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Status of the Terawatt Accumulator Accelerator project

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Abstract

The construction of the Terawatt Accumulator (TWAC) facility is nearly completed at the ITEP in Moscow. All the major milestones have been successfully passed with a beam of carbon ions, except for the final result (the high power beam accumulation), which is on the way. The beam of C^{4+} ions delivered by the laser ion source is accelerated up to the energy of 300 MeV/amu by two steps—in the linear injector I3 and in the booster synchrotron UK. The accelerated beam is extracted from the UK ring and transferred to the U10 accumulator ring. Non-Liouvillian stripping technique ($C^{4+} \Rightarrow C^{6+}$) is applied for stacking of C^{6+} batches into the accumulator ring U10. First experiments with extracted beam of ions have started in 2002. Status of the TWAC components, current results of activities aiming at mastering the ion beam stacking technique, and outlook for the TWAC advance are presented.

Keywords: Accumulator ring; Beam stacking; Booster synchrotron; Laser ion source; Linear injector

1. INTRODUCTION

The Terawatt Accumulator (TWAC) project (Koshkarev *et al.*, 1996; Sharkov *et al.*, 1998) is intended to initiate some groundwork for development and promotion of high intensity and high power ion beam technology on the basis of accelerator facilities available at the Institute for Experimental and Theoretical Physics (ITEP). A major goal of the project is an expansion of the existing ITEP experimental area into a new domain of research activity with intense heavy ion beams of a terawatt range of power providing a unique opportunity for studying solid matter in the high density plasma state. The ITEP Accelerator Facility extended to the TWAC project is shown in Figure 1. Project parameters of the TWAC are listed in Table 1. The laser ion source is used to produce highly charged ions ($Z/A \sim 0.25$–0.45) with atomic mass of up to 60 and at extraction potential of 50 keV. Preliminary acceleration of ions is carried out in the linear injector I3 up to the energy of 1–2 MeV/amu. The booster synchrotron UK accelerates an ion beam to a near relativistic energy for stacking the energetic beam into the accumulator ring U10 by using a charge exchange injection technique. The multiple injection system adjustment has been completed in 2002 by demonstrating the $C^{4+} \Rightarrow C^{6+}$ beam stacking at the energy of 200 MeV/amu. The current growth of the stacked beam by factor of 4–5 during the accumulation test has been limited by increasing beam loss through the low vacuum in the accumulator ring (10^{-8} Torr), low repetition rate (<0.3 Hz), and diminished dynamic aperture of the U10 in the absence of magnetic field correction. The nearest term aim for the TWAC advance is the accumulation of $2 \cdot 10^{12}$ bare C ions reaching the predicted beam current limit for the available facility configuration. Further plans for the TWAC development on a new concept recently proposed are now under discussion.

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2. EXPERIENCE WITH THE LASER ION SOURCE

The laser type of ion source is the best one for the TWAC as there is no other type of ion source with a comparable value

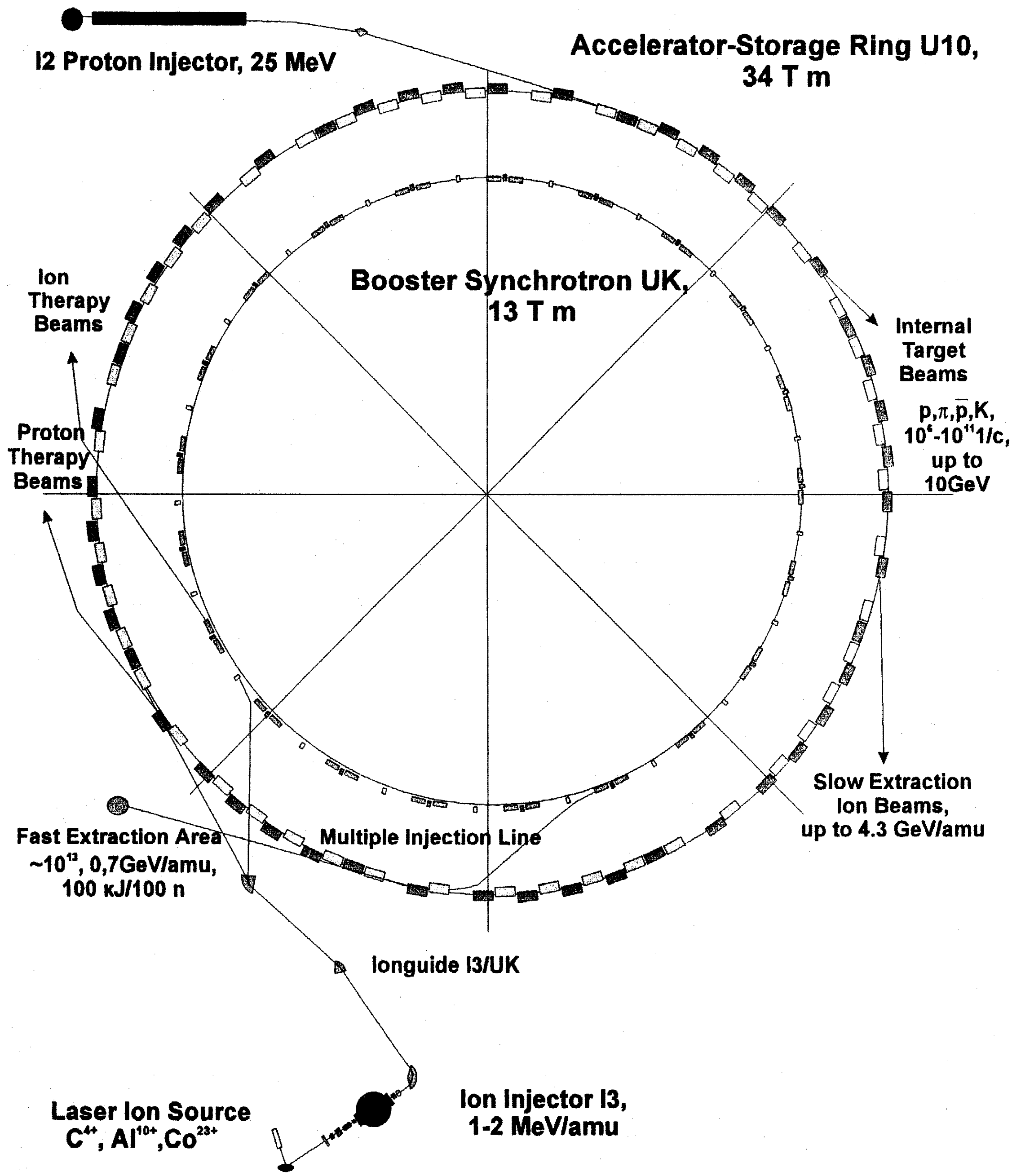

Fig. 1. Schematic layout of ITEP Accelerator Facility after reconstruction.

of output current for a high charge state heavy ion beam ($A \sim 60$, $Z/A \sim 0.25$–0.4). The 5 J/CO_2 laser ion source with carbon target installed in the linear injector I3 is good enough for adjusting of a stacking technology implemented in the TWAC project, but it is not suitable for generation of heavier ions to be used in the terawatt level facility, so this ion source has to be substituted with the 100 J/CO_2 laser ion source. From experience with the available ion source, we have studied its potentialities for using it in an intense injector. Recent modifications in the laser ion source have been implemented to improve the beam stability and raising the output beam current. The peak current of carbon ions we observe at the output of the extraction gap is in the range of 500 mA. This value is too high for the I3 acceptance and cannot be transferred without loss through the I3 matching channel, which is designed for a beam current of no more

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Table 1. *Project parameters of the TWAC*

Stacked beam energy, E_0	100 kJ
Stacked beam power, P_0	1 TW
Beam pulse length, T_0	100 ns
Beam power density, J_0	120 TW/sm^2
Electron temperature in matter, t_e	10 eV
Electron density in matter, n_e	10^{23}
Internal pressure in matter, P	10–100 Mb

Table 2. *Parameters of the injector I3*

Accelerating frequency	2.504 MHz
Number of acc. gaps	2
Voltage per gap	2 MV
Length of drift tube	1920 mm
Aperture	70–90 mm
Length of first acc. gap	250 mm
Length of second acc. gap	230 mm
Transverse acceptance	up to 2000 π mm mrad
Buncher peak voltage	10 kV
Max. output beam current	5 mA

than 50 mA. The optimum current of the C^{4+} beam for the I3 input is on the order of 30 mA. The Wien filter is used in the I3 matching channel for the beam separation. The charge state distribution of a beam is changed from the beam head to the tail. Carbon ions of fourth charge state are dominated in combination with C^{5+} ions in the beam head and with C^{3+} ions near the beam tail.

3. INJECTOR I3 SPECIALITIES

The Ion Injector I3 (Fig. 2) is one of the accelerators available at ITEP that was modified for requirements of the TWAC project. It is a single drift tube linac. The parameters are listed in Table 2. This injector is not the best choice for a high intensity ring accelerator because of low energy (4 MV), low accelerating frequency (2.5 MHz), and a high bunch current requiring a very long traveling distance for debunching. The current of the C^{4+} beam at the output of the I3 that reaches 5 mA has been cut into 80 mA/2.5 MHz short bunches. Such high bunch current cannot be transferred without loss through the U3/UK beam line and cannot provide a stable beam circulation in the UK ring because of excessive space charge forces. Transmission of the beam from the I3 output to the UK input is on the order of 50%.

4. BEAM ACCELERATION IN BOOSTER SYNCHROTRON UK

The present configuration of the booster synchrotron UK is intended to accelerate partially stripped C^{4+} ions with energy rising from 1.3 MeV/amu to 300 MeV/amu at a repetition rate up to 1 Hz (Table 3). The maximum energy for the C^{4+} beam in the UK ring is limited now by the RF variation factor, which is on the order of 15 for the available accelerating system. This variation factor is obtained from two ferrite-loaded resonators working in sequence and modulated in the frequency ranges of 0.6–2.2 MHz and of 2.2–10 MHz. The change of bucket for the bunch beam, on the ramp of the accelerating cycle, is provided without particle loss by matching RF phases and amplitudes in both resonators. The intensity of the C^{4+} beam achieved in the UK is now on the order of 10^9 ppp (Fig. 3) and it is limited by three main factors: the low injection energy, the large debunching travelling distance for the injected beam, and the vacuum loss of beam at acceleration. Subsequent improvement of the vacuum in the UK ring by factor of 2 or 3 will be achieved with the installation of additional nonevaporable getter pumping. Improvement of the ring magnet correction

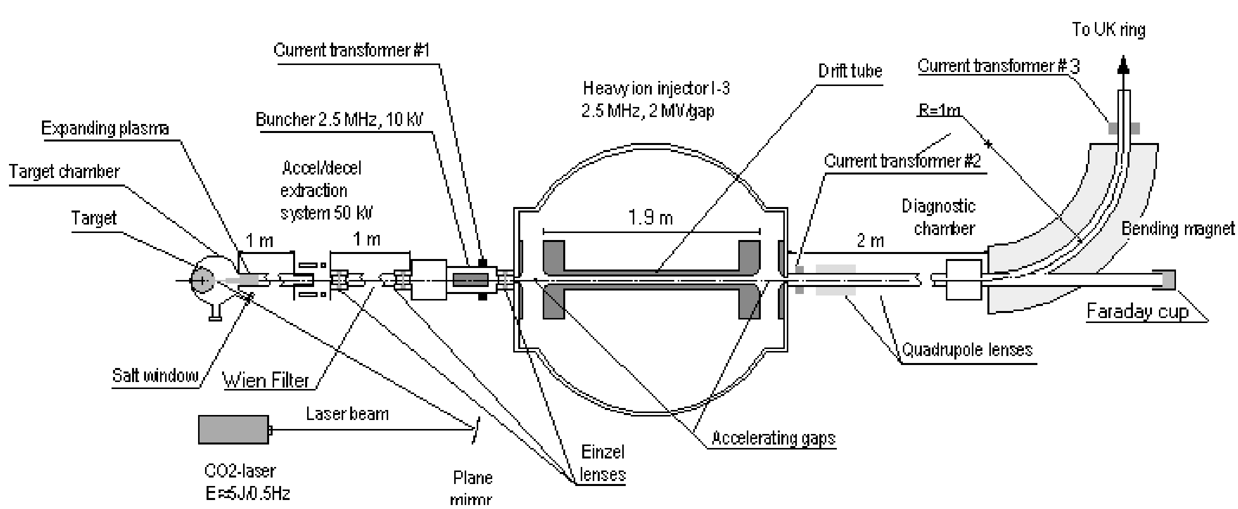

Fig. 2. Configuration of Linear Injector I3.

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Table 3. *Parameters of the booster synchrotron UK*

Orbit length	223 m
Max. magnetic rigidity	9.8 T·m
No. of long straight sections	42 × 3 m
Betatron frequency	5.75
Max. of betatron amplitude function	18.2 m
Max. of momentum compaction function	2.1 m
Vacuum	$5\cdot10^{-10}$ Torr
RF variation range	0.6–10 MHz
RF amplitude	10 kV
Horizontal acceptance	120 π mm mrad
Vertical acceptance	90 π mm mrad
Maximum repetition rate	20 Hz
Operation repetition rate	1 Hz

system and implementation the adiabatic beam capture seem to have increased the UK intensity by a factor of 2 to 3. Thus we hope to reach in the UK ring the intensity of $(5–6)\times10^9$ for the C^{+4} beam.

The beam accelerated in the UK is quickly extracted for injection into the accumulator ring U10. The extraction kicker magnet is formed of six identical modules each of effective length 300 mm. The magnets are excited from individual pulse generators charged to 45 kV. The pulse rise time is 300 ns; the flat-top time is 500 ns. The total kick strength is up to 0.16 T·m. The kicker magnet is equipped with a bakable ceramic vacuum chamber matched by the inside aperture of 80 mm to the UK circulating beam at injection.

To obtain a practically loss- and dilution-free extraction and transfer of the accelerated beam from the UK to the U10 providing reasonable gaps for kickers, a rebunching RF system with harmonic number one has to be adjusted in the UK ring by using one of accelerating resonators. The control for the RF gymnastic is being prepared for testing.

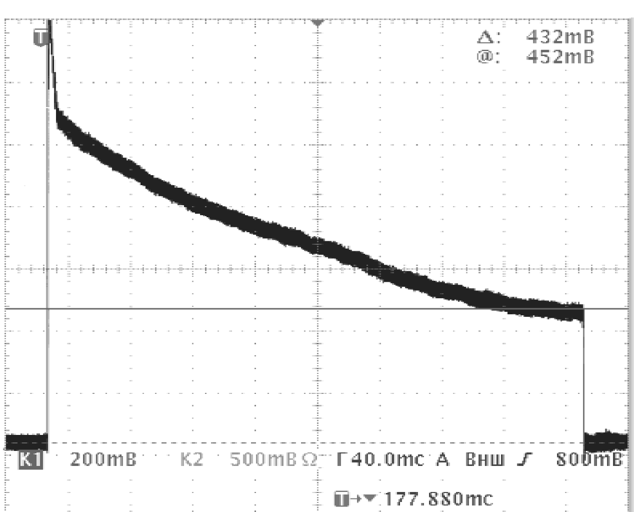

Fig. 3. Intensity of the C^{4+} beam at acceleration in the booster synchrotron UK up to the energy of 200 MeV/amu (horizontal scanning 40 ms/div, vertical scanning $5\cdot10^8$ ppp).

The position of the extraction kicker magnet and a schematic layout of the transfer line between the UK and the U10 is shown in Figure 4. This line is designed to have a transverse acceptance of 15 π·mm·mrad. Transverse matching in both planes is achieved by four quadrupole magnets positioned between two chains of C-core bending magnets. The magnets are laminated to be pulsed from a capacitor discharge power supply with a half sine waveform lasting 10 ms for the magnet SM and 19 ms for the magnet BM. The deflection in the BM is 90 mrad, maximum field is 1.5 T, and the magnetic length is 0.6 m.

5. ACCUMULATOR RING U10

Parameters of the U10 ring are listed in Table 4. This ring is adapted for ion accumulation from the 10 GeV proton synchrotron. The ion accumulation procedure (Alexeev *et al.*, 1998) is based on the charge-exchange injection using a fast bump system for minimizing the stacked beam perturbation by penetrating through the stripping foil material. The schematic layout of the beam trajectory at injection and the injection elements are shown in Figure 5. The septum magnet SMG with magnetic length of 0.8 m is placed outside of the U10 ring between magnets F503 and D504. It is pulsed from a capacitor discharge power supply with a half sine waveform lasting 20.3 ms. This magnet is used not only for the beam injection but for extraction too. The deflection of the C^{4+} beam in the septum magnet at injection is 98 mrad; the maximum field is 1.2 T. The slight gradient of the magnetic field in the septum magnet focuses the beam at extraction. The SMG steers the injected beam to the center of the stripping foil of 5 × 10 mm size, which is placed in the vacuum chamber of the F505 with a displacement of 20 mm from the ring equilibrium orbit. The fast bump system matching of both injected and circulating beams includes three kicker magnets installed in the short straight sections following magnets F411, F511, and F711. The rise and fall time for the kicker magnet pulse is 300 ns; the pulse flat-top is 500 ns. The first kicker magnet gives a kick of 3 mrad, deflecting the stacked beam to the stripping foil at a moment when the injected beam is passing through the transfer line. The two beams, becoming one after passing through the stripping foil, are set to the ring closed orbit downward by

Table 4. *Parameters of the accumulator ring U10*

Orbit length	251 m
Max. magnetic rigidity	34 T·m
Betatron frequency	9.25/9.25 h/v
No. of long straight sections	16 × 2.3 m
Vacuum	$5\cdot10^{-9}$ Torr
RF variation range	0.9–4.9 MHz
RF amplitude	50 kV
Horizontal acceptance	80 π mm mrad
Vertical acceptance	50 π mm mrad

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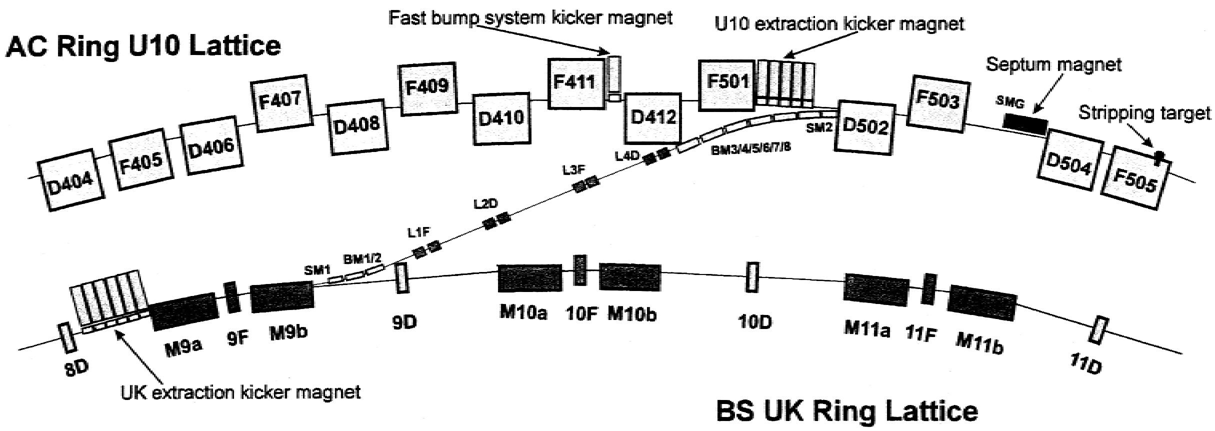

Fig. 4. Schematic layout of Beam Transfer Line UK/U10.

the kicker magnets in straight sections of F511 and F711. The scheme of the beam crossing with the stripping foil in the transverse phase space is shown in Figure 6. The foil material is mylar with a thickness of 5 mg/cm^2, that yields >90% bare carbon ions with projectile energy of >50 MeV/amu.

6. EXPERIMENTS WITH CARBON BEAM STACKING

Adjustment of the multiple injection system has been carried out in several steps. The first step was to transfer the beam through the small aperture of 30 × 55 mm in the 5-m-long, seven dipole modules, bending the magnet with total deflection of 28.8°. The transferred beam would be observed on the screen in the station following magnet F502.

The second step was to hit the stripping foil with the beam by steering the magnets SM2 and SMG. The center of the foil had been positioned at the point of the ring equilibrium orbit. The beam penetrating through the foil and ions stripping would be identified by the negative signal from the foil, indicating electrons tearing off.

When the charge-exchange process had been identified, the next step was to get the first revolution of the stripped beam in the U10 ring. Steering the injected beam trajectory and the closed orbit in the point of the foil crossing, the first revolution of the ion beam was trapped, confirming correctness of the calculated kinematics for the beam passing through the injection elements.

The circulation of the injected beam (Fig. 7) was a result of the stripping foil displacement to 20 mm from the closed orbit and the fast bump system activation for setting the stripped beam to the closed orbit trajectory.

The beam stacking test would be the next logical step for adjusting of the accumulator, but, as we found, the lifetime

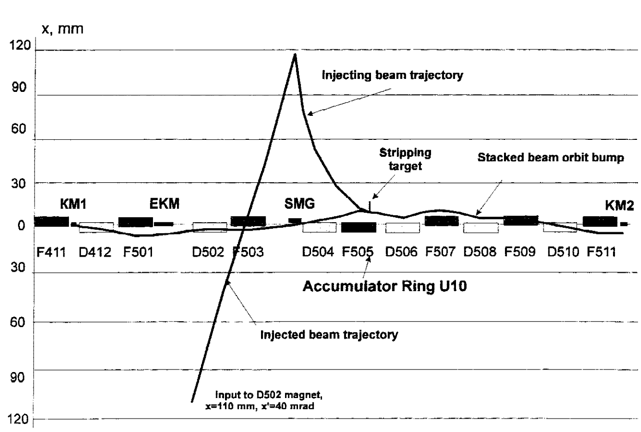

Fig. 5. Beam trajectory and multiple injection system elements in the accumulator ring U10.

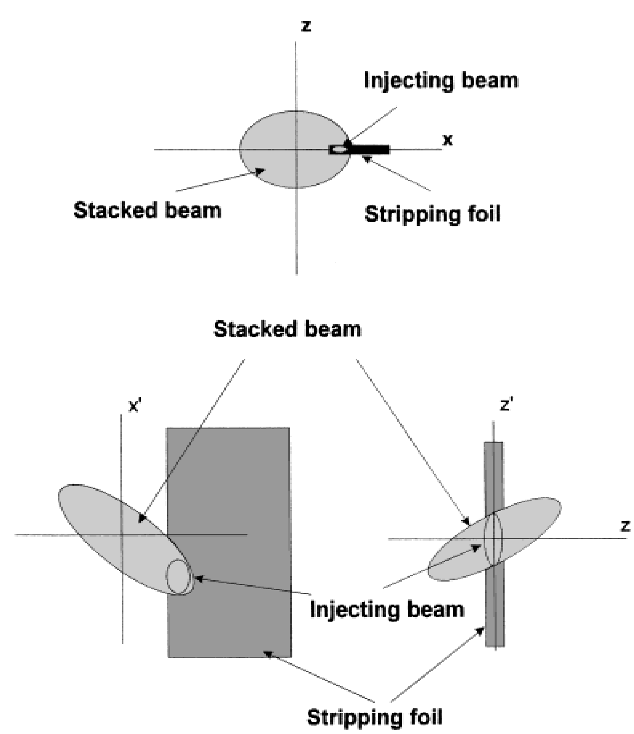

Fig. 6. Beam crossing with stripping foil in the transverse phase space at the multiple injection.

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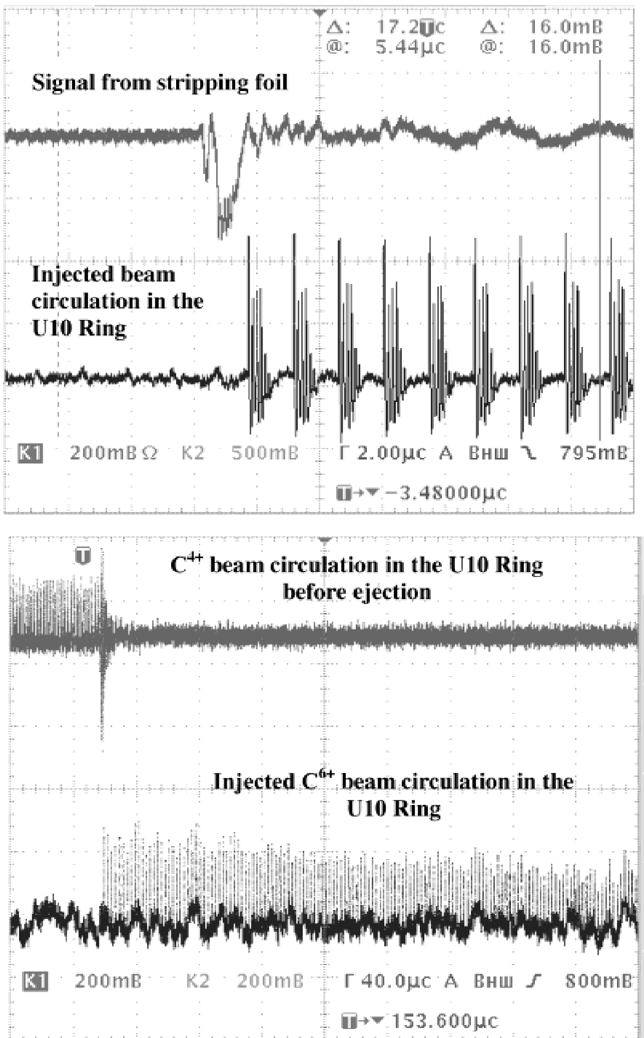

Fig. 7. Charge-exchange injection of the $C^{4+} \Rightarrow C^{6+}$ beam from the booster synchrotron UK to accumulator ring U10 at the energy 200 MeV/amu.

for the circulating beam had not been long enough for subsequent injections. As the repetition rate for the U10 multiple injection is less than 1 Hz, the required lifetime for the circulating beam has to be at least several seconds. But the beam had been stable in the U10 for only 10 ms, being pushed away by the closed orbit deformation caused by an eddy current field excited by the pulse of the septum magnet SMG in the asymmetrical construction of a steel shielding vacuum chamber. As soon as the construction of the shielding chamber had been changed and the perturbing field eliminated, the beam circulation time increased to dozens of seconds, according the vacuum conditions in the U10 ring.

The beam accumulation test was carried out in the U10 ring with the RF on with voltage of 1 kV and harmonic number 2 providing recapture of the injected beam that had been bunched before in the booster synchrotron UK with harmonic number 10. Periodicity of accelerating cycles had been set to 3.5 s. Matching of both injected and stacked beams was achieved by careful steering of the fast bump system, of the injected beam trajectory, and of the orbit position to the stripping foil. As a result of accumulator adjusting, the stacking process had been launched and a beam current in the U10 ring started to increase from cycle to cycle (Fig. 8).

7. OUTLOOK FOR TWAC ADVANCE

By achieving the stacking process in the accumulator ring U10, we have seen that the basic technological scheme of the TWAC project is really working well, and it can be successfully used for an ion beam accumulation without conservation of particle density in the phase space volume. Expansion of a dynamic aperture for the accumulator ring and mastering the multiple injection procedure is the next aim for the TWAC team. Parameters of the stacked beam seem to be achieved in the frame of available TWAC configuration taking into account the IBS limit for the stacked beam intensity given in Table 5. The stacked energy increase can be achieved by substitution of the 100 J laser ion source for the 5 J one, as it was outlined in the project. But, we understand now that this solution is not optimal for the

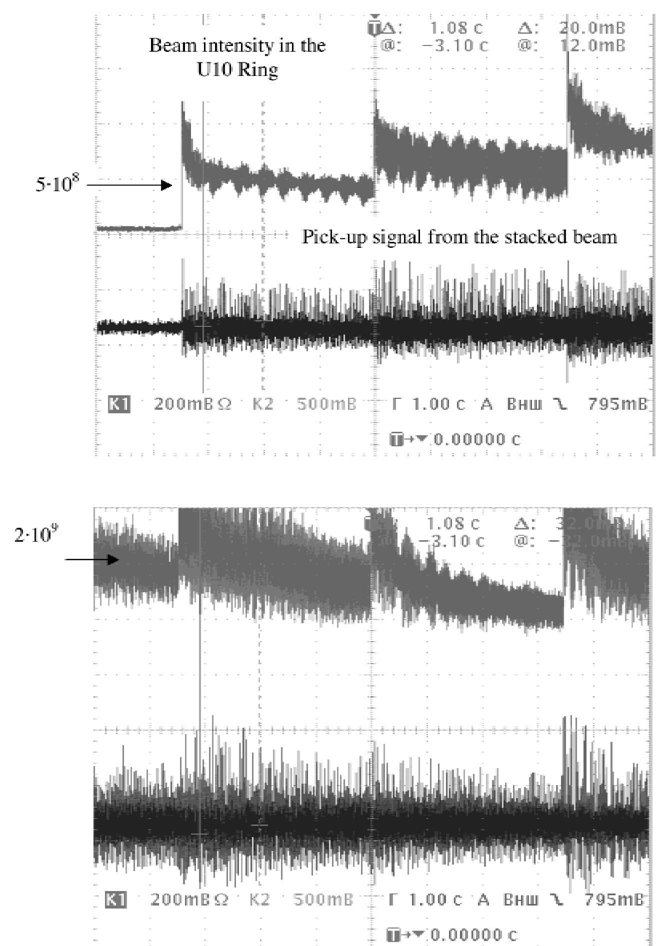

Fig. 8. The C^{6+} beam stacking in the accumulator ring U10 at the energy 200 MeV/amu (vertical scanning is $1.3 \cdot 10^9$ ions/V).

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Table 5. *Expected parameters of the TWAC in the available configuration*

Laser energy	5 J
Injector energy	4 MV
Repetition rate	1 Hz
Facility configuration	
Stacked ions	$_{12}C^{4+} \Rightarrow {}_{12}C^{6+}$
UK intensity	$6 \cdot 10^9$
Stacked ion energy	4.9 GeV
Stacked beam intensity/energy	$1.8 \cdot 10^{12}$/2 kJ

Table 6. *Expected parameters of the 20-Hz TWAC*

Laser energy	30 J	
Injector energy	7 MeV/amu	
Repetition rate	20 Hz	
Facility configuration for C and Al beams		
Stacked ions	$_{12}C^{5+} \Rightarrow {}_{12}C^{6+}$	$_{27}Al^{10+} \Rightarrow {}_{27}Al^{13+}$
UK intensity	$2.5 \cdot 10^{11}$	$1.5 \cdot 10^{11}$
Stacked ion energy	11 GeV	21 GeV
Stacked beam intensity/energy	$1.1 \cdot 10^{14}$/190 kJ	$3.9 \cdot 10^{13}$/130 kJ

TWAC because the IBS limit will not permit the considerable increase of the stacked beam current. The only way to overcome the IBS effects is to speed up the accumulation process. The TWAC Facility has a precondition to do it, as the magnets in the booster synchrotron UK are laminated for the repetition rate of 20 Hz. The expected parameters for the 20 Hz TWAC are given in Table 6.

8. CONCLUSION

1. The TWAC Facility is in permanent progress and the following stages have been successful: extraction of high charge carbon ions in the laser ion source, preliminary acceleration of the C^{4+} ion beam in the 4 MV injector I3, acceleration of the C^{4+} beam in the booster synchrotron UK up to the energy of 300 MeV/amu, and demonstration of the $C^{4+} \Rightarrow C^{6+}$ beam stacking in the accumulator ring U10.
2. The next aim for the TWAC advance is the optimization of the multiple injection procedure for the stacked beam current increase to the limit of the available facility configuration.
3. The proposed upgrade to the 20-Hz TWAC Facility is the subject of detailed consideration and discussion.

REFERENCES

Alexeev, N.N., Bolshakov, A.E., Mustafin, E.R. & Zenkevich, P.R. (1998). Simulation of Accumulation Process in ITEP-TWAC. *Proc. EPAC98*, 1141–1143.

Koshkarev, D.G., Alexeev, N.N. & Sharkov, B.Yu. (1996). ITEP Accelerator Facility Upgrade. *Proc. XV Workshop on Charged Accelerator, Protvino* **2**, 319–321.

Sharkov, B.Yu., Koshkarev, D.G., Churazov, M.D., Alexeev, N.N., Basko, M.M., Goluber, A.A. & Zenkevich, P.R. (1998). Heavy ion fusion activities at ITEP. *Nucl. Instrum. Methods Phys. Res. A* **415**, 20–26.

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