New Stacking Technology for High Power Nuclei Beams Generation in ITEP-TWAC Accelerator Facility

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Abstract. The ITEP-TWAC accelerator complex is now in progress for acceleration and accumulation of high current and high power ion beams. Modification of Non-Liouvillian multiple charge exchange injection technique has been employed for nuclei accumulation in storage ring by means of particles density increase in a small separatrix area of phase space that allows forming a beam bunch to be compressed before ejection and focusing to a target spot of minimal size and of maximal heavy ion plasma temperature. Activities are focused on development of new experimental tools for investigations into the physics of high- brightness beams generation that opening wide opportunities for variety of practical application.

1. Introduction

The ITEP-TWAC Facility was appeared in 2003 as upgrading of the ITEP's 10 GeV Proton Synchrotron U10 for the heavy-ion Accelerator-Accumulator [1]. The strategy of reconstruction and basic project parameters of the complex given in Table 1 are guided by requirements of machine development broadening in different spheres of physical research and industrial applications, in particular assimilation of a new research field in high density of energy in a matter with using of high power heavy ion beams.

Table 1. Project parameters of the ITEP-TWAC Facility

Operation mode	Beam parameters	
Proton Accelerator	Energy, GeV	10
	Intensity, c^{-1}	10^{11}
Ion Accelerator	Accelerated ions	to U
	Energy, GeV/amu	2-4
	Intensity, n/c	10^{11}
Ion Accumulator	Accumuletad ions	to Zn
	Particle energy, MeV/amu	to 700
	Beam energy/power, kJ/TW	100/1

Technological scheme of the heavy ion facility was commissioning and experiments were started with carbon beam acceleration and accumulation. During the reconstruction, a 4 MV ion linear injector I-3 was built [2], an ion booster synchrotron UK was put into operation [3] and a multiple injection of ions from the UK into the U-10 ring using charge exchange injection technique was realized [4]. Several modes of machine operation are now in using for experiments and applications: secondary beams generation in internal targets by proton and relativistic carbon beams, fast extraction of proton and carbon beams with momentum of up to 3Z GeV/c, fast extraction of stacked and compressed carbon beam with energy of up to 400 MeV/amu.

2. Current operation of ITEP-TWAC facility

The ITEP-TWAC Facility (Fig.1) runs in three operation modes accelerating protons up to the energy of 9.3 GeV, accumulating nuclei at the energy of 200-400 MeV/u and accelerating ions and nuclei up to the energy of 4 GeV/u. The total operation time of machine in 2008 is 4306 hours (in 2007 – 3937 h), divided between operation modes as the following: 2420 h of protons acceleration, 1316 h of carbon nuclei, 564 h of Fe and Al nuclei accumulation. The new configuration of laser ion source with 100J CO^2-laser has been started to use for heavier beam generation, acceleration and stacking in the storage ring U-10 using multiple charge exchange injection technique. 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

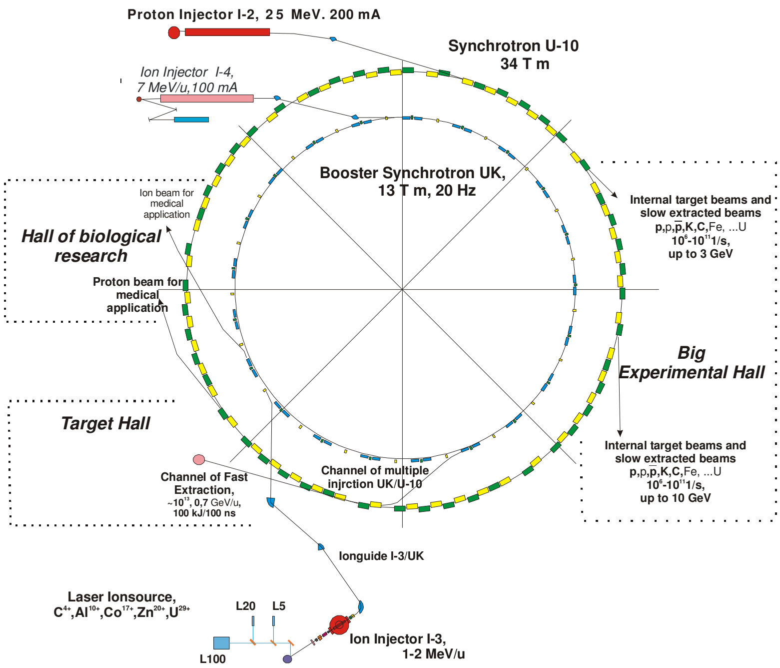

FIG. 1. Layout of ITEP-TWAC-Facility

3. Experience with nuclei beam accumulation

The ion accumulation procedure is based on the charge-exchange injection with using a fast bump system for minimising the stacked beam perturbation over penetrating through the stripping foil material [3]. Parameters of the stacked beam achieved in accumulator ring U-10 are listed in Table 2. The injection efficiency is defined now by the rise time of the pulse in the UK ejection kicker magnet and some particle losses in beam transfer line between booster and accumulator ring. The efficiency of beam stacking is near to absolute for particles crossing stripping foil. The stabilized process of the beam accumulation is shown on Fig.2.

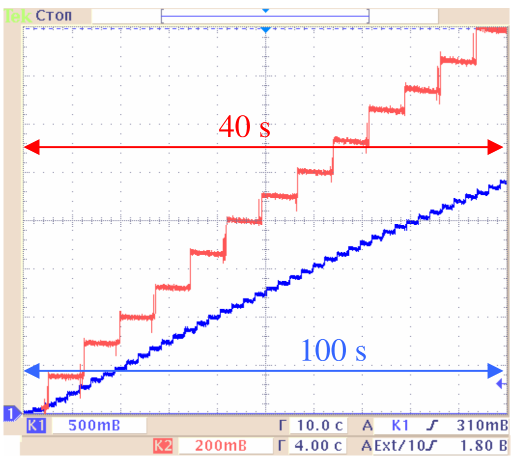

FIG. 2. The stairs of C^{6+}-beam stacking in the U10 ring.

Table 2. Parameters of the C^{6+} beam stacking

	Achieved	Expected	Plans
Energy, MeV/amu	300	400	700
Injection rep. rate, Hz	0.3	0.5	1
Booster UK intensity, ppp	~10^9	~3 10^9	~ 10^{10}
Momentum spread, %	±0.04	±0.03	±0.02
Emittance, π mm·mrad	~5	~4	~3
Injection efficiency, %	~60	~80	~80
Beam stacking efficiency,%	>90	>95	>95
Stacked beam intensity	>4·10^{10}	>3 10^{11}	>10^{12}

The efficiency of accumulation process is characterized by lifetime of the stacked beam with fast bump system on (τ_Σ) and off (τ_o). Results of these measurements at some state of machine and vacuum in the accumulator ring of ~10^{-8} Torr give τ_Σ=200 s, and τ_o =300 s.
Using equality $\tau_o=25\cdot A_{x,z}$, we get estimation of the accumulator ring dynamic acceptance as $A_{x,z}$ ~ 12 π mm·mrad. Designating δA as acceptance reduction from the orbit displacement by the fast bump at injection, and considering equality $(\tau_o\tau_\Sigma)/(\tau_o-\tau_\Sigma)=20(A_{x,z}-\delta A)$, it gets estimation of δA ~ 20 π mm·mrad. The factor of stacked beam losses at injection of a new portion of particles is calculated as $\delta=(\tau_o-\tau_\Sigma)/(f_{inj}\tau_o\tau_\Sigma)=0.005$, and the factor of stacking intensity increase is equal to $k_\infty=(f_{inj}\tau_\Sigma)=70$.
Parameters of stacking Fe^{26+} and Al^{13+} beams obtained in first experiments compared with C^{6+} are listed in Tab.3.

Table 3. Parameters for nuclei stacking

Stacking ions	${}_{12}C^{4\to6}$	${}_{27}Al^{10\to13}$	${}_{56}Fe^{16\to26}$
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	2x10^{-9}		
Acceptance filling	central		peripheral
Booster UK intensity, ppp	~2x10^9	~5x10^7	~1x10^8
Momentum spread, %	±0.04		
Emittance, π mm·mrad	~5		
Stacked beam intensity	>4x10^{10}	>5x10^8	>2x10^9

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 multiple Coulomb scattering and electron pickups increasing resulting 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. The low efficiency of Fe-nuclei stacking at the energy of 165 MeV/u indicates the unexpectedly high cross section of particles losses by electron pickups in the stripping foil and at the beam circulation in vacuum of 10^{-8} Torr. Plans are being made to continue experiments and check efficiency of stacking process for Fe-beam of higher and lower energy

4. Development of nuclei beam stacking technology

The nuclei beam stacking technology that used in ITEP-TWAC is based on three propositions: 1) charge exchange injection technique, 2) one turn bump system in storage ring, and 3) stripping of injecting ions to the state of bare nuclei. There are a lot of additional conditions to be satisfied for beam stacking with high efficiency and maximal yield of accumulation process [x]. Main speciality of charge exchange injection technique allowing to evade Liouvillian theorem is usually employed for beam packing to an outlined region of transverse or longitudinal phase space. Beam packing in horizontal plane of transverse phase space is shown in Fig.3. The stacked beam displaces to stripping foil for one turn to absorb injection beam.

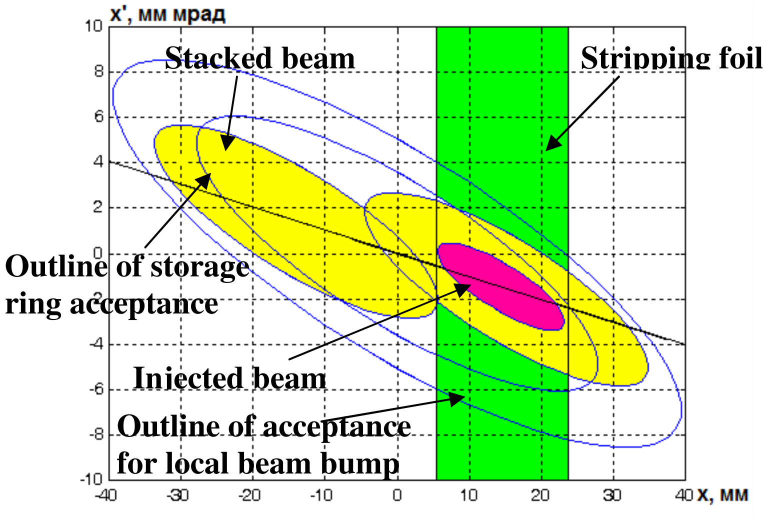

FIG 3. Beam packing in transverse phase space

An area of longitudinal phase space occupied by the beam circulating in the ring is forming in separatrix regions or buckets bounded to stationary phase of accelerating RF field. The procedure of several beam buckets packing in one separatrix of storage ring is started in accelerating ring by changing harmonic number of accelerating frequency to the value of one at ramp as shown in Fig.4 or using beam adiabatic trapping at magnetic cycle flat top as shown in Fig.5. The last one is preferable as keeping area of phase space occupied by the total beam to be ejected from accelerator for stacking in storage ring. Fine formed region of 6D phase space occupied by the beam in accelerator that named 6D emittance has to be matched at transfer to storage ring with its 6D acceptance. This operation is more or less trivial with using of beam transfer line quadruples, RF amplitude variation in both rings and synchronization of injecting bunch with RF phase and with bunch of stacked beam in storage ring.

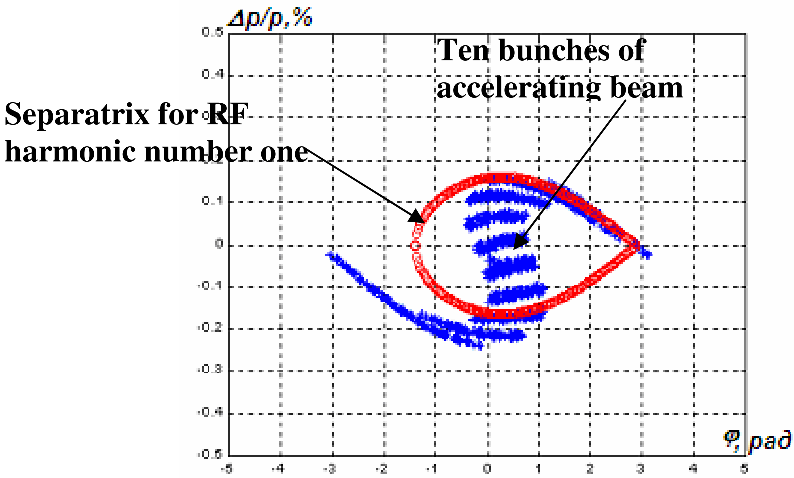

FIG. 4. Beam bunching with harmonic number one at ramp of magnetic cycle

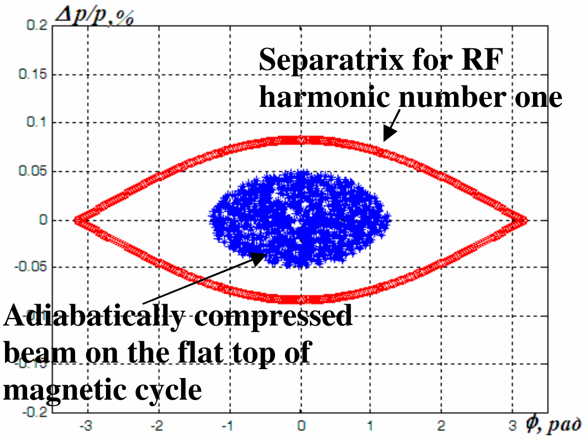

FIG 5: Beam bunching with harmonic number one using adiabatic trapping at the flat top of magnetic cycle

RF manipulation in storage ring permits to keep stable the longitudinal emittance of circulating beam in the process of multiple charge exchange injection of beam bunches from accelerating ring. As a result of this technique, we get stacked beam with minimal 6D emittance and of high enough charge density obtained in the single bunch circulating in storage ring at minimal value of accelerating voltage. Stability of high intensity bunched beam has to be provided by minimizing ring impedances and using active damping systems for transverse and longitudinal oscillations. Additional compression of circulating beam has to be obtained by means of sharp increasing of accelerating voltage directly before beam .ejection to experimental target.

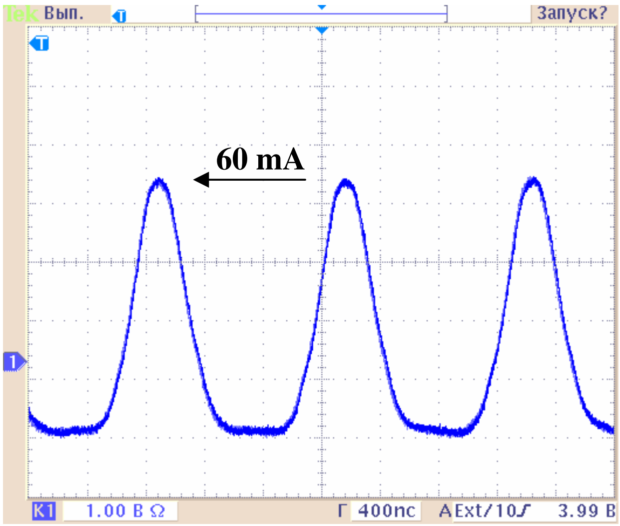

FIG. 6. Circulating bunch of stacked beam of C^{6+} nuclei with energy of 200 MeV/u.

5. Compression of stacked beam

The stacked beam longitudinal compression is fulfilled now in ITEP-TWAC by increasing accelerating voltage from ~1 kV which forms separatrix for beam stacking to 10 kV. Dynamics of beam compression is shown in Fig.6. Due to the Non-Liouvillian saving of the longitudinal phase space for the stacking beam at multiple charge exchange injection, the particle density seems to be maximal after compression and the grade of compression depends on beam emittance on the factor of accelerating voltage increase. Result of beam compression up to the pulse width of 150 ns is illustrated on Fig.7.

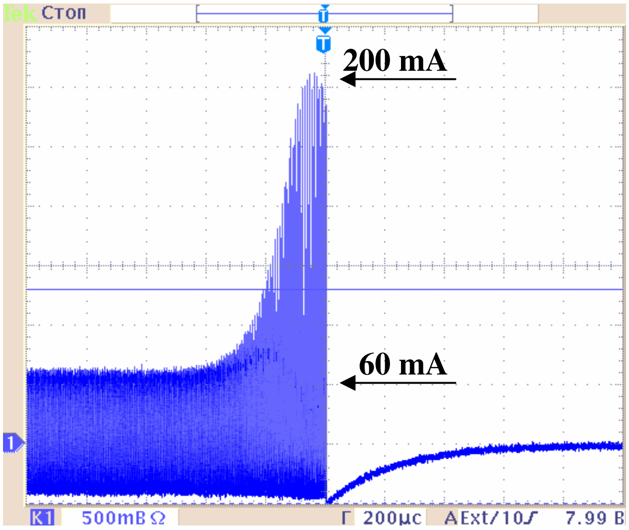

FIG. 7. Beam bunch envelope in the process of longitudinal compression.

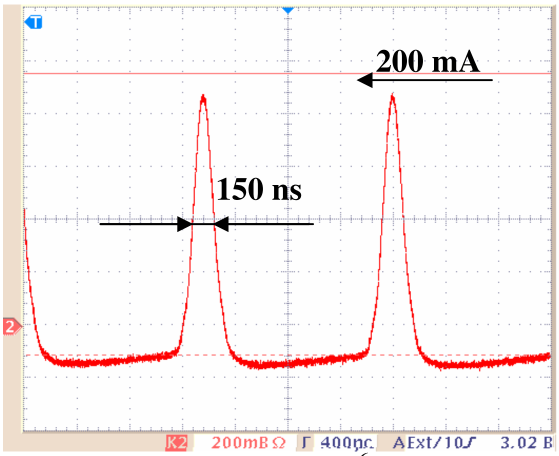

FIG. 8. Compressed bunch of stacked beam of C^{6+} nuclei with energy of 200 MeV/u.

6. Conclusion

The ITEP-TWAC facility at ITEP-Moscow is in routine operation since 2004 using a non-Liouvillian stripping technique for stacking C^{6+} ion pulses accelerated in the UK booster synchrotron into the U-10 storage ring. Its ultimate goal is to produce a particle beam power of about one TeraWatt with ~ 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.

The stacked beam compression adjusted in accumulator ring with charge exchange injection technique and one accelerating station at the RF voltage of 10 kV provides the bunch width of ~150 ns at compression factor of 3 that will be increased to ten, using total RF voltage of 50 kV from the five of accelerating stations installed in the storage ring

References

[1] D.G.KOSHKAREV et al., “ITEP Accelerator Facility Upgrade”, XV Workshop on Charged Accelerator, Protvino, v.2 (1996) p.319. N.N.Alexeev, et al. “Accumulator-Accelerator ITEP-TWAC”. Particle and Nuclei, Letters. 2004. No 3(120), 78-87
[2] N.ALEXEEV, D.KOSHKAREV, B.Sharkov,”Laser ion source of multicharged ions for ITEP accumulator facility” Laser and Particle Beams (2002) V 20, N3, 385-392
[3] B.JU.SHARKOV, ET AL., “Power plant desing and accelerator technology for heavy ion inertial fusion energy”. Nucl.Fusion 45 (2005) 291-297
[4] N.N.ALEXEEV, et al.”Accelerator-Accumulator ITEP-TWAC” Particle and Nuclei, Letters. 2004. No 3(120), 78-87
[5] B.SHARKOV in “The Physics and Technology of Ion Sources”, edited by I.G.Brown, 2004 WILEY-VCH, p.233-256.
[6] N.N.ALEXEEV, et al. . “Experiments with Fe-Ion beam generation, acceleration and accumulation in the ITEP-TWAC”. Proc. ||EPAC-2008, 352-354.