from the upgraded accelerator U-70 will measure the δ_{CP} phase at 30% of its full range.

Study of the «LSND anomaly»

High intensity neutrino beam can be also used to study neutrino interactions in the near detector situated by a few hundred meters from the target. One of the problem that can be investigated in such experiment is the confirmation or refutation of the effect of neutrino oscillations discovered by the LSND experiment. In this experiment a $\bar{\nu}_e$ appearance signal was observed in the $\bar{\nu}_\mu$ beam at the level of 3.8σ above the background [A. Aguilar et al. (LSND Collaboration), Phys.Rev. D64, 112007 (2001), arXiv:hep-ex/0104049.]. This effect can be considered as an indication to the existence of antineutrino oscillations $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ with the values of Δm^2 = 0.1-10 eV^2, $\sin^2 2\theta > 10^{-3}$. Being confirmed this effect would require an introduction of one or more light sterile neutrinos.

In the $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) oscillation experiment at the near detector the effects of the LSND oscillation can be studied . To study of neutrino oscillations in the Δm^2 ~ 0.1-Δ 10 eV^2 range it is necessary to have a value <L>/<Eν> ~ 0.1-10 (km/GeV). Here <Eν> is the average energy of the neutrino beam, <L> is the average distance from the neutrino production point to the detector. For the beam with the energy <Eν > ≈ 1 GeV the distance <L> has to be ≤ 1 km, that is a near detector has to be located by a few hundred meters from the target.

The $\nu_\mu \rightarrow \nu_e$ oscillation experiment at the near detector with $4.3 \cdot 10^{20}$ protons at the target (~ 100 days running at the upgraded accelerator U-70) was considered for guidance. The fiducial mass of the detector is 100 tons, the used neutrino energy range is 0.5 ÷1.5 GeV, <L> ~ 650 m.

A sensitive range of $\sin^2 2\theta$, Δm^2 values for this experiment is shown in Fig. 3.3. For a comparison it is also represented the range of $\sin^2 2\theta$, Δm^2 values explaining the LSND anomaly. It is clear from this figure that the experiment at the near detector with a high-intensity neutrino beam can study $\nu_\mu \rightarrow \nu_e$ oscillations in the $\sin^2 2\theta$, Δm^2 range typical for the LSND experiment.

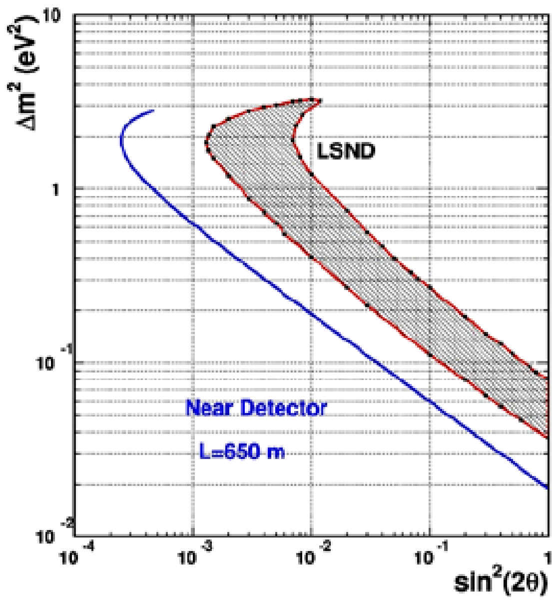


Figure 3.3. A sensitivity of $\sin^2 2\theta$, Δm^2 values for the near detector experiment ($\sin^2 2\theta$, Δm^2 values to the right of the blue curve). It is also shown the range of $\sin^2 2\theta$, Δm^2 values (shaded area), explaining the LSND anomaly.

The LSND effect can be studied also with neutrino beam using high intensity protons from the RC PS U-3.5. The exclusion region for the experiment with 100 days run with 100t detector is plotted in Figure 3.4

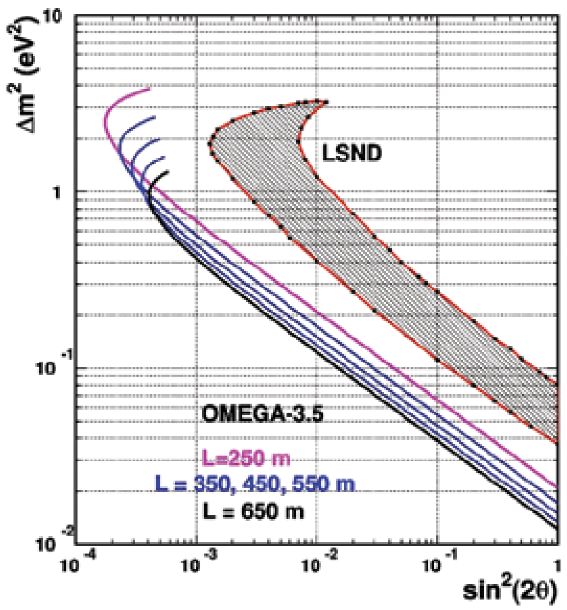


Figure 3.4. A sensitivity range of $\sin^2 2\theta$, Δm^2 values for the experiment with the U-3.5 neutrino beam for various distances from the target.

The same level of sensitivity can be reached also with neutrinos from stopped π+ generated in the target of spallation neutron source.

3.3. Muon physics

This section briefly describes muon experiments on search the effects beyond the Standard Model. High intensity proton beams with parameters optimized for experiments with muons provide unique opportunity for high priority searches and studies. Muon experiments could become the important part of research program at The OMEGA Facility.

Use of U-70 for beam storage and stretching

In this mode the U-70 accelerator is working all the time at the injection energy 3.5 GeV. The beam is injected into the U-70 (3 cycles of U-3.5 – 0.12 s) and then it is extracted from U-70 by slow extraction in about 1 s. In such a mode the time structure of the beam can be optimized for specific experiments. For example, it is possible to organize short bunches every ~ 2 μs, that is extremely important while studying the muon decays.

Beam extraction from the U-70 in this mode can be organized at straight section # 22 in the direction of south zone of the experimental hall.

Muon Physics

The muon has a unique position among the known elementary particles, thanks to a long lifetime of 2.2 ms and its low mass of 105 MeV, which makes it possible to obtain a large number of muons for detailed studies. The muon is the simplest unstable particle that does not consist of a combination of other elementary objects (quarks). That allows the study of the fundamental interactions in a pure form. The OMEGA Project will increase the intensity of the muon beam by 3-4 orders of magnitude, compared with the existing beams.

Muon experiments can be split up in two directions: the search for rare muon processes involving violation of lepton quantum numbers (decays $\mu \rightarrow e + \gamma$, $\mu \rightarrow 3e$ and $\mu \rightarrow e$ conversion process) and precise measurements of muon properties (its decay parameters, magnetic and electric dipole moments.

Rare processes

The observation of lepton flavor violation (LFV) processes would indicate a new physics beyond the Standard Model. Even in the case of the detection at the LHC of a new heavy particles beyond the Standard Model, searches of rare muon processes can provide significant new results, since they often have a much higher level of sensitivity to the mass scale of new particles involved in these interactions. Increased sensitivity of an experiment by factor of $10^2 - 10^4$ over current limits in the search for rare muon processes could lead to LFV observation and could probe new interactions mediated by new heavy particles in a mass range of 1000 TeV which is not directly accessible at present and near future at high energy accelerator experiments. The current theory of elementary particles can not predict the best candidate process to search for LFV, since various models give different rates. Searches for all three rare muon processes in one experimental setup would increase the probability of a LFV discovery.

An idea for an experimental setup allowing the increase of muon source intensity and of sensitivity of an experiment by a few orders of magnitude was proposed in [R. M. Djilkibaev, V. M. Lobashev, Sov. J. Nucl. Phys. 49, 384 (1989)] and developed in the MELC [V. S. Abadjev et al., MELC proposal, Preprint 786/92, INR (Moscow, 1992)], MECO [M. Bachman et al., MECO BNL Proposal P940 (1997)], PRIME [S. Machida et al., J-PARC PRIME LOI (2003)], Mu2e [R. M. Carey et al., FNAL Mu2e LOI (2007)] and COMET [D. Bryman et al., J-PARC COMET Proposal (2007)] proposals for a $\mu \to e$ conversion experiment. This idea is based on using a pulsed proton beam and on joining the muon source, selection system and detector setup in one magnetic system with a graded field as shown in Figure 3.5. An approach to search for the three rare muon processes in one setup, was proposed in [R. M. Djilkibaev , V. M. Lobashev, Phys. of Atom. Nucl., 73, 2012 (2010).], extends the idea of using S-shaped solenoid to get an intensive source of negative muons to search $\mu \to e$ conversion, and positive muons to search $\mu \to e + \gamma$ and $\mu \to 3e$ decays. As well as proposed to use a modular detector construction of tracker, calorimeter and hodoscope, allowing for reconfiguration to meet the requirements for each of the processes.

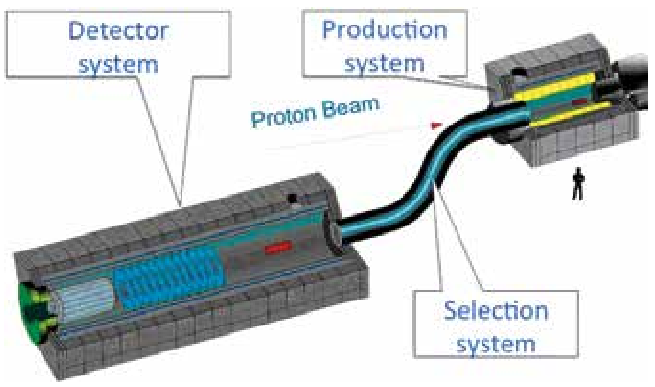


Figure 3.5. 3D view of μ3in1 (Mu3in1) setup.

Decay $\mu^+ \to e^+ + \gamma$

Muon decay $\mu^+ \to e^+ + \gamma$ at rest in the final state there are positron and a monochromatic photon with energy equal to half the mass of the muon, flying in the opposite directions. There is a limit on the relative probability of the decay $\mu^+ \to e^+ + \gamma$ is equal to the value of Br <2.4 10^{-12}. There is a proposal to upgrade the experiment MEG (PSI, Switzerland) in order to improve the sensitivity of the experiment to a level of 10^{-13}. A reachable level of the experiment sensitivity is determined mainly by two factors: the level of suppression of the unavoidable physical background of the radiative decay of the muon $\mu^+ \to e^+ + \gamma + \nu_e + \nu_\mu$ and the background level of random coincidences with the registration of the positron from the main muon decay $\mu^+ \to e^+ + \nu_e + \nu_\mu$ and a photon from the radiative decay of the muon. The main limitation on the achievable level of the experiment gives the energy and angular resolution of the calorimeter to measure the energy and position of the photon. The magnetic spectrometer for the detection of positrons has a much better energy and angular resolution than the calorimeter.

The OMEGA Project can increase the sensitivity of the experiment to search for the decay $\mu^+ \to e^+ + \gamma$ for two orders of magnitude compared to the current limit and will detect this process or to determine the upper limit on the branching ratio at the level of 10^{-14}.

Decay $\mu^+ \to e^+ + e^+ + e^-$

In this decay in the final state are charged particles (positrons and electron), which are measured with a magnetic spectrometer with a higher accuracy compared to photons in the calorimeter. Better resolution can suppress the irreducible physical background related to the muon decay $\mu^+ \to e^+ + e^+ + e^- + \nu_e + \nu_\mu$ and accidental background, in spite of the three-fold coincidence, and thereby increase level of the experiment sensitivity on the one order of magnitude in comparison with the experiment to search $\mu^+ \to e^+ + \gamma$ decay. The current limit on the relative probability of the decay $\mu^+ \to e^+ + e^+ + e^-$ is equal to the value of Br <1.0 10^{-12}. Currently there is a proposal for an experiment Mu3e at PSI in Switzerland [A. Blondel et al., Mu3e LOI PSI (2013)] to search of the decay $\mu^+ \to 3e$ with a sensitivity level equal to 10^{-15}.

The OMEGA project can increase the sensitivity of the experiment to search for the decay $\mu^+ \to e^+ + e^+ + e^-$ for three orders of magnitude compared to the current limit and will detect this process or to determine the upper limit on the branching ratio at the level of 10^{-15}.

Process $\mu^- \to e^-$ coherent conversion in a muonic atom

In this process, the muon atom with a muon, located mainly in the lower orbit the nucleus of charge Z, interacting with the nucleons in the nucleus is converted into an electron with energies close to the mass of the muon. This process has a very simple signature in the final state is a monochromatic electron with energy equal to the mass of the muon minus the binding energy of the muon with the nucleus and the energy of the recoil nucleus. Therefore, in the process the accidental background is missing, so one can use in the experiment the intensity of the muon beam into several orders of magnitude higher than in experiments ($\mu^+ \to e^+ + \gamma$, $\mu^+ \to e^+ + e^+ + e^-$) where one has to measure two or three particles in coincidence, respectively. This allows achieve the sensitivity of the experiment by several orders of magnitude higher compared with the experiments ($\mu^+ \to e^+ + \gamma$, $\mu^+ \to e^+ + e^+ + e^-$). The currently achieved limit on the relative probability of $\mu \to e$ conversion is equal to the value of Br <7.0 x10^{-13}. At present two experiments are being prepared in search of the $\mu \to e$ conversion Mu2e at FNAL in USA and COMET at J-PARC in Japan with a sensitivity level of the relative probability of the process is equal to 10^{-17}.

The OMEGA project can increase the sensitivity of the $\mu \to e$ conversion experiment by four orders of magnitude compared to the current limit and will detect this process or determine the upper limit on the branching ratio at the level of 10^{-17}.

3.4. Hadrons

In this section three selected directions in hadron physics are briefly described:

- Physics of kaons
- Spectroscopy
- Spin physics

3.4.1. Physics of Charged and Neutral Kaons

Kaons are unique objects for searching new particles and new interactions. New particles can appear both in real forms among the products of kaon decay and in virtual forms through the influence on kinematic characteristics of decay products. Study of charged kaons decays gives unique information concerning fundamental laws of nature, such as CP and T symmetry violation.

At present time the OKA setup (IHEP-INR-JINR) starts data-taking at U-70. This facility operates with separated beam of kaons with energies of 12.5 GeV and 17.7 GeVat intensity of slow extraction ~ 10^{13} ppp).

In order to obtain further high level results in this field it is necessary to study more and more rare processes. Planned increasing of slow extraction intensity up to ~10^{14} ppp satisfies perfectly to this purpose.

Experiments with neutral kaons

Generally recognized high priority research trend in neutral kaon physics is the search for super rare decay $K_L \to \pi_0 \nu \bar{\nu}$. Theoretical value for its relative probability in Standard Model is (2.8 ±0.4)×10^{-11}. By increasing the slow extraction intensity up to 10^{14} ppp at U-70 it is possible to form the beam of neutral kaons with unique parameters optimized for study decay $K_L \to \pi_0 \nu \bar{\nu}$. Neutral kaon beams of high intensity will give the opportunity to make an advance in searching for other extremely rare decays, for example $K_L \to \mu$ e.

Experiments with charged kaons at low energy beams

Such beams are formed with the help of electrostatic E × B separators. The best beam of such type was used at BNL. It had the intensity ~5·10^6 K^+ at 10^{13} extracted protons. In this beam 7 events of the decay $K^+ \to \pi^+ \nu \bar{\nu}$ were observed. At U-70 this result can be substantially improved.

In U-70 program, besides the study of this decay, a search for transversal muon polarization in the decay $K^+ \to \mu^+ \nu \pi^0$ can be performed with high sensitivity. Such a polarization is sensitive to physics beyond Standard Model. The present limit P_T < 4·10^{-3} could be considerably, by one order of magnitude, improved at upgraded U-70 complex. Slow kaons are, as well, of great interest for experiments on baryon spectroscopy.

Experiments with charged kaons at high energy beams

The most principal and primary trend here is the study of rare and super rare decays, such as $K^+ \to \pi^+ \nu \bar{\nu}$. To observe ~100 events of this decay it is necessary to have kaon beam with intensity of ~10^7 /sec. Slow extraction with intensity >10^{14} /spill at U-70 and upgraded system of superconducting RF deflectors with RF field of ~ 5 mV/m are required.

3.4.2. Hadron Spectroscopy

Spectroscopy of light hadrons is one of the main methods of experimental study of strong interactions in non-perturbative area. IHEP has long-standing traditions of researches in this field.

Energy of the U-70 accelerator is exceptionally convenient for studying light hadrons spectroscopy by following reasons:

– states with masses up to 2.5-3 GeV are produced in various exclusive reactions with sufficiently large cross-sections;

– as a rule, the phase space of reactions is sufficiently high for effective separation of different processes;

– most of the reaction products has convenient kinematical parameters, where particles can be identified and their characteristics can be measured with high accuracy.

Two directions of research look especially promising and having potential for discoveries:

– search for and study of exotic states

– study of high excitation states

Beam line with optimal parameters for experiments on spectroscopy can be constructed on the base of slow extracted protons with intensity of ~2·10^{13} ppp.

3.4.3. Spin Physics

The understanding of particle structure and interaction dynamics is impossible without detailed knowledge of spin effects. It is established that spin effects should be associated with the non-perturbative dynamics, for example, with phenomenon of spontaneous breaking of chiral symmetry. Thus, the studies of the spin phenomena allow one to obtain new information on dynamics of particle interactions and to perform detailed analysis of various theoretical ideas.

In experiments with high intensity beams a spin asymmetries can be measured in inclusive and exclusive reactions for all light stable particles and for all light resonances (~10^2 in total) in nearly full kinematical region.

The beams of polarized protons and antiprotons will allow to resolve a principally new problem – the study of spin characteristics in the reactions producing charmed particles. This study will allow to investigate the spin structure of proton by measuring the distribution functions of longitudinally and transversally polarized quarks with the help of various one-spin and two-spin effects. Formation of such states in collisions of nucleons is especially interesting, since the final particles with quantum numbers $J^{PC}=1^{--}$, 1^{++}, 2^{++} provide the information about gluon density in nucleons.

The experimental program is oriented mostly on using high intensity beam of polarized protons and beam of polarized antiprotons, which do not yet exist anywhere. Such secondary (tertiary) beams can be produced on the base of a new high intensity target in proton beam extracted from U-70. At $2 \cdot 10^{13}$ ppp spilled on target the intensity of polarized proton beam will be ~$2 \cdot 10^7$ protons. Polarization of protons is correlated with their coordinate on vertical collimator and achieves in maximum 65%. Intensity of polarized antiprotons will be ~$3 \cdot 10^5$ per cycle. The beamline is supposed to provide the rotation of polarization.

4. Application of LU-400 and U-3.5 Beams

The accelerator U-3.5 will provide proton beam for comprehensive program of fundamental and applied researches.

The most challenging element of the applied research program is the pulsed spallation neutron source, intended for life and material science at nanometer and subnanometer scale. On top of it, high intensity proton beam provides the unique opportunities for development of the other promising topics:

- isotope production;
- studies with ultracold neutrons;
- proton and neutron radiography;
- measurements of neutron-nuclei reactions by time-of-flight technique;
- Doppler spectroscopy of dynamic processes;
- radiation material science;
- studies of subcritical Accelerator Driven Systems.

4.1. Thermal and Cold Neutrons

Parameters of neutron source

The layout of spallation neutron source is presented in Fig. 4.1. The proton beam with the energy E = 3.5 GeV and power 1.1 MW is directed on the target of neutron source. Pulse duration of the beam is 1.5 μs, repetition rate is 25 Hz. A target, where the neutrons of wide energy spectrum are produced in spallation reactions, is surrounded by the radiation shielding, cooling and ventilation systems. In the vicinity of the target there are cryogenic moderators, where neutrons are decelerated and thermalized. About 20 neutron channels are looking at these moderators. The channels can be opened or closed by means of massive shutters with the remote control. The channel lengths depend on specific experiments and varies from ten to hundred meters.

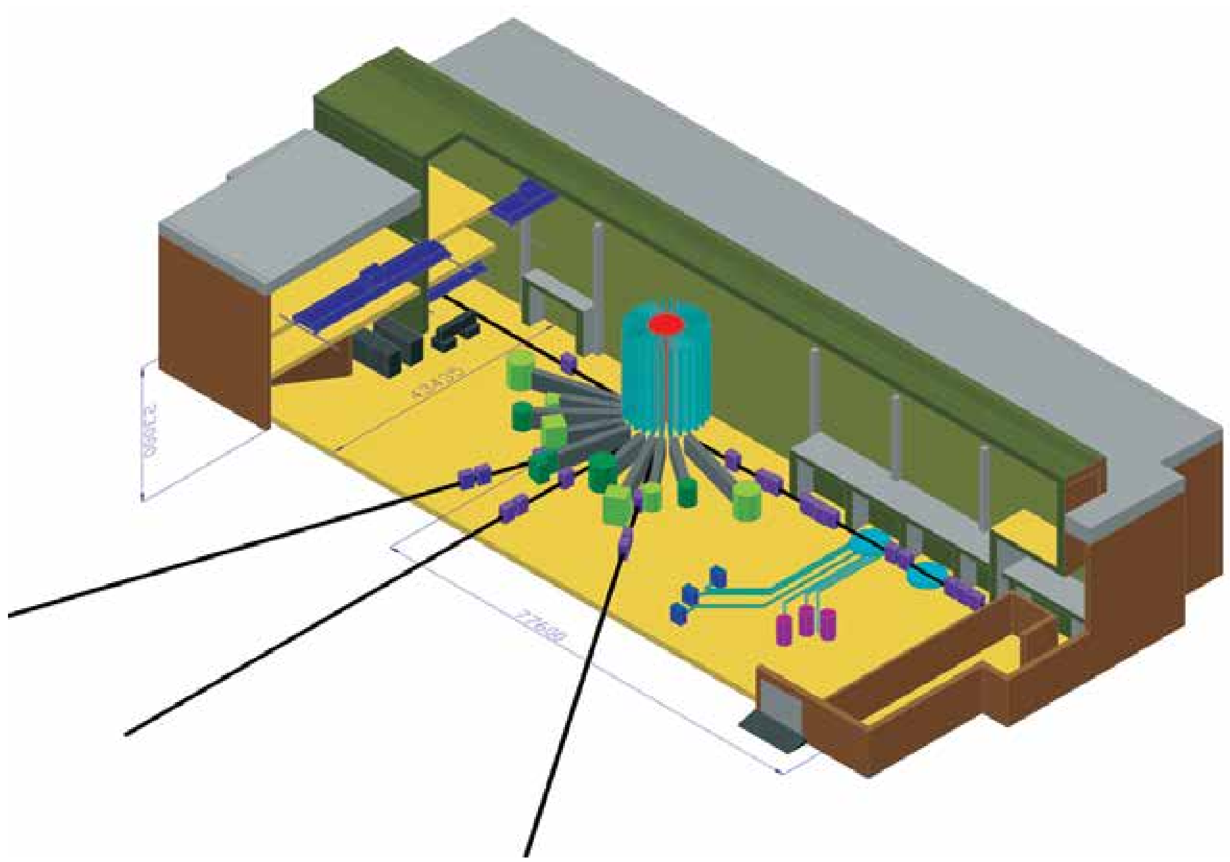


Figure 4.1. Layout of experimental hall with target, system of channels and facilities for experiments with thermal and cold neutrons.

The neutron yield from thick lead target as a function of a proton energy is given in Figure 4.2. At the energy of 3.5 GeV each proton produces about 70 neutrons, so that at the beam power of 1.1 MW approximately $1.3 \cdot 10^{17}$ neutrons per second will be produced at the target. The pulsed flux intensity will be 2-3 orders of magnitude greater, depending on moderators design.

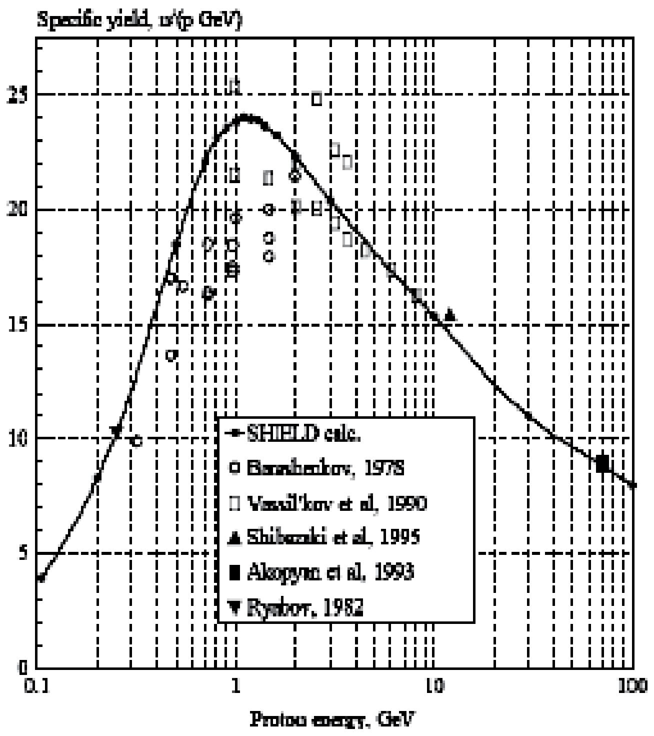


Figure 4.2. Specific yields of neutrons (n/p[GeV]) from thick lead target.
(fromV.S.Barashenkov, EPAN, 9-11,1978)

The neutron spectrum crucially depends on the design of the target and moderators. With thermal and cold moderators the significant part of neutrons has the wavelength in the range from 0.1 to 1 nanometer. This wavelength is very convenient for research in chemistry, condensed matter physics, materials science, engineering and biology.

For majority of experiments, duration of the neutron pulse is as important parameter as intensity, because the energy resolution at fixed geometry is determined by this very value. For neutrons with the energy less than 1 eV this duration parameter is more than two microseconds:

Δt (µs) = 2 / √E (эВ)

[D. F. R. Mildner and R. N. Sinclair, J. Nucl. Energy 6, 225 (1979)].

As a result the duration of proton pulse from the U-3.5, which is equal to 1.5 µs, would not deteriorate the neutron flash duration.

We have to draw attention to this important feature of the project. There are three different approaches to the construction of high intensity pulsed neutron sources:

- proton linear accelerator with energy around 1 GeV, very high (>150 mA) current in a pulse and high (>5 mA) average current (project ESS, Europe);
- linear accelerator with energy around 1 GeV with H- source and pulse current of 50 mA and accumulator ring, which compresses pulse from ~1 ms to fractions of microseconds (project SNS, USA);
- linear accelerator with energy ~400 MeV, average current H- up to ~0,5 mA and rapid cycling synchrotron, with energy up to ~3 GeV (J-PARC, Japan).

The proposed project uses the topology of the J-PARC project, but differs significantly in a few important details. The main difference consists in the orbit perimeters, which is rather long at the U-3.5 synchrotron. Such a solution gives a room for practically perfect optics, decreases the number of particles in a single bunch and, as a result, provides opportunity for the beam intensity increase. The payment for those advantages is some growth of neutron pulse duration, but as we have seen above, it does not compromise the ultimate parameters of neutron source. **Within this approach one can reach record parameters for neutron researches at nanometer and subnanometer wavelength scale.** The important advantage of proposed approach using the rapid cycling synchrotron, over the facility, based on the linear accelerators only, is a lower construction cost.

To compare the characteristics of the proposed source with what can be reached at nuclear reactors one should take into account the two parameters: average intensity of neutron fluxes and pulsed intensity. Comparing the proposed source with the research reactor ILL (Grenoble), one can find that average neutron fluxes at reactor are of about one order of magnitude greater than the fluxes in megawatt spallation source. At the same time, the pulsed neutron fluxes in megawatt spallation source are almost two orders of magnitude greater than these in reactor. As a result, for wide class of experiments the megawatt spallation neutron source appears to be more effective.

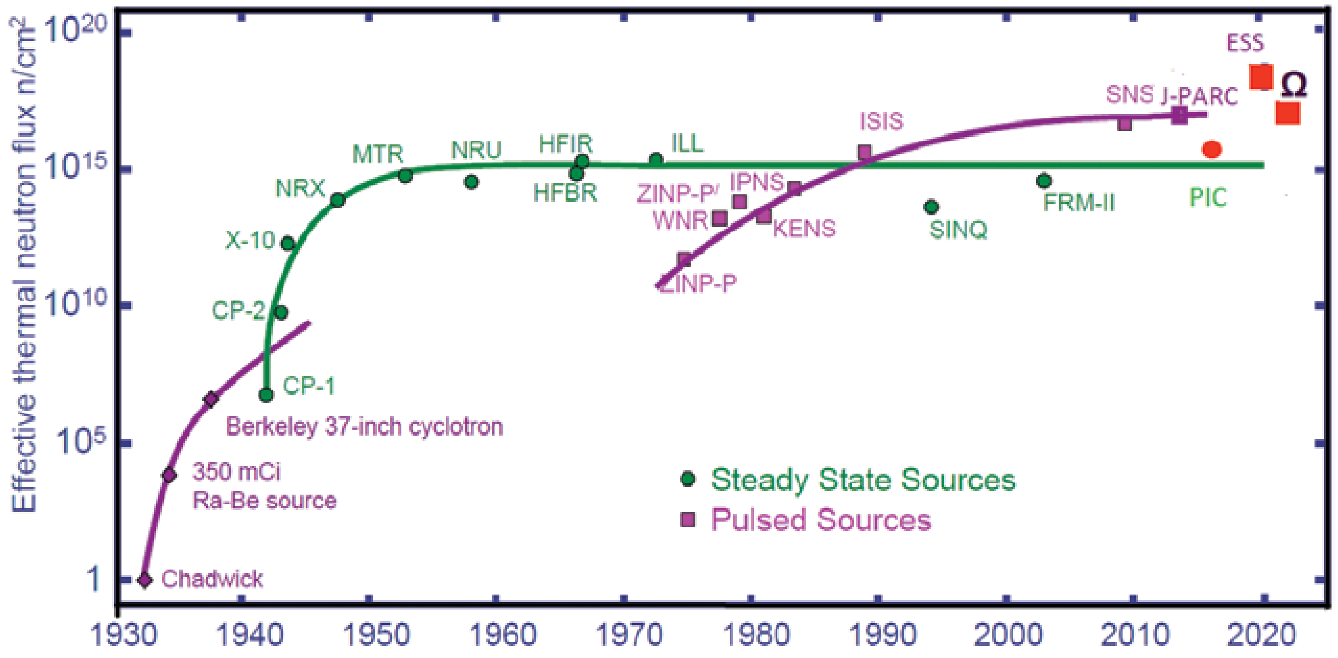


Figure 4.3. Effective thermal neutron flux intensity for different sources
(updated from Neutron Scattering, K. Skold and D. L. Price, eds., Academic Press, 1986)

Basic methods and trends of research with the neutron source

Various projectiles are used for research at nanometer and subnanometer scale: synchrotron (X-ray) radiation, electron beams and neutrons. The main advantages of neutrons are: the wide range of neutron energies, high penetration power, high sensitivity to light nuclei (protons) and minimal influence on studied objects.

Some examples of spallation neutron source applications:

- Solid state physics
- Physics of nanostructures
- Biology
- Chemistry
- Materials
- Environment
- Medicine

At this stage we don't fix the list of specific facilities, instead we estimate the total number of channels: it should be sufficiently big, around twenty.

4.2. Applied Research

Nuclear physics

A number of data on nuclear reactions with neutrons can be obtained with the dedicated channel for researches with time of flight (TOF) method. This method helps to study reactions induced by neutrons at wide range of energies on samples with masses as small as 1 mg. That is extremely important while working with highly active materials. Nuclear data from these experiments can be used for nuclear power facilities and for astrophysics.

Accelerator Driven System (ADS)

Proton beam falling on target made of heavy material generates flux of the secondary neutrons, which "triggers" the process of fission in nuclear fuel surrounding the target. The extracted beams of U-3.5 or LU-400 can be used for the prototype of ADS aimed for researches in power engineering and for prototyping technological solutions for would be commercial ADS.

In future the uranium target can also be used to create a pulsed neutron source with extremely high intensity.

Muons

Intensive muon beam can be used for researches on muonic catalysis. Negatively charged pions produced by proton beam decay to µ- and antineutrino ν_μ. Muons pass to synthesizer filled with mixture of deuterium and tritium, where mesoatoms and mesomolecules are produced with further nuclear fusion. In principal, such process could be interesting for nuclear power development.

Study of muon catalysis also gives the information for fundamental physics including:

- Light nuclei structure.
- Mesomolecular processes.
- Physics of atomic collisions.

One more direction in muon physics is µSR (Muon Spin Rotation/Relaxation/Resonance), the study of substances with muons used as a probe. Positive muons can be considered as impurity particle modeling the behavior of single-charge impurities (for example, proton). Exotic atom of muonium (μ^+e^-) formed in a substance is similar to hydrogen atom and can be used in study fast chemical processes. Negatively charged muons stopped in a substance form muon atoms, which can be used for crystal lattice studies.

At The OMEGA Facility by using the small fraction (<1%) of U-3.5 proton beam it is possible to form high quality muon beams with low energies and intensity above 10^6 µ/s. This intensity satisfies the requirements of µSR experiments.

Isotopes

Radioactive isotopes are widely used in diagnostic and therapeutic nuclear medicine, industry and research projects. The production of isotopes can be organized both at linear accelerator and at the U-3.5.

The following isotopes are widely produced and applied: I^{123}, F^{18}, C^{11}, N^{13}, O^{15}, $Rb^{81, 82}$, Ga^{67}, Ta^{201}, Re^{188}, Sr^{82}, Sn^{117m}, Se^{72}, Ac^{225}. The widening of available spectrum of isotopes could significantly affect the development of this perspective area of nuclear technologies.

Energy range of linear accelerators (100-400 MeV) is well suited for production of “traditional”, widely used radioactive isotopes. Comparatively high energy of U-3.5 protons gives additional possibility to produce neutron-deficit isotopes such as: Ag^{110}, $At^{204, 210}$, Cu^{61}, Er^{165}, I^{124}, $In^{111, 114m}$, Ir^{192}, Mo^{99}, Re^{186}, Rh^{103}, Tc^{99}, Tm^{170}, Yb^{169}.

Within the proposed facility the system of linacs has a reserve for intensity increase. That is why isotope production on linac system can be made without intensity losses at the U-3.5.

Study of dynamic processes with Doppler spectroscopy

High intensity proton beams opens the unique possibilities for study dynamic processes by means of Doppler spectroscopy of slow neutrons. In this method the pulsed proton beam is used for production of high intensity neutron flux with energies of tens of eV. Neutrons pass through investigated sample and are scattered (absorbed) on the admixture nuclei. Admixture element has narrow absorption lines at energies in a range of 5-50 eV. Position and width of absorption line are determined by neutron spectra measured with the TOF method. The motion of sample relatively to the source leads to Doppler shift, and the sample heating leads to the line broadening. With this method the data on state equations for various substances at very high temperatures and pressures realized in dynamic processes can be obtained.

4.3. Studies of Fundamental Processes

Ultracold neutrons

High intensity proton beam can be very effective for the ultracold neutron generation ($E<10^{-7}$ eV). Such neutrons are produced while slowing down the cold neutrons in supercooled (t ~1K) helium or in solid deuterium.

There are several sources of ultracold neutrons built on neutron beams extracted from reactor. The density of ultracold neutrons up to 10^3 n/cm^3 can be obtained with these sources. The construction of ultracold neutron source near active zone of reactor, in regions with highest neutron flux, is faced with two problems:

- as a rule, reactors have no enough space for demanded large cryogenic tools;
- the heat load on cryogenic system prevents from placing it near active zone.

There is only one project (reactor WWR-M at PNPI), where these obstacles are planned to be overcome.

At the spallation neutron source based on high intensity proton beam all these problems are reduced, because at the target station, where neutrons are generated, there is more space to arrange the cryogenic tools and, in addition, five times more neutrons are produced at spallation source than at the nuclear reactor of the same power. This approach to ultracold neutron source is realized at Los-Alamos (LANSCE), Zurich (PSI) and is projected in Canada (TRIUMF).

High intensity source of ultracold neutrons with density around ~10^4 n/cm3, which can be realized at The OMEGA Facility, can be used for experiments in various directions of fundamental science:

- search of electrical dipole moment (EDM) of neutron;
- measurement of neutron lifetime;
- measurement of β-decay asymmetry of neutron;
- study of macroscopic quantum effects for neutron;
- search for neutron-antineutron oscillations;
- search for neutron-mirror neutron oscillations.

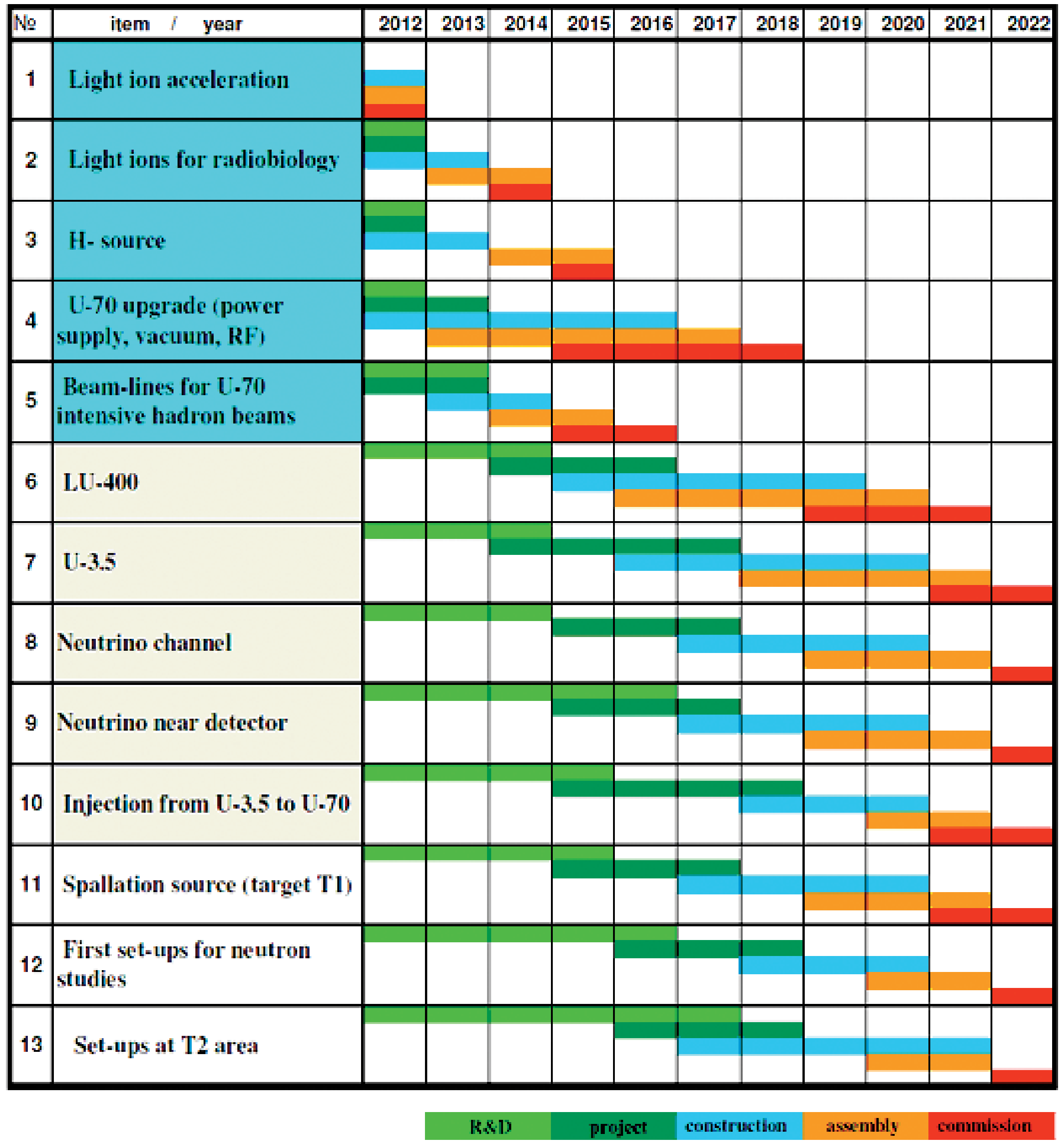
The dedicated target station with beam power >100 kW is necessary for this source.

5. Tentative Construction Schedule and Cost Estimations

Provisional construction schedule

Table 5.1 represents the provisional schedule for the OMEGA project.

Table 5.1.



The items 1-5 marked with blue color (Table 5.1) are not part of the project. These tasks are to be performed in the framework of the already planned programs. They are shown in Table 5.1 in order to represent the scope of the IHEP accelerator complex development. The items 6-10 in gray addressed to accelerator construction and fundamental physics, in white (11-13) – to applied research.

There are several milestones in this overall schedule:

- 2012: acceleration of deuteron and carbon ions in the U-70; first experiments with the accelerated nuclei;
- 2013: start of the U-70 upgrade in the frame work of the targeted federal program;
- 2014: delivery of the medium energy carbon beams for the radiological and biomedical studies;
- 2015: start of the H-minus source operation;

: the high intensity beams zone construction;

: the design completion for the new high intensity accelerator complex;

- 2016: improvement of the U-70 basic technological systems; completion of the Technical Design for The OMEGA Project and getting its approval;
- 2017: the start-up of the front-end part of linear accelerator; starting initial operation with high intensity beam;
- 2019: start-up of the linac LU-400;
- 2021: start-up of the RC PS U-3.5;
- 2022: injection of high intensity proton beam to the U-70 machine

: construction of neutrino channel (if the proposed neutrino studies prioritized)

- 2023: starting the operation with megawatt spallation neutron source (if applied neutron studies prioritized);

Cost estimations

Table 5.2 provides the capital costs estimations for the Facility of Intense Hadron Beams.

Table 5.2.

№	Object	Cost (million rubles)
1	Linac LU-400	7 200
2	RC PS U-3.5	10 100
3	Neutrino channel	1 500
4	Near Neutrino Detector	1 000
5	Neutron source (target station T1)	8 400
6	Neutron research set-ups	1 500
7	Injection from U-3.5 to U-70	800
8	Target stations T2 and T3	800
9	Infrastructure	700
10	Total	32 000

These cost estimations are based in particular on the cost data for facilities already completed or the projects under design or the proposed ones. For OMEGA project the R&D expenses are estimated at the level of 4 billion Rubles in the current prices.

Fig. 5.1 represents the funding profile required for the project completion during the time period of 10 years from the start of the R&D program funding.

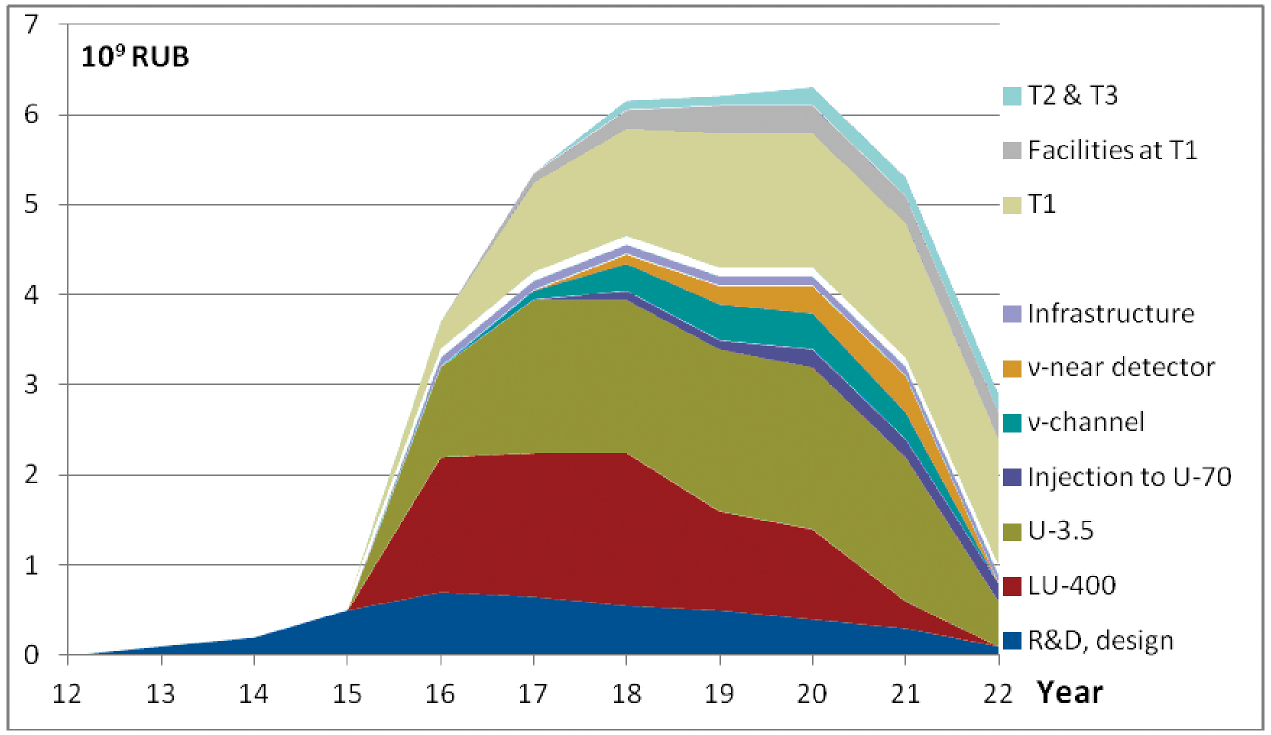


Figure 5.1. Funding profile. White line separates fundamental physics and applied research. The "top cap" is needed for construction of applied research facilities.

The organizational matters

The proposed project appears to be a natural development and continuation of the already performed or ongoing tasks conducted at IHEP in the frameworks of various programs.

Realization of such a large-scale project requires participation of a considerable number of highly skilled scientists and engineers. This is one of the most important prerequisites. It is to be solved in several ways:

1. The use of NRC «Kurchatov Institute» synergetic capabilities in scientific, technical and managerial matters and already existing experience in realization of megaprojects.

2. IHEP has a large experience in teaching and training. During many years IHEP is the basic Science&Education Center for the chairs of MSU, MIPT and MEPhI specialized in high energy physics and accelerators.

3. The OMEGA project assumes wide participation of the organizations having the required competences both in the R&D and construction phases. These organizations include not only the Russian accelerator laboratories traditionally cooperating in large accelerator projects, but also scientific and engineering institutes and companies with the experience in development of nuclear power facilities. In fact, the development and construction of the target stations for the high intensity beams assume a specific knowledge, and the experts on nuclear reactors are the most competent specialists in the field.

4. Creation of the new world-class neutrino facility as well as the pulsed spallation neutron source will open the unique possibilities for research in various fields of science. It will provide the basis for collaboration with organizations of fundamental and applied science as well as cooperation with the universities, for which the proposed facility should become the basic ones for their research programs.

Realization of The OMEGA Project will require development or restoration of the technologies in such fields as special electronics, high vacuum systems, powerful RF-systems, powerful pulsed systems, cryogenics and some others. These technologies are among the crucial ones determining the tendencies for innovative development. The main feature of the project is that the major part of the contracts will be addressed to high-tech sectors of the industry. That will provide conditions for the new jobs appearance and boost for the industry.

6. Prospects for Further Development

In this section possible ways of further development of The Facility for Intense Hadron Beams are considered for a long term perspective. Despite these options are not included in the project, the dedicated analysis is mandatory for optimization of the whole project structure and for the choice of technical solutions.

Antiproton Source

The beam power of the U-70 protons will achieve 450 kW according to the project. By this parameter the future facility will be very effective for production of antiprotons. At this stage the antiproton program is not considered as a top-priority one because it requires construction of the additional high-tech accelerating facilities for accumulation and cooling of antiprotons. In the future the experiments with antiprotons could become one of the central parts of scientific program.

High Intensity Synchrotron with the Energy up to 100 GeV

The existing U-70 synchrotron will remain the central element of the IHEP accelerator complex during a long time. In the framework of the proposed project the U-70 functionality will be essentially extended.

Nevertheless the main parameters of U-70 will limit development of a number of important trends in long term perspective. The U-70 accelerator is to be eventually replaced by a new synchrotron with the energy of about 100 GeV and the beam power of the megawatt range. The accelerator U-3.5 could serve as an excellent injector for such a synchrotron.

Storage Ring in the UNK Tunnel

The proposed development of the IHEP accelerators would open new possibilities for the use of the existing 21 km UNK tunnel. The 50 GeV storage ring may be assembled in this tunnel. This could be done by using the equipment earlier produced for the UNK project.

Proton storage ring with the energy of 50 GeV opens the new opportunities for multi-frame proton radiography of rapid processes. Indeed, the UNK ring is filled with proton bunches (29 or 27 bunches) during each of 14 cycles of the U-70. The bunch space is equal to 160 nanoseconds. Then the train of about 400 bunches is extracted from the storage ring in single turn (70 µs) and directed to the object under study.

Accelerator of Super High Intensity

Both the high intensity accelerator with the energy of 100 GeV (as an injector) and the existing 21 km long tunnel open the possibility to suggest in the future the construction of high energy accelerator (300÷500 GeV) with extremely high beam power of the order of 5 MW. This machine would use the conventional warm magnets because of high irradiation and is to be rapid cycling one with several seconds cycle duration. The large machine perimeter will allow acceleration and extraction of the super high intensity beams. The scope of their potential use is extended from the fundamental neutrino experiments to applied use of high beam power as well as of extremely high pulsed power.

The above considerations demonstrate the options for the further development of The OMEGA Project. Open architecture of the project and well developed technical infrastructure at IHEP are the significant features determining variety of the opportunities.

Conclusion

Studies of the fundamental properties of matter as well as studies of substances, materials, biological and other objects are the ultimate research clusters for the state progressing its economy on the innovative basis. The Facility for Intense Hadron Beams (The OMEGA Project) will boost such investigations on a frontier level.

This project is based on the IHEP expertise in the accelerator technologies and instrumentation as well as in physics research. The necessary condition for successful realization of the project is participation and cooperation of the Russian accelerator laboratories in the project.

The project will initiate development of the new advanced technologies and the new jobs in high-tech industries. As a result, number of new highly skilled personnel will appear in the advanced field of science and technologies.

Attachment

Useful formulas

Beam current:
J [Ampere] = N [second-1] × Q [Coulomb]
Beam current = Beam intensity × Particle charge
For U-3.5:
$N = 7.5 \times 10^{13} \times 25$ s-1
$Q = 1.6 \times 10^{-19}$ C
$J = 7.5 \times 10^{13} \times 25 \times 1.6 \times 10^{-19} = 0.30$ mA

Beam power:
W [W] = J [A] × E [eV] or W[MW] = J [mA] × E[GeV]
Beam power = Beam current × Beam energy
At beam current of 0.3 mA and beam energy of 3.5 GeV the power W = 1.05 MW

Characteristic neutron energy at thermal equilibrium with moderator at temperature t:
E [eV] = t [K] × k[eV/K], where $k = 8.6 \cdot 10^{-5}$ eV/K is Boltzmann constant
At t = 300K $E = 2.6 \times 10^{-2}$ eV

Wavelength of neutron with energy E:
λ[m]=2π × ђc[MeV·m] / p [MeV]
ђc = 1,97 × 10-7 eV·m
For $E = 10^{-2}$ eV $p = \sqrt{(2 mn \times E)} = 4{,}3 \times 10^{3}$ eV
$\lambda = 2\pi \times$ ђc/ p = $2{,}9\ 10^{-10}$ m = 0,29 nm
In convenient units: λ [nm] = 0,029/√E [eV]

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