Multi-Purpose Accelerator-Accumulator ITEP-TWAC for Nuclear Physics and Practical Applications

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Abstract. The ITEP-TWAC facility consisting of proton injector I2, ion injector I3, booster synchrotron UK and accelerator-accumulator U10 is now in operation delivering 4000 hours per year of proton and heavy ion beams in several modes of acceleration and accumulation using multiple charge exchange injection technique. A new design of laser ion source with 100J CO^2-laser has been started to use for high current Al- and Fe-ion beam generation for experiments with particle energy of several hundred MeV/u. Experimental area of ITEP-TWAC facility includes now five zones of beam utilization. Two fast extracted beams from U10 ring to the target hall and to the building for nuclear physics and practical applications. The 25 MeV beam of linac I2 is used in parallel for both injection to synchrotron U10 and different applications. Some progress is achieved also in extension of experimental area and multi-purpose utilizing of machine to be used in a time sharing mode and running in parallel of several experiments and routine operation with various beams for a number of users. The machine status analysis and current results of activities aiming at both subsequent improvement of beam parameters and extending beam applications are presented[*].

1. Introduction

The “TeraWatt Accumulator” (ITEP-TWAC) facility at ITEP-Moscow [1-4] is in routine operation since 2004 using a non-Liouvillian stripping technique for stacking C^{6+}, Al^{13+}, Fe^{26+} ion pulses accelerated in the UK booster synchrotron into the U-10 storage ring [3]. Its ultimate goal is to produce a particle beam power of about one TeraWatt with $\sim 10^{13}$ of A ~ 60 ions in bursts of 100 ns, to be accelerated to nearly 0.7 MeV/u.

Due to the very high particle density aimed at in phase space, many challenges on IFE related topics in accelerator physics and technology itself are being addressed:

- efficient beam injection into the accelerator chain from an intense ion source capable of producing 10^{10} - 10^{11} heavy ions in pulses of some microseconds length at repetition rates of ~ 1 Hz,
- non - Liouvillian stacking technique is needed to accumulate sufficient ions before extraction to experimental target,
- pulse compression of almost a factor of ten in time has to be mastered just before extraction,
- fast extraction, low-losses beam transport, generation of hollow beams and focusing.

Recent systematic efforts resulted in improvement of the stacking process when the beam current in the accumulator ring increased up to the level of $4\ 10^{10}$ in course of 70 cycles accumulation before being saturated. The compression of accumulated coasting beam from 1 μs to ~ 170 ns (FWHA) has been demonstrated by application of the 10 kV/695 kHz RF bunch rotation technique.

2. Operation modes of the facility

The ITEP-TWAC facility runs in three operation modes accelerating protons up to the energy of 9.3 GeV, accumulating nuclei at the energy of 200-300 MeV/u and accelerating ions and nuclei up to the energy of 4 GeV/u. The total operation time of machine in 2008 is ~ 4300 hours divided between operation modes as following: 2268 h of protons acceleration, 828 h of carbon nuclei accumulation, 648 h of carbon nuclei acceleration up to relativistic energies. Distribution of ITEP-TWAC between different research fields and applications in 2007-2008 is given in Table 1.

Research fields and applications	Beams	Operation time, hours		
		2007	2008	Dem.
Relativistic nuclei physics	p,C,	1030	1200	1000
Methodical research	p,C,	1338	1500	2000
Physics of high density energy in matter	C,Al,Fe,Zn	344	350	500
Radiobiology	p,C	2520	2350	5000
Proton therapy	p			
Ion therapy	c	0	0	
Radiation treatment of materials	p,Fe,Sn,U	802	1200	6000
Total		6034	6600	14500

TAB. 1. Operation of ITEP-TWAC for different subjects.

This table shows the trend of machine operation time increase for applications of proton and ion beams in biology, medicine and radiation treatment of materials. The demanded beam time for users exceeds the possible one by factor of two. This discrepancy has to be eliminated in a result of machine infrastructure development and extension of its experimental area.

The ITEP-TWAC development is aiming at increase of accelerated and accumulated beam intensity as well as at raising of compressed beam power. Important is also the extension of ion species spectrum based on progress of the laser ion source technology.

The 100J CO_2-laser system, based on a Master Oscillator – Power Amplifier (MO-PA) configuration has been designed, constructed and tested for the first time at CERN in 2003 [5,6]. Afterwards this laser has been moved to ITEP to be re-assembled for using in the TWAC Facility. For the first step of this work, the PA configuration of laser operated in free-running regime has been assembled to start testing the TWAC facility with heavy ions of up to A ~ 56.

An important issue in intensity upgrade of the whole accelerator-accumulator scheme is the forthcoming commissioning of the new high current linear injector [7]. The respective RFQ module 1,6 MeV/u 80 MHz undergoes the RF tests now. The subsequent SP RFQ 6 m long sections are in design phase aiming at 16 mA/15 µs, ~ 7 MeV ion pulses for z/A=1/3.

3. Development of ITEP-TWAC infrastructure

Experimental area of ITEP-TWAC facility (Fig.1) includes now five zones of beam utilization. Two of them are secondary beams of internal targets installed in second and third periods of U10 lattice. Two another's are fast extracted beams from U10 ring to the target hall and to the building for medical applications. The 25 MeV beam of linac I2 is used in parallel for both injection to synchrotron U10 and different applications.

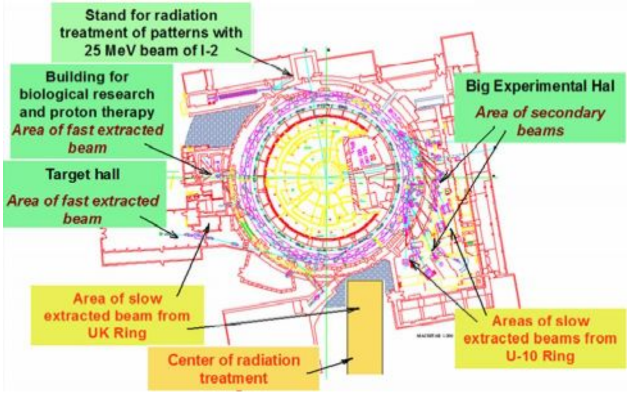

FIG. 1. Experimental area of ITEP-TWAC facility, green - in operation, yellow - in projecting.

Extension of experimental area is planned by construction in two slow extracted (SE) beams from U10 and UK rings as shown in Fig.1. First SE system for beam extraction from 203-blok of U10 ring (Fig.2) has been constructed and its testing is now going on. Second order resonance in vertical plane is exited by single sextupole for beam extraction to existing beam transfer lines which are used also for transfer of secondary beams generated in the 203 internal target.

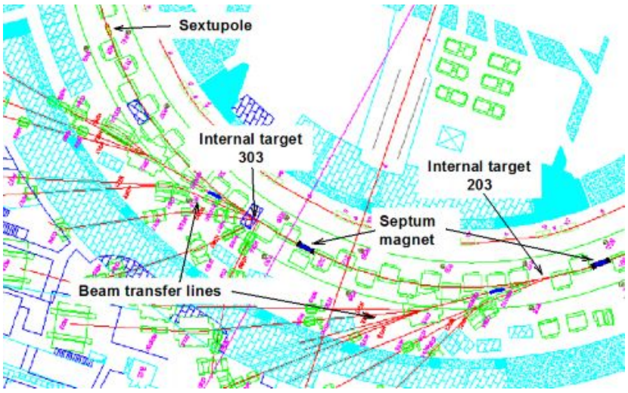

FIG. 2. Slow extraction system of U-10 ring.

Continuous extraction of the carbon nuclei beam stacked in the U10 ring is shown in Fig.3. The working point of storage ring in this mode of beam extraction has been set near sextupole resonance so circulating particles scattered on molecules of residual gas and in stripping foil putting on unstable trajectories to be extracted.

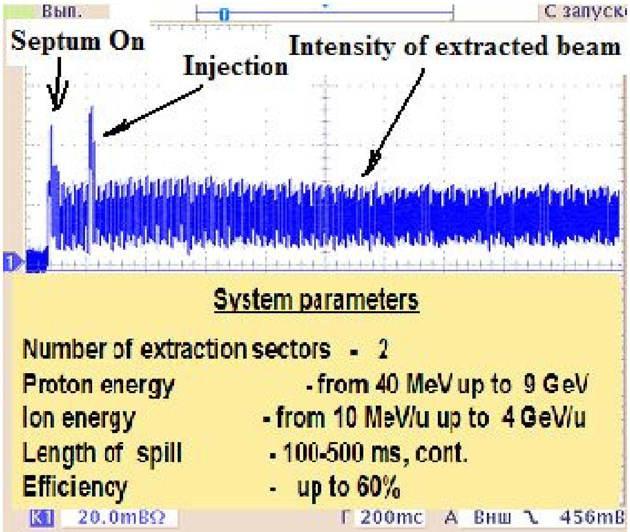

FIG. 3. Extraction carbon beam accelerated in the UK ring up to the energy of 200 MeV/u at repetition rate of 0.25 Hz using U10 ring as stretcher.

4. The 100J CO_2-laser running for Fe-ion beam generation

The new LIS optical scheme described in [8-10]. Typical laser radiation pulse in free-running mode of the laser operation is characterized by the sharp spike of 150 ns at the pulse front and a long low intensity radiation tail of 1-2 (j.s duration that contains up to 60% of the total laser pulse energy. Stretching in time of the radiation energy deposition into the target results in low-charge state ions domination and in intense evaporation of the target material.
Typical signal of the ion beam extracted from laser plasma of Fe-target and measured at the extraction gap outlet shows (Fig.4) the presence in the beam the high current pulse of charge particles passing through the extraction gap before Fe-ions. This forward pulse of ions is created in vacuum chamber by X-rays emitted from plasma spot on the target and ionizing residual gas.

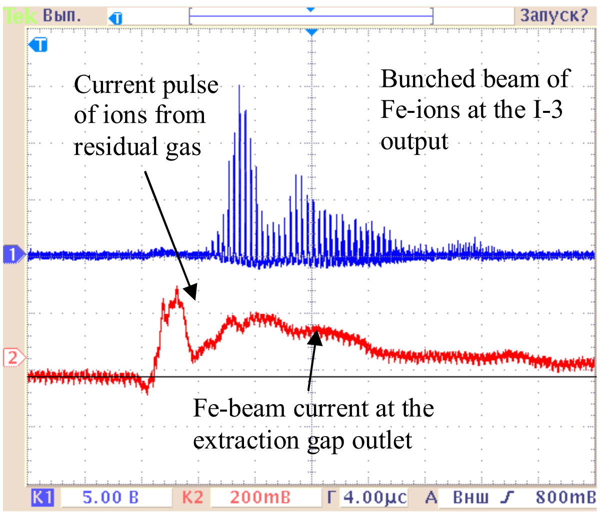

FIG. 4. Signals of Fe-ion beam generated in LIS.

It can be seen in Fig.5 that Fe-ions of only few charge states of 14-16 are there at the head of beam pulse generated in LIS. Charge states of Fe-ions at the second vertex of the total beam current pulse are found in the expanded range of values from 12 to 16.

The total number of Fe-ions of charge states from 12 to 16 is estimated by the value of ~ 10^{12}, the number of Fe^{16+} ions at the head of the beam pulse is order of $5 \cdot 10^{10}$.

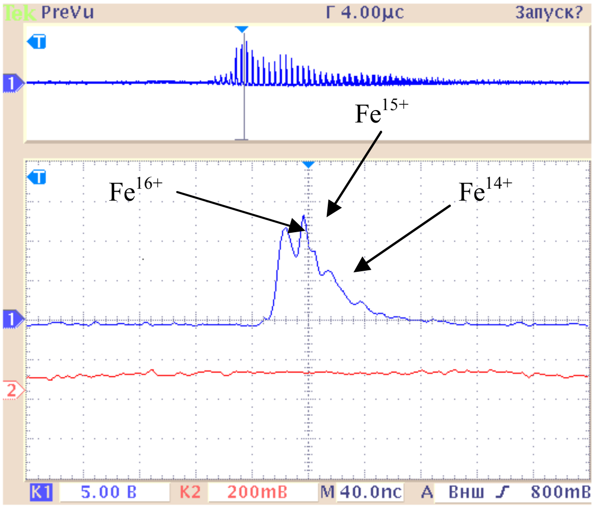

FIG. 5. The Fe-ion species at the head of LIS beam.

The first run of the 100J laser for heavy ions generation has been continued three week scheduled by 12 hours per day at repetition rate of 0.25 Hz. Most part of run time has been spent for with the Fe-beam and two last days -with Al-beam. The laser has turned out more than 10^5 shots with high enough stability of pulse amplitude and energy distribution. Parameters of ion beam haven't been so stable in time because of dynamic processes in the target caused by intensive evaporation of target material, and in the vacuum volume of plasma drift tube due to intensive adsorption of residual gas from surfaces bombarded by high current beam.

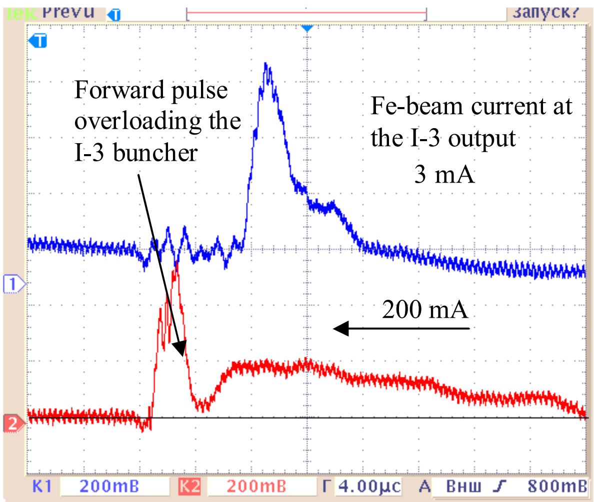

FIG. 6. Current signals of total Fe-beam at the LIS extraction gap outlet and Fe^{16+}-beam of 64 MeV at the I-3 linac output.

5. Results of Al and Fe nuclei stacking in the storage ring U-10

The charge-exchange injection technique is used in the TWAC facility from 2002 for carbon nuclei stacking at particles energy of 200-300 MeV/u. Optimized staking process by scheme of C^{4+}=>C^{6+} is characterized by stacking factor of $k_\propto$ ~ 70 and by maximum number of $4 \cdot 10^{10}$ stacked carbon nuclei [9].

Parameters of stacking beams and injection system are listed in Tab.2. Energy of ions is high enough for its stripping to bare nuclei but the foil thickness provides 99% bare ion yield for C and Al and only 65-70% for Fe. Reduced yield of Fe-nuclei in stripping foil has to be compensated by decreasing of multiple Coulomb scattering and electron pickups increasing beam stacking efficiency. It was expected to get at experiments a little less efficiency of stacking for Fe-beam but a little more for Al-beam than it was obtained for C-beam.

Stacking ions	${}_{12}C^{4\rightarrow6}$	${}_{27}Al^{10\rightarrow13}$	${}_{56}Fe^{16\rightarrow26}$
Energy, MeV/amu	213	265	165
Charge changing factor	0.67	0.77	0.615
Injection rep. rate, Hz	0.3	0.25	
Stripping foil thickness, mg/cm^2	1.5 (of mylar)		
Vacuum, Torr	$2\cdot10^{-9}$		
Acceptance filling	central		peripheral
Booster UK intensity, ppp	$\sim 2\cdot10^{9}$	$\sim 5\cdot10^{7}$	$\sim 1\cdot10^{8}$
Momentum spread, %	±0.04		
Emittance, π mm·mrad	~ 5		
Stacked beam intensity	$>4\cdot10^{10}$	$>5\cdot10^{8}$	$>2\cdot10^{9}$

TAB. 2. Parameters for nuclei stacking.

Main experimental results shown in Fig.7 are the following: Fe^{16+}-ions are stripping in the foil with predicted probability, but Fe-nuclei loss rate in the target (Fig.7) and in vacuum of 10^{-8} Torr is order of magnitude higher than it was predicted by the theory [11,12].
The resulting process of Al-nuclei stacking have been as expected little differing from the C-nuclei stacking. The factor of Al-nuclei stacking was limited by the lack of optimization time and by injected beam instability depending on imperfection of the LIS target station which has to be improved.

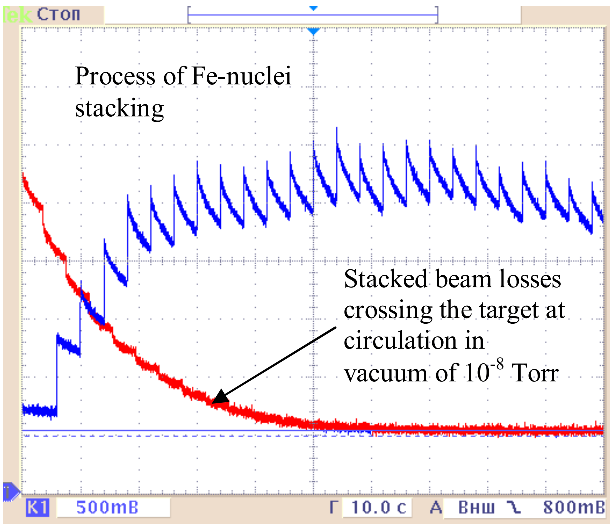

FIG. 7. Stacking of Fe^{26+}-nuclei in the U-10 ring.

6. Conclusions

ITEP-TWAC project is well in progress. The accelerator-accumulator facility provides ion beams for increasing experimental activities on beam-plasma interaction physics and on verity of practical applications. The facility is now successfully in operation by more than 4000 hours yearly accelerating proton and ion beams and stacking carbon nuclei for physics experiments and for radiation damage tests technologies.

The nearest progress in the ITEP-TWAC project depends now on the Laser Ion Source commissioning with the master oscillator mode of the 100J CO_2 laser operation required for a heavier ion beam generation with ionization potential of more than 1 kV.

7. References

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