ITEP-TWAC RENEWAL AND UPGRADING PROGRAM

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Abstract

The ITEP-TWAC facility has been put out of operation this year as a result of some equipment damage by the fire, so the program of machine renewal and its equipment upgrading for accelerated beams parameters improvement and experimental area expansion is now under processing and development. Main items of this program and status of machine restoration activity are presented.

INTRODUCTION

ITEP Ring Accelerator Facility has celebrated last year 50-th anniversary of first 7 GeV accelerated proton beam, so substantial part of the ITEP-TWAC components has been in keeping with its age requiring some additional efforts for rejuvenation of obsolete equipment, communications and structural components and the problem of machine upgrade has been discussed last few years [1]. The main directions of the ITEP-TWAC upgrade were considered for realisation in parallel with machine operation with proton and heavy ion beams in different applications on a base of new accelerator technologies development. The laser ion source technology development was oriented to getting of high current and high charge state ion beam of Z/A up to 0.4 for elements with A ~ 60 to be effectively stacked in the accumulator ring with multiple charge exchange injection technique at the beam energy of up to 700 MeV/u. The new high current heavy ion linac was under construction. Design of proton injection and beam slow extraction for UK ring was performed for its utilizing as self-depending synchrotron in medical application and for imitation of cosmic radiation.

Decommissioning of accelerator facility in this year and destruction of some part of its equipment forced to reconsider the program of machine upgrade on the basis of achieved results in development of ITEP-TWAC project and substantial refinery of the ultimate aim, purpose and main tasks of the proposed reconstruction.

STATUS OF ITEP-TWAC IN 2011

The ITEP-TWAC facility (Fig.1) consisting of main synchrotron-accumulator U-10 with 25 MeV proton injector I-2 and linked to U-10 Ring booster synchrotron UK with 4 MV ion injector I-3 has been in several operation modes accelerating protons in the energy range of 0.1-9.3 GeV, accelerating ions in the energy range of 0.1-4 GeV/u and accumulating nuclei up to Cu at the energy of 200-300 MeV/u. Accelerated beams were used in following modes: secondary beams generated in internal targets of U-10 Ring transferred for experiments to Big experimental hall (BEH); beams extracted from U10 Ring in one turn transferred to Target hall (TH); and proton beam bunch extracted from U-10 ring was transferred to Biological research hall (BRH). Some of secondary beam lines were used for transferring of slow extracted beams from U-10 Ring.

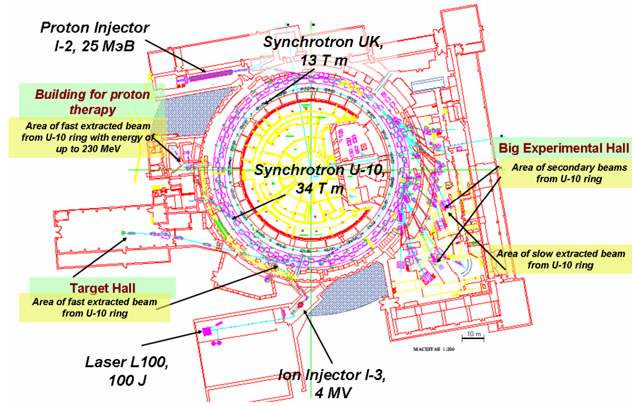

Figure 1: Layout of ITEP-TWAC Facility.

Statistic of machine operation time is shown on Fig.2. The total beam time of near 4000 hours per year was divided between three operation modes: acceleration of protons (~50%), acceleration of ions to intermediate and relativistic energy (~30%) and nuclei stacking (~20%).

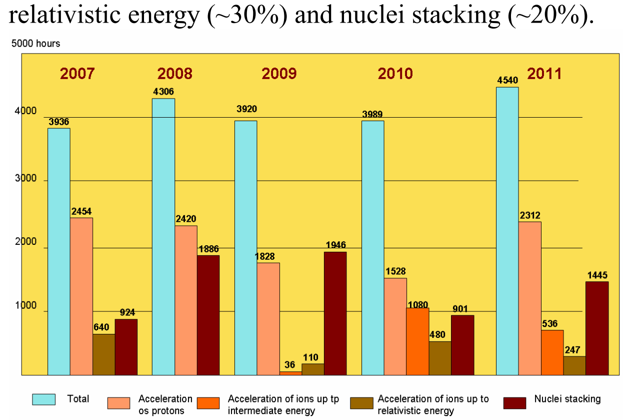

Figure 2: Statistic of ITEP-TWAC operation time.

Statistic of machine using for different research fields (Fig.3) shown the tendency of beam time increase for applications such as biology, medicine, protonography and testing of heavy ion radiation steadiness of electronics destined for cosmic apparatus. The demand for beam time exceeded the offering one by factor of two. This discrepancy was supposed to be cardinally reduced in a result of machine infrastructure improvement.

One of a challenge technologies implemented in ITEP-TWAC is laser ion source (LIS) with high power CO_2-laser. Charge states of ions generated in the LIS are shown in Fig.4.

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Research fields with proton and ion beams	Beams	Accelerator operation time, hours		
		2009	2010	2011
Adron physics and relativistic nuclear physics	p (2-9 GeV, $10^{11}s^{-1}$) C (4 GeV/u, $10^{8}s^{-1}$)	1100	850	702
Methodical research	p (1-9 GeV, $10^{11}s^{-1}$) C, Fe(0,2-4 GeV/u, $10^{8}s^{-1}$)	2100	2045	2450
Physics of high density energy in matter	C, Al, Si, Fe (300 MeV/u, $4x10^{10}s^{-1}$)	350	330	288
Radiobiology and medical physics	p (250 MeV, $10^{11}s^{-1}$) C (200-400 MeV/u, 10^{9} s^{-1})	2150	2040	2320
Proton therapy	p (250 MeV, $10^{11}s^{-1}$)			
Radiation treatment of materials	p (20-800 MeV, $10^{11}s^{-1}$) Fe, Ag (40-200 MeV/u, 10^{8} s^{-1})	1100	550	779
Total		6800	5815	6539

Figure 3: ITEP-TWAC usage for different research fields.

Generation of Fe-ions shows pick current for charge state specie Fe^{16+} with IP= 506 V. The higher level of charge state specie Fe^{17+} with IP=1168 V has been also observed but in very few quantity. Generation of Ag-ions shows maximal charge state specie Ag^{20+} with IP= 816 V and very few specie Ag^{21+} with IP= 895 V has been also observed in some measurements.

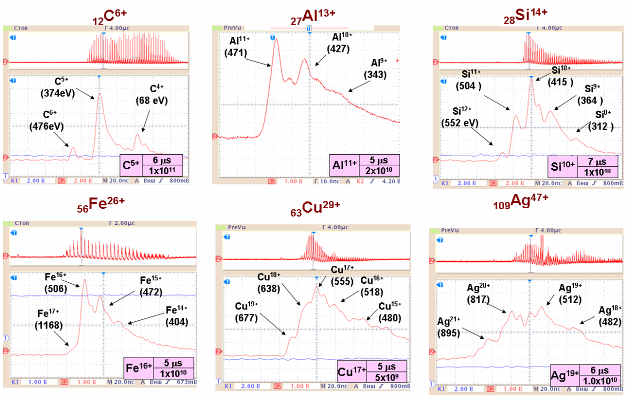


Figure 4: Ions generation in LIS with laser L100.

Acceleration of different ions in synchrotron UK is illustrated by typical oscillograms on Fig. 5. It's seen that the beam loss on the ramp is large enough due to very low injection energy (4 MV) and vacuum as $1x10^{-9}$ Torr.

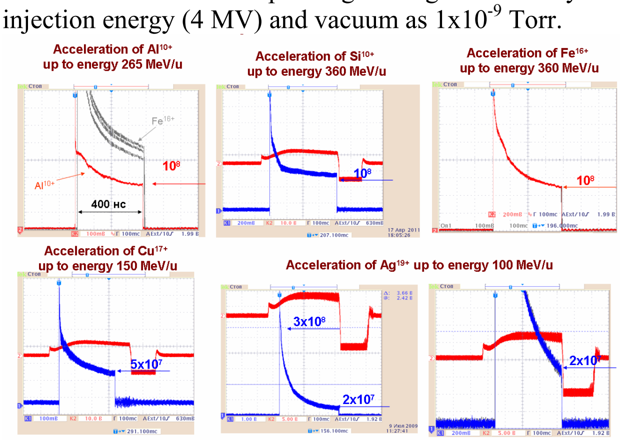


Figure 5: Acceleration of different ions in UK Ring.

Technology of Fe-nuclei acceleration up to relativistic energy of 3.6 GeV/u using three step scheme I-3/UK/U10 is illustrated by sequence of oscillograms on Fig.6.

The charge exchange injection technique has been used for accumulation of C-, Al-, Si - nuclei at the beam energy of ≤300 MeV/u with stacking factor up to several tens. The maximal stacking factor been achieved at optimization of carbon nuclei stacking (Fig.7). The optimal conditions for Al- and Si- nuclei stacking (Fig.8) were not yet obtained to be subject of forthcoming experiments.

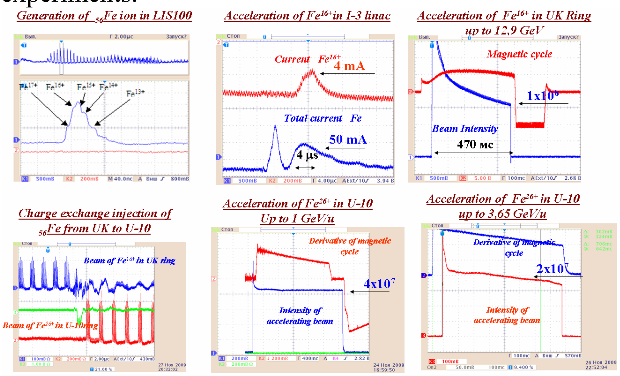
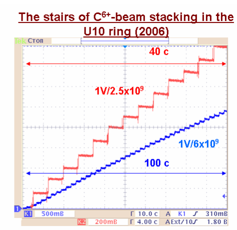


Figure 6: Fe-nuclei acceleration up to relativistic energy.

Energy	300 MeV/u
Intensity of injecting beam	$6x10^{8}$
Repetition rate, s	3
Acceptance, A_x, π mm mrad	10
Vacuum, Torr	$\sim 1x10^{8}$
Stacking factor	~70
Intensity of stacked beam	$4x10^{10}$



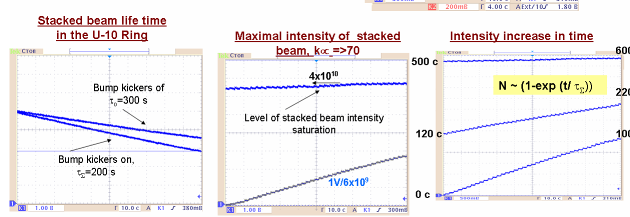


Figure 7: Optimization of carbon nuclei stacking in U-10 Ring by scheme of C^{4+}=>C^{6+}.

	Al	Si	Fe
Energy, MeV/u	265	240	230
Intensity of injecting beam	$\sim 1x10^{8}$	$\sim 5x10^{7}$	$\sim 1x10^{8}$
Repetition rate, s		4	
Acceptance, A_x, π mm mrad		10	
Vacuum, Torr		$\sim 1x10^{8}$	
Stacking factor	~30	~ 20	~10
Intensity of stacked beam	$\sim 3x10^{9}$	$\sim 1x10^{9}$	$\sim 1x10^{9}$

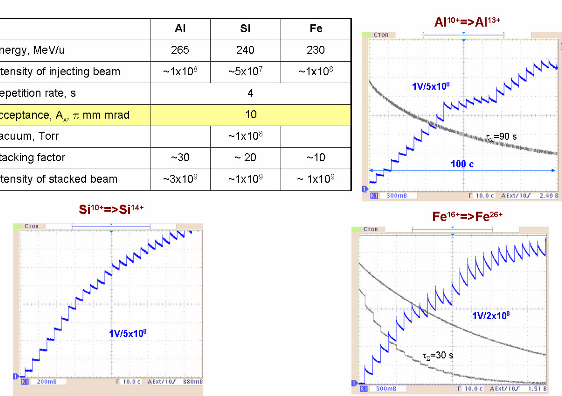


Figure 8: Stacking of nuclei: Al, Si, Fe.

The efficiency of Fe- and Cu- nuclei stacking at the energy of ~200 MeV/u was limited on the level of stacking factor ten due to disturbing effects of beam interaction with stripping foil [2]. Efficiency of beam stacking for nuclei of mass number A~60 has to be essentially increased with progress in LIS technology and at increasing the energy of injected beam up to 600-700 MeV/u. For nuclei with A<30, disturbing effects of beam interaction with stripping foil of optimal thickness are small enough and efficiency of beam stacking was a

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function of injection scheme parameters and of storage Ring dynamic aperture.

CONCEPTION OF ITEP-TWAC FACILITY RENEWAL AND UPGRADING

Proton and ion beams generated in ITEP-PWAC in a wide range of parameters have been demanded for different research fields having the tendency of beam time increase for applications as it's shown above. Renewal of multipurpose proton-ion accelerator and nuclei accumulator ITEP-TWAC will allow to resume suspended at the present time:

- fundamental and applied research with relativistic proton and ion beams in the energy range from 1 GeV/u up to 10 GeV for protons and 4 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 of particles with atomic number up to ~60 in the energy range of ~1 GeV/u;
- technological research for high charge state and high intensity heavy ion beams generation, acceleration, stacking, compression, extraction and focusing;
- expansion of scientific and educational activity on the subject of nuclear technologies.

Qualitatively new level of accelerator facility will be achieved as a result of upgrading relevant ITEP-TWAC systems for:

- extending of accelerated ions set up to A ~ 200;
- cardinal increasing of intensity for accelerated ion beams on a base of ion injector upgrading and accelerator technology improvement;
- cardinal increase of intensity and power for stacked nuclei beams on a base of charge exchange technology development;
- mastering of multimode machine operation with maximal efficiency for experiments and applications with proton and ion beams in parallel.

DEVELOPMENT OF LIS TECHNOLOGY

Configuration of LIS includes now CO_2- lasers L5 and L100 with the energy of radiation, respectively, 5 and 100 J per pulse. Laser L5 is used for generation of C-ions only, LIS with laser L100 is in operation from 2008 and it has been used with target materials of C, Al, Si, Fe, Cu and Ag operating ~1000 hours per year.

The first configuration of laser L100 was assembled as auto-generator [2], then it was modified for operation as amplifier and this mode of operation brings increasing three times the pulse amplitude of radiation power as can be seen on Fig.9. Out-of-axis scheme of laser ray focusing on the target don't allow to get the size of radiation spot less then 0.5 mm, so the maximum power density on the target surface is limited now by 1.5×10^{12} W/sm^2.

Experiments on the ion beam generation in LIS give evidence of optic imperfection reducing considerably the laser radiation power density on the target surface.

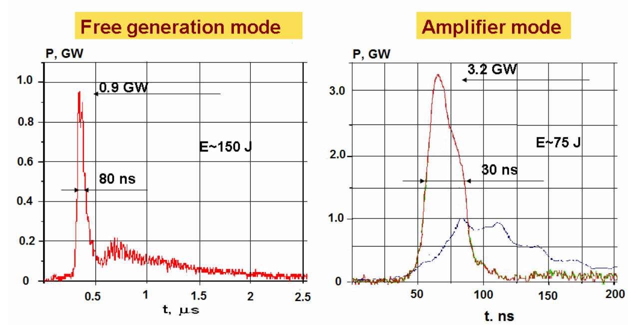

Figure 9: Pulses of L100 radiation for auto-generator and amplifier modes of laser operation.

New focusing scheme for target station is elaborated on a base of new target station construction for axis-symmetrical scheme of laser ray focusing which is free of aberration. Substantial factor of power density increase will be achieved replacing KCl-windows by them of better quality. The elimination of the optical channel defects will allow to increase the radiation power density on the target to the value of more $>10^{13}$ W/sm^2

UPGRADE OF INJECTION COMPLEX

Injection complex with operated in parallel proton and ion injectors I-2 and I-3 is adequate to multipurpose designation and multimode operation of ITEP-TWAC accelerators. However, low energy (4 MV) and low accelerating frequency (2.5 MHz) of ion injector I-3 significantly limit parameters of accelerated and stacked ion beams. Upgrade of ion part of injection complex has to solve the problem of UK Ring intensity increase on the level of no less than 10^{11} nucleons in the pulse for any type of ions from C to U..

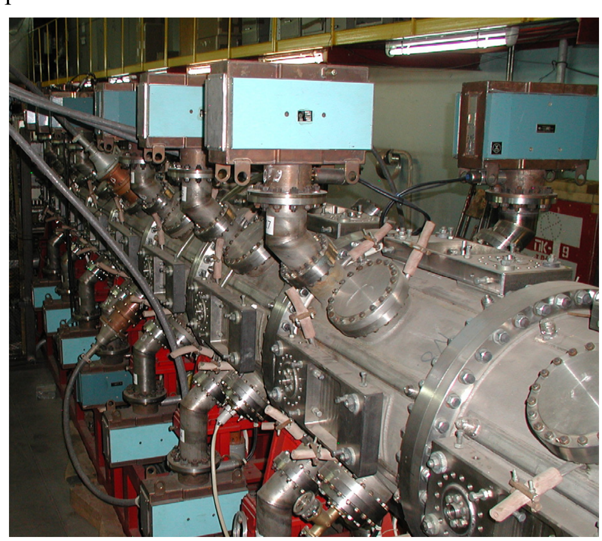

Figure 10: RFQ section of linac I-4.

Proceeding from ion parameters of LIS, optimal on the necessary resources scheme of upgraded injection complex includes two ion injectors: linac I-4 accelerating light ions with $A/Z \leq 3$ to the energy of 7 MeV/u [3] and modified linac I-3 for acceleration of heavy ions with $A/Z \geq 3$ to the energy of ~12Z/A MeV/u.

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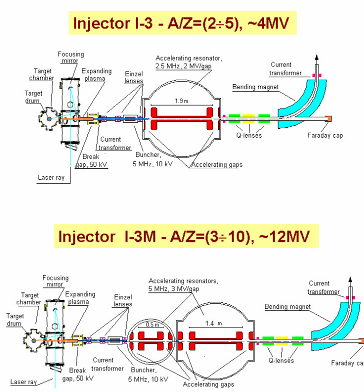
RFQ section of I-4 (Fig.10) on the energy 1.6 MeV/u is now constructed and first beam test has been successfully carried out with proton and $H2^+$ beams [4]. Two options of following resonator sections for I-4 is now considered. The first one is three DTL sections based on H Cavity with magnetic quadruples between them for beam focusing [5]. The second one is DTL section based on H Cavity with RFQ insertions for beam focusing [6]. The final version of section will be selected in the near future

Proposed scheme of injector I-3 modification for improvement of accelerated beam parameters (Fig.11) is based on the use of existing two gap resonator which has to be retuned on 5 MHz. Accelerating structure of I-3M will be composed of two resonators with drift tubes optimized for acceleration of ions with A/Z ~ 6. The width of accelerating gaps has to be adjusted for accelerating voltage of 3 MV per gap. The edge focusing of the beam in the first accelerating gap with specially optimized electrodes profile provides transverse stability of accelerating beam along the line channel. Main parameters of this structure is given in Table on Fig .9.



Comparison parameters of I-3 and I-3M

Injector	I-3	I-3M
Accelerating frequency, MHz	2.504	5.0
Number of resonators	1	2
Accelerating gaps	2	4
Accelerating voltage, MV	4	12
Bunching voltage, kV	10	
Accelerating ions, A/Z	2-5	3-10
Injection energy, kV	50	
Trans. acceptance, π· mm mrad	~1000	
Output momentum spread, Δp/p, %	±1	
Transmission factor, %	~50	

Figure 11: Scheme of ion injector I-3 upgrading.

UPGRADE OF UK RING

Increasing of beam energy at the output of ion injector simplifies but doesn't eliminate the problem of heavy ion acceleration in synchrotron. The existing quality of UK Ring vacuum system provides the vacuum of $1x10^{-9}$ Torr which allows to accelerate ions with A no more than ~100. The quality of UK Ring vacuum system has to be cardinally improved on a base of developed technologies [7] and successfully implemented at GSI [8].

Combination of UHV sputter ion pump (IP) and Titanium sublimation pump (TSP) having a pumping speed of S_{IP} = 100ℓ/s, and S_{TSP} = 900 ℓ/s for hydrogen will be used as basic element of distributed pumping system. The outgassing rate of chamber surface for hydrogen has to be reduced to ~ $4x10^{-13}$ Torr×ℓ/s×cm^2. Technology of Non evaporable getter (NEG) has to be mastered for uniform pumping of the whole chamber. Comparison of vacuum system parameters for UK (2011), SIS18 (GSI) and UK (project) is given in Table 1. Calculated distribution of static pressure along the UK chamber with and without NEG pumping is shown on Fig. 12.

Table 1. Comparison of UK and SiS18 Vacuum systems

Parameter	UK (2011)	SIS18 (GSI)	UK (project
q_{H2}, Torr·ℓ/s	~$2x10^{-12}$	$4x10^{-13}$	$4x10^{-13}$
T_{bake}, C^o	150	200	200
S_{IP}, ℓ/s m	7	6	9
S_{TSP}, ℓ/s m	-	50	60
S_{NEG}, ℓ/s cm^2		0.2	0.2
P, Torr	$1x10^{-9}$	$1x10^{-12}$	$1x10^{-11}(10^{-12})$

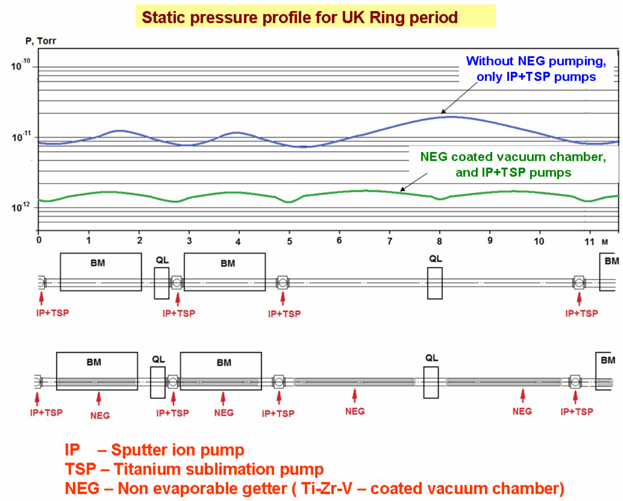


Figure 12: Scheme of UK Ring vacuum pumping.

Upgrade of UK accelerating system is aimed to increase main magnet ramping rate by factor of 3÷4 for reducing the time of ion acceleration up to the maximal energy to ~150 ms. Tuning range of accelerating frequency (0.7÷10) MHz is overlapped by two cavities using procedure of beam recapture from one accelerating cavity to another.

Table 2. Upgrade of UK accelerating system

Parameter	UK(2011)	UK(project)
Magnet ramping rate, T/s	1÷2	4÷6
Number of cavities	2	42
Accelerating peak voltage, MV	10	20
Accelerating frequency, MHz	0.7÷2.5 /2.2÷10	

Parameters of accelerated ion beam in upgraded UK synchrotron with injectors I-4 and with I3M are listed in Tables 3. Maximum intensity of accelerated beams is calculated on incoherent Coulomb limit. Real intensity will be limited by beam current at the outlet of LIS.

Table 3. Ion acceleration in upgraded UK Ring

Accelerated beam parameters with injector I-4						
A/Z≤3, U_{inj}=7MV/u, β_{inj}=0.122, f_{acc}=(0.7-6) MHz, T_{UK}=6.1μs						
A/Z	3.0	2.8	2.45	2.4	2.33	2.0
Ion	C^{4+}	Si^{10+}	Al^{11+}	C^{5+}	Si^{12+}	C^{6+}
E_m,MeV/u	668	774	910	940	980	1230
N_m	$8x10^{11}$	$3x10^{11}$	$2x10^{11}$	$5x10^{11}$	$2x10^{11}$	$3x10^{11}$
Accelerated beam parameters with injector I-3M						
A/Z≥3, U_{inj}=(1-3)MV/u, β_{inj}=(0.05-0.1), f_{acc}=0.7-8MHz, T_{UK}=(9-16)μs						
A/Z	10	9	8	6	4	3
Ion	U^{24+}	U^{28+}	Au^{25+}	Ag^{16+}	Fe^{16+}	Ni^{18+}
E_m,MeV/u	80	100	120	200	400	670
N_m	$2x10^{10}$	$1.7x10^{10}$	$2x10^{10}$	$3x10^{10}$	$4x10^{10}$	$5x10^{10}$

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UPGRADE OF U-10 RING

The program of U-10 Ring upgrade has been composed last year to be realised during next two-three year and includes the following:

- replacement of vacuum chamber for the expansion of hor. acceptance to 200 π·mm·mrad and improvement vacuum to <10^{-9} Torr;
- expansion of aperture in septum magnet outlet of charge exchange injection channel and improvement of beam bump kickers waveform;
- installation of additional magnet inflector for injection of ions from UK Ring without stripping.

The scheme of U-10 Ring upgraded vacuum pumping is similar to existing one. The improvement will be obtained mainly due replacement of vacuum chamber and reducing of outgassing.

Modification of charge exchange injection system will allow to expand hor. acceptance of the Ring for stacking beam and to increase efficiency of beam stacking by elimination of stripping foil re-crossing by circulated beam at injection of another potion of ions.

Installation of additional magnet inflector in the strait section 505-506 will allow injecting to U-10 Ring the beam of any accelerated in UK synchrotron ions but not only stripped to the nucleus state.

DEVELOPMENT OF ITEP-TWAC INFRASTRUCTURE

Elaborated strategy of ITEP-TWAC infrastructure development is aimed to redouble beam time for physical experiments and applications extending functional capabilities of UK synchrotron for protons acceleration and for generation of slow extracted beams to the area of beam using for applications.

Expanded Injection Complex of ITEP-TWAC with additional beam lines from injectors both I-2 and I-4 to UK Ring was presented in [1].

New projected beam line for slow extracted beam from UK Ring for applications [2] is directed to free space of Target Hall (where setup will be installed for biological research) and linked with beam line from U-10 Ring to Medical Building used now for proton therapy.

We consider also possibility of construction the combined (fast end slow) extraction system for U-10 Ring to BEH (Fig.13) for the beam of maximal momentum 10Z GeV/c. The slow extracted proton or ion beam will be used for research on nuclear and particle physics. The fast extracted proton beam with regulated time intervals between bunches will be used for protonography of fast processes. Area of this beam using in the corner of BEH has to be separated for radiation shielding by additional concrete walls from surrounding environment.

Three modes of machine operation with proton and ion beams in parallel or in time-sharing mode can be realized: 1) acceleration of protons in U-10 Ring and protons or ions in UK Ring; 2) acceleration of ions in U-10 Ring and protons or ions in UK Ring; 3) stacking of nuclei in U-10 Ring with acceleration of protons or ions in UK Ring.

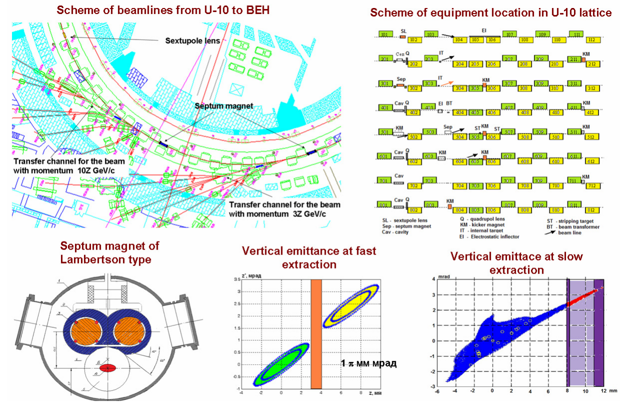

Figure 13: Combined extraction of beam from U-10 Ring.

CONCLUSION

1) Conception of ITEP-TWAC renewal and upgrading is based on demanding of fundamental, applied and technological research with proton and ion beams in the wide range of intermediate energies for nuclear science, industry, biology, medicine and education on the subject of nuclear technologies.

2) The progress in technology of Laser Ion Source with 100J CO_2 laser L100 gives possibility of high charge state ion beam generation with Z/A≥0.4 for ions up to A~60 and with Z/A≥0.1 for ions up to A~200.

3) Upgrading of the heavy ion injector I-3 and commissioning of new light ion injector I-4 will be the base for cardinal increasing of intensity for accelerated in UK Ring ion beams in wide range of mass number values.

4) Acceleration of heavy ions with mass number up to A~200 in synchrotron UK will be achieved first of all as a result of ring vacuum system upgrade on the base of modern vacuum technology implementing for the vacuum less than 1x10^{-11} Torr.

5) Upgrading of U-10 Ring Accelerator systems will be directed on cardinal increasing of intensity for accelerated proton and any kind of ion beams and further development of multiple charge exchange injection technology for getting of super high density heavy ion beams.

6) Development of ITEP-TWAC facility Infrastructure is aimed mastering of multimode machine operation making generation proton and ion beams of both U-10 and UK synchrotrons in parallel.

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