ACCELERATOR TECHNOLOGIES DEVELOPMENT AT ITEP

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Abstract

Restart of scientific activity at ITEP associated with join it to the pilot project of NRC "Kurchatov Institute" is the occasion for summing up of intermediate results and existing capability of accelerator physics and technologies development in the institute. School of accelerators construction at ITEP has old traditions and refers on studying, invention, mastering and implementation to operation of technological features of proton and ion beams generation, transportation, acceleration, accumulation, extraction and space-time formation for usage of accelerated beams in physical experiments and applied research works. Historical survey and current state of accelerator science activity at ITEP are presented.

INTRODUCTION

The heyday of the accelerator areas in the country can be attributed to the mid 70-ies of the last century, when the proton synchrotron U-70 in Protvino occupied a leading position in the world and attempts were made to maintain this leading position in almost all areas of development accelerator science and technology. It was difficult to find such physical Institute, which would not have or were not going to have an accelerator facility for experiments in nuclear physics and physics of elementary particles or the practical use of the accelerated beams for applied purposes. In ITEP at that time, it was reconstructed the country's first alternating gradient synchrotron U-7, was created new experimental setups, was implemented proton therapy, were studied and begin to be realised new ideas for creating a linear accelerator with radio-frequency quadrupole focusing of the accelerated beam, were developed intensively technology of ion sources, was discussed actively the idea of creating high-current accelerators for use in electronuclear installations and in experiments on heavy ion fusion. Created in those years in ITEP scientific-technical potential, technology base and high school for training of specialists were allowed to retain up to the present time the leading position of the Institute in the development of accelerator science and technology, despite the constantly changing not for the better conditions for the development and implementation of promising projects.

Historical analysis of distance travelled from emergence of accelerator subjects in ITEP to the current state of Affairs and possible directions in the future use and development of existing scientific and practical groundwork is the basis for the search of optimal ways of combining the efforts of stakeholders in the revival of the accelerator industry in the country to a new level of technological development and expansion of the practical use of charged particle beams

FIRST ACCELERATOR IN ITEP

The first accelerator appeared at ITEP in 1948, three years after the establishment of the Institute It was a cyclotron capable of accelerating protons to an energy of 6.2 MeV, deuterons up to 12.5 MeV and the α-particle up to 24 MeV, with relatively high current of the accelerated beam: current of deuteron at work on the inner target was reached 600 μA, the current of extracted beam was 70 μA. The cyclotron has successfully operated more than 20 years and was dismantled in 1972. If it was known then, where we will come in 40 years, it would have to be preserved.

HISTORY OF THE FIRST ALTERNATING GRADIENT SYNCHROTRON IN RUSSIA

In Russia the principle of alternating gradient focusing became aware of the messages that appeared in the October 1952 American popular science magazine Scientific American. On the initiative M.S.Kozodaev, drew attention to the importance of this message and entrusted to A.A.Tyapkina to check the correctness of this idea, in early January 1953, a meeting was organized in the office of the Minister of medium machine building M.G.Pervukhina [1], which was attended by all the leading accelerator scientists at that time in the country: V.I.Veksler, A.A.Kolomensky, M.S.Rabinovich, V.V.Vladimirsky, and other. In spite of serious doubts as to the correctness of this principle, expressed at the meeting, it was approved the proposal of V.V.Vladimirsky to build on the territory of the ITEP proton synchrotron U-7 on energy 7 GeV to check the beam stability at alternating gradient focusing , and, if successful, to begin the design of the 70 GeV accelerator U-70 and finding a place for its construction.

Design of U-7 (Fig.1) and U-70 began under the leadership V.V.Vladimirsky in 1953, and in 1961 the U-7 was put into operation with electrostatic injector [2].

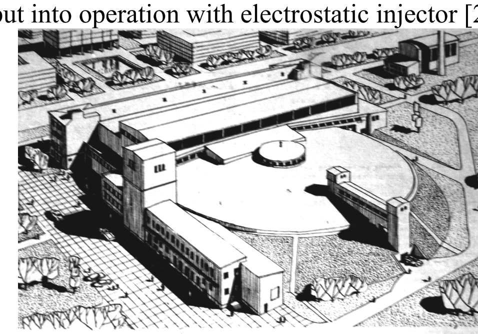

Figure 1: General view of U-7 Accelerator in ITEP

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The main role in actually opening new directions for the development of accelerator science and technology in Russia belongs to the Director of ITEP academician A.I.Alikhanov, which, due to the high personal authority, has made the Government's decision to build two proton AGS synchrotrons - U-7 in Moscow, and U-70 in Protvino, city, whose existence is also obliged A.I.Alikhanov.

CONSTRUCTION OF PROTON LINEAR INJECTORS

Projects of proton synchrotrons ITEP (U-7) and IHEP (U-70) were designed for operation with injected beam current of about 100 mA. Available at that time, the experience of linac construction with grid focusing (KIPT and JINR) could not be used directly, since it was possible to obtain the output current of the proton beam not higher than 1 mA.

The design of linear injectors I 2 on the energy 25 MeV for U-7 and I-100 (100 MeV) for U-70 began in 1958, under the leadership I.M.Kupchinsky. Design, development and construction of both of these injectors were carried out under the general guidance of V.V.Vladimirsky and academician A.L.Mintz, head of RTIAS. The work involved several dozen research institutes and industrial enterprises of the country.

Obtained in the laboratory of I.M.Kupchinsky calculations have allowed to develop a theoretical justification and to determine the parameters of the injectors I-2 and I-100 [3,4]. The launch of accelerator I-2 (Fig.2) took place on 2 November 1966 [5], when it was obtained a record beam current of 135 mA, which was later increased to 250 mA.

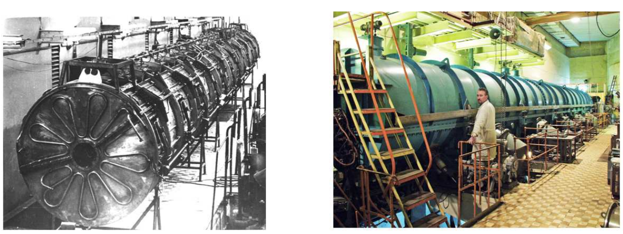

Figure 2: Resonator and tank of linac I-2

The project energy 100 MeV was achieved on the accelerator I-100 28 July 1967 at the current of the accelerated beam 5 mA. By the end of 1967, the output current of the I-100 beam was raised to 60 mA, which enables the injection of the beam during physical launch of synchrotron U-70. Shortly after starting up the machine all work on I-100 moved fully to the staff of IHEP

RECONSTRUCTION OF U-7

Reconstruction of the U-7 synchrotron was carried out in 1973 [6]. In addition to the change of the ring lattice were reconstructed virtually all systems of the circular accelerator: the accelerating tubes were replaced with ferrite resonators, the vacuum system was completely replaced, lamp low voltage electronics was replaced by transistor one, it was created new main power supply, and entirely new distribution system for secondary beams on experimental installations, computer control began to be implemented.

The main result of the reconstruction: the increase in the intensity of the secondary beams more than tenfold. The intensity of the accelerator has exceeded the level of 10^{12} particles per pulse and reached the value of $1.5x10^{12}$.

PROTON THERAPY IN ITEP

The ITEP medical proton facility has been working since 1969 [7]. Energy value was regulated in the range 70-200 MeV by the time of beam ejection from the synchrotron on the ramp of magnetic cycle. One bunch from the four accelerated was used for medicine. The remaining 3 bunches were accelerated further to be used by physicists. Four treatment installations placed in three treatment rooms were used: that for stereotactic multidirectional irradiations of intracranial targets, that for eye and orbit tumors irradiations, that for urogynecological tumors, and that for general oncology.

Up to 1988, 8000 patients has been proton treated in the world, 2500 of them in the USSR. There were 3 proton therapy facilities in Russia: in Moscow (ITEP), in Leningrad (LNPI) and in Dubna (LNP. JINR), 77% of Russia-treated patients had been irradiated in Moscow, 20% in Leningrad, and 3% in Dubna.

DEVELOPMENT OF HIGH CURRENT LINACS

Acceleration of high current beams of proton or ions requires strong focusing of the beam at the initial stage of acceleration to compensate Coulomb forces in the beam. This problem has been solved by V.V,Vladimirsky, I.M.Kapchinsky and V.A.Teplyakov inventing SHQF – Specially Homogenous Quadrupole Focusing (1968) [8], renamed later Radio Frequency Quadrupole (RFQ) [9].

The first accelerator based on this principle was implemented by Teplyakov in 1974 as 2H resonator [10].

In ITEP, the first high-current proton RFQ-1 was developed under the guidance of I.M.Kapchinsky in the period 1976-1982 as four vane resonator [11, 12]. Fig, 3 shows a detail of a vane machined with a constant radius of curvature. This RFQ-1 accelerated protons from 88 keV to 3 MeV with beam pulse current 250 mA.

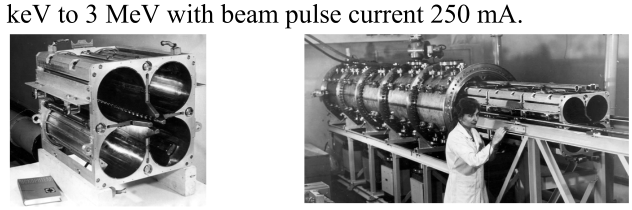

Figure 3: Inlet section of 4-vane resonator and assembled one with vacuum shell

However, RFQ-1 was found to have some drawbacks, main among which was insufficient heat sink for operation with a maximum average beam current

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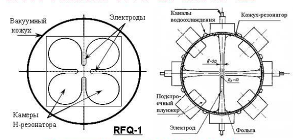
An improved version of RFQ2 (Fig.4) was developed and implemented in 1998 [14]. The design of the sections and scheme of cooling channels allow to receive the average beam current up to 5 mA.

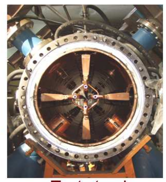
Cross sections of RFQ1 and RFQ2



Parameter of RFQ2 (1998)

Injection energy, keV	81
Output energy, MeV	3
RF, MHz	148.5
Repetition rate, Hz	25
Pulsed beam current, mA	200
Average beam current, μA	500
Resonator length, m	4.5
Resonator diameter, mm	449
Transmission, %	>90

Inlet section



Test stand

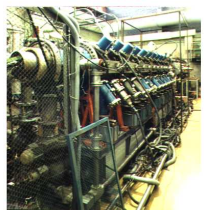
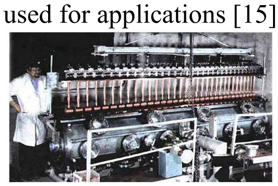


Figure 4: Design and parameters of RFQ-2

The RFQ-2 structure was to be used in the accelerator ISTRA56 on the energy of 56 MeV and beam current of 500 μA. It consists of the RFQ followed by an Alvarez linac with permanent magnetic quadrupole focusing (Fig.5). The planned linac had to serve as an new injector to synchrotron U-10 replacing the old linac I-2 and to be used for applications [15].



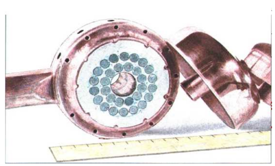


Figure 5: Drift tube line of resonator DTL1 and PMQ

A new version of 90^o – apart-stem RFQ structure, has been proposed by V.A.Andreev [16], hence–forth called "4-ladder ", which combines the merits of 4-vane and 4-rod RFQ's, has been developed in the frame-work of a collaboration between ITEP and INFN-LNL. It has good RF efficiency (quite reliable mode separation and field distribution) and maintains such merits of a 4-vane structure as simplicity of manufacture and mechanical stability. Upgraded version of "4-ladder" RFQ successfully operates since 2001 at a frequency of 27 MHz on the accelerator of heavy ions TIPr (Fig.6). This RFQ designed to accelerate 15 mA of U^{4+} ions from 1.5 to 110 keV/u. Combination of quadrupole and coaxial modes is excited in the structure and provides a reliable separation between operating mode and dipole ones [17].

Ring-connected RFQ

Z/A of ions	1/60
Injection energy, keV/u	1.5
Output energy, keV/u	110
RF, MHz	27
Length of resonator tank, m	12
Inner tank diameter, m	1.2
Aperture radius, mm	6.4
Shunt-impedance, MΩ m	1.49
Transmission at 15 mA, %	96
Beam pulse width, μs	400
Average beam current, μA	5

Figure 6: Prototype of heavy ion driver for inertial fusion

ITEP-TWAC FACILITY

The task of creating heavy ion accelerating-storage complex for experiments of ion beams on physics of high energy density in matter began to be solved at the ITEP accelerator complex on the proposal D.G.Kochkarev and B.Ju.Sharkov in 1996. For generation of high-current beams of multiply charged ions, it was assumed to use laser ion source (LIS) with powerful pulsed CO_2 laser. Available in the ITEP two magnetic rings, synchrotron U-10 and the retaining ring UK, are allowed to consider the scheme of obtaining the maximum intensity and, accordingly, high power beam using technology of multiple charge-exchange injection of heavy ions into the storage ring [18].

During execution of this work, it were resolved following main tasks:

It was developed and brought into practical use in accelerators new technology of generation and formation of high-current beams of multiply charged ions in LIS with using of high power pulsed CO_2 laser.

It was developed and mastered the technology of multiple charge-exchange injection of heavy ions and accumulation of nuclei beams that monotonically increase of particles density in phase space to reach the extreme nuclei intensity in the circulating beam.

On the basis of the developed technology, it has been created a unique heavy ion complex ITEP-TWAC [19], and implemented acceleration up to relativistic energies of ions with mass number up to 100, including ions Ag^{19+} up to 10 GeV with intensity 2.5x10^7 and nuclei Fe^{26+} (200 GeV, 2x10^8). In the U-10 Ring, it has been received stripping accumulation of nuclei C, Al, Si, Fe in the energy range of 200-300 MeV/u with factor of beam stacking up to 70 (Fig.7).

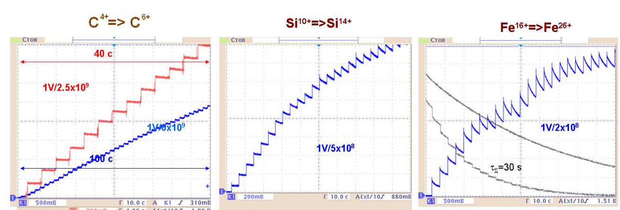


Figure 7: Stacking of nuclei C, Si and Fe in U-10 Ring

PROJECT OF MULTIPURPOSE ACCELERATOR COMPLEX

Created structure of the accelerating-storage complex ITEP-TWAC [20] focused on fundamental and applied research using accelerated beams of protons and ions can be considered as the basis for creating multi-purpose proton-ion accelerating-storage complex (MAC) that meets the needs of many interested in the use of proton and all types of ions beams of intermediate energies areas of modern science, engineering and technology, and to be able with maximum efficiency to meet these needs.

The main areas of MAC includes [21]:

- fundamental and applied research with relativistic proton and ion beams in the energy range from 1

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GeV/u up to 10 GeV for protons and 5 GeV/u for ions;

- applied research with proton and ion beams in the energy range from 10 MeV/u up to 1000 MeV/u in industry, biology and medicine;
- fundamental and technological research with high power stacked nuclei beams in the energy range of <1 GeV/u;
- technological research for generation, acceleration, accumulation, compression, extraction and sharp focusing of high charge state and high intensity heavy ion beams;
- expansion of scientific and educational activity in the areas of nuclear technologies.

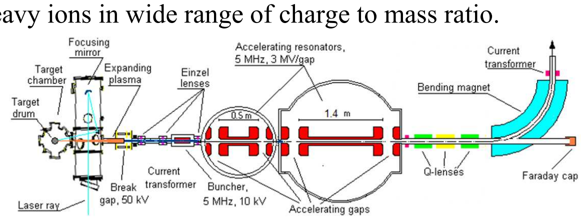
Practical implementation of MAC in ITEP is based on:

- high current proton and ion linacs development;
- extending of accelerated ions up to A~200;
- cardinal increase of intensity for accelerated ion beams in UK Ring on a base of ion injector and synchrotron upgrade;
- cardinal increase of intensity for stacked nuclei beams in U-10 Ring on a base of charge exchange injection technology improvement;
- expansion and development of machine experimental area;
- mastering of multimode machine operation in parallel with proton and ion beams for maximal efficiency jf machine operation.

The basis of MAC parameters is upgraded injection complex of circular accelerators. Three independent injectors for protons, heavy ions and light ions provide enhanced opportunities for multi-use machine operation.

Upgrade of proton injector I 2 will allow raising of beam intensity to empower applied use of the beam. The new injection channel from I-2 to UK will allow accelerating in this Ring not only ions but protons too.

Upgrade of I-3 (Fig.8) will raise the beam energy to 12 MV and accelerating frequency from 2.5 to 5 MHz. This accelerator will be used with laser L-100 for acceleration of heavy ions in wide range of charge to mass ratio.



Accelerating ions, A/Z	3-10	Parameter	R1	R2
Injection energy, kV	50	Height, mm	2500	2970
Resonance frequency, MHz	5	Diameter, mm	1500	1985
Accelerating voltage, MV	12	Spiral diameter, mm	700	700
Trans. acceptance, π· mm mrad	1000	Spiral length, mm	1000	1500
Output momentum spread, Δp/p,%	1	Length of drift tube, mm	500	1400
Transmission factor, %	>50	Aperture, mm	70	
Quality	~6000	Width of accelerating gap, mm	250	

Figure 8: Layout and parameters of upgraded linac I-3

New high current injector I-4 is designed for the acceleration of light ions with a current up to 100 mA and will be used with laser L20 (Fig.9). The beam intensity of linac I-4 is limited by LIS on the level of ~10^{11} particles per pulse

Upgrade of the booster synchrotron UK is aimed before all at reducing the loss of accelerated ions due to the cardinal improvement of the vacuum system and increase the rate of beam acceleration. The result of UK upgrade should be getting vacuum <10^{-11} Torr and a doubling of the magnetic field ramp that will minimize particle losses during acceleration.

Parameters
RF - (~80 MHz)
Energy - 5÷7 MeV/u
Z/A - ≤1/3
Imax - up to 100 mA

RFQ section for the energy of 1,6 MeV/u

Parameters of RFQ section

RF, MHz	81.5
Z/A	≤1/3
Energy, MeV/u	0.02/1.57
Voltage, kV	182.5
Input emittance, mm mrad	3.27*π
Output emittance, mm mrad	2.3*π
Beam current, mA	до 100
Repetition rate, Hz	до 1
Beam pulse width, μ	100
Beam energy spread, %	±1.5
Resonator length, m	6.258
Resonator diameter, m	0.564
Quality	11000

Figure 9: RFQ section and parameters of linac I-4

New system of beam slow extraction will be created to extend the use of this ring for applied purposes.

Intensity of ion beams accelerated in the synchrotron UK is limited LIS with laser L20 for I-4 and L100 for I-3. Since the beam intensity, however, is quite high (Fig.10), we do not consider now the possibility of using other types of ion sources.

Accelerated beam parameters with injector I-4
$A/Z \leq 3$, U_{inj} =7 MV/u, β_{inj} =0,122, F_{acc} =0.7÷10 MHz, T_{UK}=6.1 μs, p_{max}=4 GeV/c

A/Z	3(C^{4+})	2.8(Si^{10+})	2.45(Al^{11+})	2.4(C^{5+})	2.33(Si^{12+})	2 (C^{6+})
E_{max}, MeV/u	668	744	910	941	981	1229
N_{max}, p/p	8,1x10^{11}	3,0x10^{11}	2,4x10^{11}	5,2x10^{11}	2,1x10^{11}	3,6x10^{11}
N_{exp}, p/p	3.0x10^{11}	1.4x10^{11}	1.3x10^{11}	1.4x10^{11}	1.3x10^{11}	2.0x10^{11}

Accelerated beam parameters with injector I-3M
$A/Z \geq 3$, U_{inj} =(1÷ 3.5)MV/u, β_{inj} =(0.05÷0.09) , F_{acc} =0.7÷10 MHz, T_{UK}=9÷16 μs

A/Z	10(U^{24+})	9(U^{28+})	8(Au^{25+})	7(Ta^{26+})	6(Ag^{19+})	5(Ag^{22+})	4(Fe^{16+})	3(Ni^{18+})
E_{max}, MeV/u	78	95	120	154	204	283	417	668
N_{max}(T_b=5 μs)	2x10^{10}	1.7x10^{10}	2.4x10^{10}	2.8x10^{10}	3.5x10^{10}	2.4x10^{10}	4.3x10^{10}	5.1x10^{10}
N_{exp}, p/p	6.0x10^{9}	5.5x10^{9}	6.0x10^{9}	6.0x10^{6}	8.0x10^{9}	7.0x10^{9}	9.0x10^{9}	8.5x10^{9}

Figure 10: Ion beams accelerated in synchrotron UK

Upgrade of the U-10 rings is focused on three main objectives: 1) creating opportunities to accelerate any type of ions to relativistic energies; 2) improvement of technology for stripping accumulation of ions; 3) creation system of combined (fast and slow) extraction of the beam for protonography and nuclear physics.

Modification of charge-exchange injection scheme for the range of Z/Z_o variation from 0.27 to 0.87 will allow to accelerate in U-10 Ring any type of ions. The parameters of light and heavy ions accelerated in the U-10 Ring up to relativistic energies are shown on Fig.11.

Upgrade of charge exchange stacking system is aimed at the real achievement of terawatt power level for stacked beam of nuclei with energies <GeV and includes improvement of one turn bump system and stripping

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targets mechanics for increase of injection efficiency up to absolute value, and implementation of new systems for dynamic expanding of accumulator acceptance at beam stacking to 100 π mm mrad and stochastic cooling of stacked beam which will eliminate the disturbance of the circulating beam after injection of another portion of the particles. The expected result should be an increase of stacked beam intensity up to $>10^{13}$ (for C^{6+}, 0.9 GeV/u) and $>10^{12}$ (for Co^{27+}, 0.5 GeV/u).

Parameters of injected light ions

$A/Z \le 3$, E_{inj} =(200÷300) MeV/u, p_{inj}=2Z GeV/c, T_{inj}=1.5 μs, h=2, F_{inj} =1.4÷1,7 MHz,

Overcharge	$_{12}C^{4+}$=>C^{6+}	$_{28}Si^{10+}$=>Si^{14+}	$_{27}Al^{11+}$=> Al^{13+}
E_{inj}, MeV/u	214	242	306
E_{max}, MeV/u	4250	4250	4060
N_{exp} with I-4, p/p	$3.0x10^{11}$	$1.4x10^{11}$	$1.3x10^{11}$
N_{exp} with I-3, p/p	$2.0x10^{11}$	$7x10^{10}$	$3x10^{10}$

Parameters of injected heavy ions

$A/Z>3$, E_{inj}=(100÷250) MeV/u, p_{inj}=(2÷4)Z GeV/c, T_{inj}<2 μs, h=2, F_{inj} =1.0÷1,5 MHz

Overcharge	U^{28+}=>U^{92+} U^{28+}=>U^{90+}	Au^{25+}=>Au^{79+}	Ag^{22+}=>Ag^{47+}	Fe^{16+}=>Fe^{26+}
$E_{инж}$, MeV/u	105	121	179	242
E_{max}, MeV/u	2960	3180	3240	3800
N_{exp}, p/p	$2x10^9$	$4.0x10^9$	$6.0x10^9$	$8.0x10^9$

Figure 11: Ions accelerated in U-10 Ring

Experimental area of MAC is shown on Fig.12. the complex infrastructure compactly arranged for extraction of protons and ions beams and placement of experimental installations and test stands. BEH is divided into two areas: the protected area of the extracted beams of high intensity and momentum up to 10Z GeV/c and the area of secondary beams, combined with zone of slow extracted beams of low intensity for radiation testing of electronics. MH and TH is used for applications and experiments on physics of high energy density in matter. All of the experimental installations and stands are supplied with protons and ions. Linear accelerators are also equipped with stands for applied purposes.

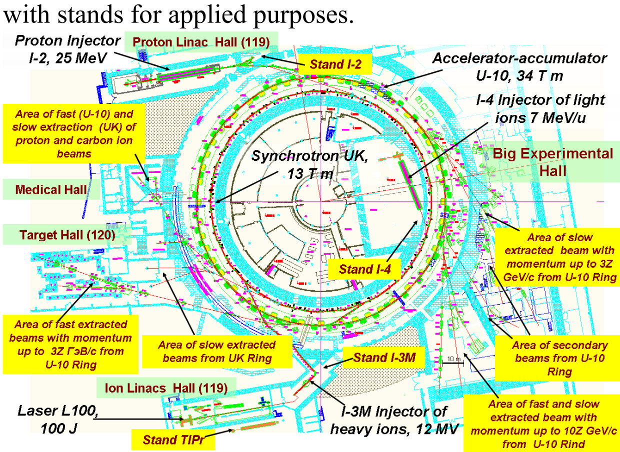

Figure 12: Layout of Multi-purpose Accelerator Complex

CONCLUSION

More than sixty-year history of the development in the thematic areas of accelerator science and technology in ITEP marked a number of significant stages of elaboration and implementation of ideas and projects that helped create accelerator facility: U-7, I-2, I-100, U-70, U10, RFQ1, RFQ2, HIP1, ISTRA10, ISTRA36, TIPr, I-3, UK, ITEP-TWAC.

Accumulated in ITEP scientific and technical potential has allowed to create the technological base and scientific school for training of highly qualified engineers and scientists in the field of physics of charged particle beams and accelerator technology.

Construction of accelerator facilities at ITEP has always been focused on the development of the experimental base of the Institute, on carrying out fundamental and applied research with beams of protons and ions of intermediate energies, as well as studying and elaboration of promising technologies for generation, acceleration and accumulation of protons and heavy ions beams for accelerators and experimental facilities of future generations.

The proposed project of Multi-purpose Accelerator Complex created on the basis of ITEP Ring Accelerators with using of existing technological reserves will ensure continuous improvement of technical and scientific level of the research in line with the growing requirements of the physical experiment in the composition of the world's leading heavy ion complexes of intermediate energies .

Solid and reliable foundation for the creation in the ITEP experimental area on the basis of the upgraded accelerator complex ITEP is in demand in various fields of fundamental and applied research and the perspective of effective use of accelerated beams of protons and ions generated in a wide range of operating parameters.

REFERENCES

[1] A.Tjapkin, .http://bourabai.ru/tyapkin/publications.
[2] PTE №4 (1962)
[3] V.K.Plotnikov et al. Preprint ITEP, N389, 1965
[4] I.M.Kapchinsky et al. Preprint IHEP, 67-38, 1967
[5] PTE, N5 (1967)
[6] N.N.Alexeev, et.al Proc. of VI Rus. Acc. Conf. v.1, p.327 (1975)
[7] V.S.Khoroshkov, et al.. Int. J. Rad. Onc. Biol. Phys., 15, N4 (1988)
[8] V.V.Vladimirsky et al., Avt. svid. USSA № 265312. Bjull. OIPOTS, N10, p. 75 (1970)
[9] I.M.Kapchinsky et al. Proc. of VII Int. Part. Acc. Conf., v.1, p.153 (1970)
[10] V.A.Teplyakov et al. Proc.of VI Int. Part. Acc. Conf. p.125 (1967)
[11] I.M.Kapchinsky et al. PTE, №2, 1970, p.19.
[12] B.L.Ioffe et al., Proc. of VI Rus. Acc. Conf. v.1, p.236 (1978)
[13] E.M. Pottmeyer. Proc. of VI Rus. Acc. Conf. v.1, p.264, (1978)
[14] V.S.Artemov et al., Proc. of XVI Rus. Acc. Conf. v.1, 1998, p.223,
[15] A.I.Balabin et al. Preprint ITEP, № 157, (1989)
[16] V.A.Andreev, G.Parisi. Proc. of the 1993 Part. Acc. Conf., Washington D.C., (1993)
[17] D.Kashinsky et al.. Proc. of EPAC'00, p.854, (2000)
[18] N.N.Alexeev et al. Let. of JETP, v.77-3, p.149 (2003)
[19] N.N.Alexeev et al. Atomic Energy, v..93, p.474 (2002)
[20] N.Alexeev, et al., IPAC'11, p.2193-2195, (2011)
[21] N.Alexeev, et al., RuPAC'12, p.112 (2012

ISBN 978-3-95450-170-0