EXPERIMENTS WITH Fe-ION BEAM GENERATION ACCELERATION AND ACCUMULATION IN ITEP-TWAC FACILITY*

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Abstract

The laser ion source (LIS) developed in collaboration ITEP-TRINITI-CERN [1] with an upgraded version of powerful 100J CO_2-laser has been used for Fe-ion beam generation at the input of the pre-injector I-3 delivering separated species of Fe^{16+} ions with energy of 1.1 MeV/u to booster synchrotron UK for acceleration up to the energy of 165 MeV/u and accumulation in the storage ring U-10 using multiple charge exchange injection technique. First results of Fe-ion beam treating from laser ion source to accumulator ring are presented.

INTRODUCTION

Experimental and numerical calculation results devoted to development of an optical system for an ion source based on a high-power CO_2-laser described in [1]. 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 [2]. 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 ~ 50. Well known imperfections of LIS operation with free-running laser regime [1] leads to essential decreasing of LIS target spot temperature and as a result to lesser average charge state for generated ions. But it was not very imported for the first beam experiments taking the aim to check the new laser system reliability and specialty of generated beams acceleration and stacking in the accumulator ring.

THE 100J CO_2-LASER RUNNING FOR Fe-ION BEAM PRODUCTION

The new LIS optical scheme is shown in Fig.1. The laser radiation is transferred to the target in the optical channel with nine Cu-mirrors at the distance of ~40 m. The length of a drift tube for generated plasma is 1.7 m. The typical laser radiation pulse at the free-running regime of laser operation is characterized by the sharp spike of 30-250 ns (depending on the resonator active medium parameters) at the pulse front and a long low intensity radiation tail of 1-2 µs duration that contains up to 60% of the total laser pulse energy. Stretching in time the radiation energy investment to the target results in low-charge state ions domination in a generated ion beam and intensive evaporation of a target material.

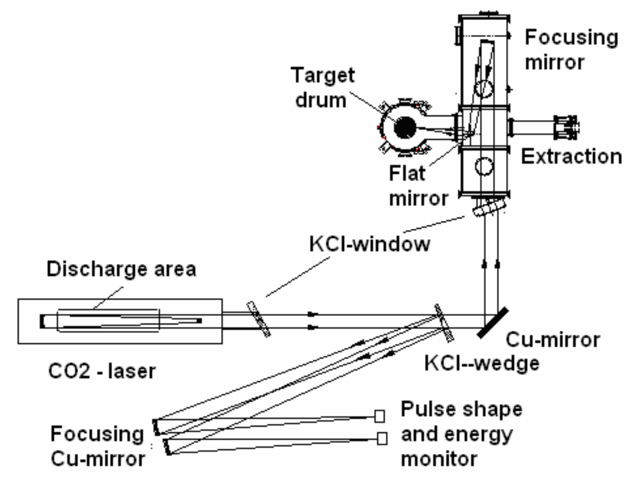

Figure 1: The 100J CO_2-laser ion source optical scheme.

Typical signal of ion beam extracted from laser plasma in Fe-target and measured at the extraction gap outlet shows (Fig.2) 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.

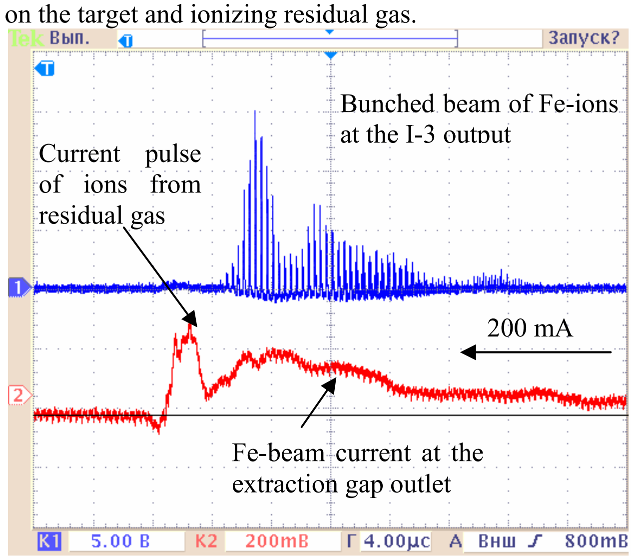

Figure 2: Signals of Fe-ion beam generated in LIS.

It can be seen in Fig.3 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 $\sim 10^{12}$, the number of Fe^{16+} ions at the head of the beam pulse is order of 5×10^{10}.

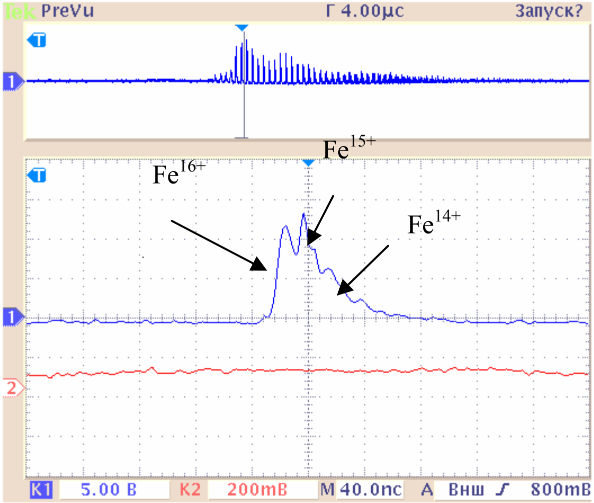

Figure 3: The Fe-ion species at the head of LIS beam.

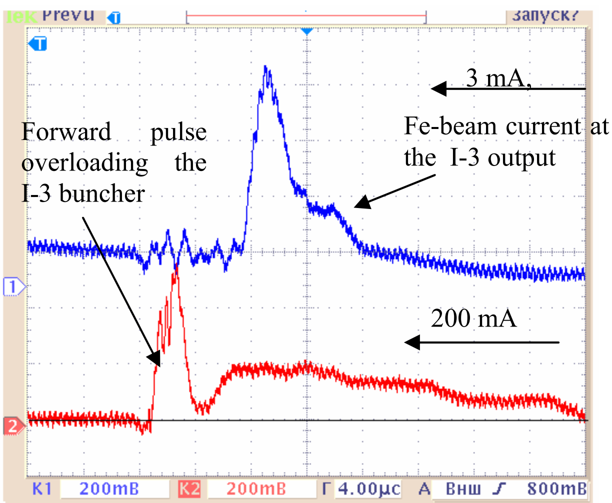

Figure 4: Current signals of total Fe-beam at the LIS extraction gap outlet and Fe^{16+}-beam of 64 MeV at the I-3 linac output.

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. Regime of target rotation for irradiated spot changing has been tuned experimentally for a maximum of the ion beam stability. For Fe-beam generation, optimized time of target position changing found to be 40-50 minutes at displacing irradiated point on 5-6 mm. The maximum amplitude of Fe^{16+}-beam pulse shown in Fig.4 has been observed usually before Fe-material of 2 mm thickness pierced through. At new target position, the amplitude of beam current has been increasing for ten – twenty successive pulses stabilizing on the half maximum level. For Al-beam generation, the target drum has been rotated after any laser shot displacing irradiated point on 0.5 mm. The shape of Al-beam current pulse has been similar to the Fe-beam but at very high instability of current amplitude. The Fig.5 shows the LIS target drum treated by laser beam: the Fe-strip is pierced through; the surface of Al material is pierced through (by ten laser pulses to fixed target) or worked out on the depth of ~1 mm at slow motion of irradiating point.

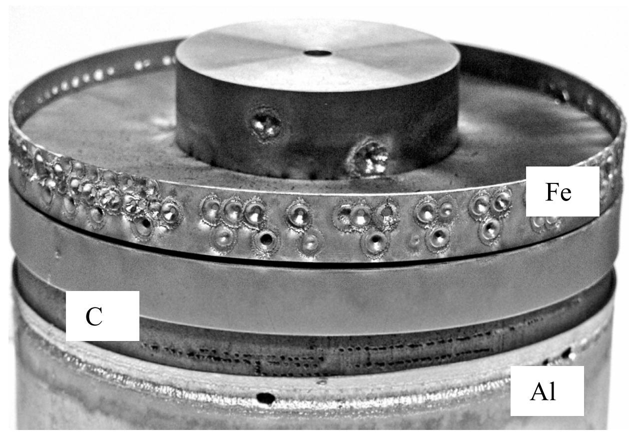

Figure 5: The LIS target drum after long time operation with Fe- Al- and C- beam generation.

ACCELERATION OF IONS IN BOOSTER SYNCHROTRON UK

Ions of C^{4+}, Al^{10+} and Fe^{16+} accelerating in the booster synchrotron UK up to the energy of 165, 200 and 265 MeV/u at similar conditions have been differed by factor of particle losses during acceleration cycle as 2, 1.5 and 3 correspondingly. Those beam losses can't be explained by vacuum which is estimated by value of $1x10^{-9}$ Torr confirmed in experiments for studying of C^{4+}-ions vacuum losses in the UK ring. Taking into account experimental results, the beam loss factor by vacuum can't be more than 10%. The beam loss at acceleration is apparently explained by the great dispersion of particle tune shift which is not corrected in this ring and estimated at the beam injection by the value of $\Delta Q_{x,z}=\pm 0.1$. Different rate of betatron resonances crossing causes some variation of particles losses for various ion species. Chromaticity correction system for the UK ring is now under construction to solve the problem of beam loss.

FIRST 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. Staking process by scheme $C^{4+} \Rightarrow C^{6+}$ is shown in Fig.6 at stacking factor of $k_\infty \sim 70$ and number of stacked particles $4x10^{10}$. [4]

First experiments with Fe- and Al- beam stacking have been very important for testing of multiple injection kinematics at different ion charge changing in the stripping foil which is installed in the fixed point of the storage ring which is optimized for changing of ion charge as $Z_i/Z_n=0.7$ at the permissible range of $\Delta(Z_i/Z_n)=\pm10\%$ for ideal closed orbit of stacked beam. An orbit perturbation in the azimuth point of stripping foil position causes some changing of injection kinematics requiring specific correction of machine orbit and injection trajectory for different value of Z_i/Z_n.

Parameters of stacking beams and injection system are listed in Tab.1. 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 (Fig.6).

Table 1: 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	$\sim2x10^9$	$\sim5x10^7$	$\sim1x10^8$
Momentum spread, %	±0.04		
Emittance, π mm·mrad	~5		
Stacked beam intensity	$>4x10^{10}$	$>5x10^8$	$>2x10^9$

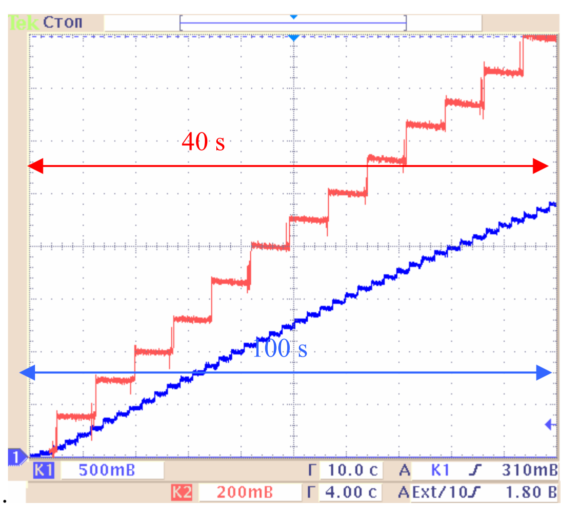

Figure 6: The stairs of C^{6+}-beam stacking in the U10 ring.

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) is order of magnitude higher than it was predicted by the theory [5-7]. The loss of Fe-nuclei traversing large distance in vacuum of 10^{-8} Torr approximately corresponds to the beam loss in the target. The resulting Fe-nuclei stacking process gives the cross section of particles losses as much as $4x10^{-21}$ cm^{-2}.

The resulting process of Al-nuclei stacking have been as expected little differing from the C-nuclei stacking shown on Fig.6. 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.

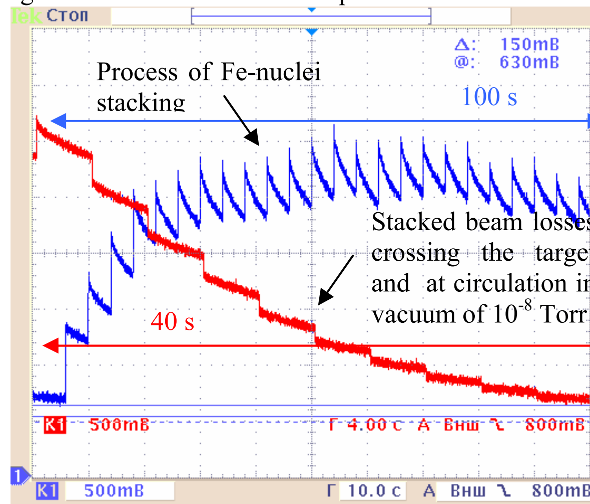

Figure 7: Stacking of Fe^{26+}-nuclei in the U-10 ring.

CONCLUSION

The nearest progress in the ITEP-TWAC project will be the LIS 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. First experiments with Fe- and Al-ions generated in LIS with the laser operated in free-running regime have shown up some shortcomings of target station construction to be eliminated for the high current beam stability increase.

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.

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