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Project of TWAC Electron Cooler

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Abstract

The ITEP-TWAC is a new heavy ion accumulator facility under construction at ITEP in Moscow [B. Sharkov *et al.*, Nucl. Instr. Meth. **A415**, 20(1998)]. The TWAC project directs on development and promotion of high intensity and high power heavy ion beam technology. The main goal of the TWAC project is accumulation in the storage ring of intense ion beam, its longitudinal compression and using the extracted beam for plasma experiments.

An electron cooler with electron energy of 380 keV provides a small ion bunch size during charge-exchange injection into the U10 accumulator ring [I. Meshkov *et al.*, Design project of electron cooling system for TWAC accumulator ring (Dubna, 2001)]. The cooling time is compared with the storage time during charge-exchange multi-turn injection. The electron cooler allows us to significantly improve the beam parameters at the target (specific energy, specific power and so on) and to suppress the beam losses by an order of magnitude. The application of electron cooling allows an increase in of the final power of an extracted ion beam on a target by a factor 2–3.

1. Introduction

The TWAC project (Fig. 1, Table I) is intended to initiate some groundwork for development and promotion of high intensity and high power ion beam technology based on accelerator facilities available at ITEP [1,3–4]. 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 terawatt range of power providing a unique opportunity for studying solid matter in the high density plasma state.

A laser ion source is used for production of highly charged ions ($Z/A \sim 0.25 \div 0.45$) 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 an energy of $1 \div 2$ MeV/u. The booster synchrotron UK accelerates an ion beam to near relativistic energy for stacking an energetic beam into the accumulator ring U10 with use of a charge exchange injection technique (Fig.1). Adjusting the multiple injection system has been completed this year by demonstration of C^{6+} ion beam stacking at the energy of 200 MeV/amu during the charge exchange injection of C^{4+} ions. The current growth of the stacked beam by a factor of 4–5 at the accumulation test has been limited by increasing beam loss through the low vacuum of 10^{-8} Torr in the accumulator ring, low repetition rate of 0.3 Hz, and diminished dynamic aperture of the U10 in the absence of magnetic field correction.

The nearest 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. The ion beam energy has been corresponding to 3–5 kJ, the ion beam pulse duration is 50–100 ns and the beam power is 30–50 GW.

However, in fact the pulse duration may be much longer because of intra-beam scattering (IBS), resulting in an increase of the r.m.s. momentum spread and a decrease of the maximal compaction degree. Additional problems can appear due to extreme transverse heating caused by the following phenomena: noise of kicker magnets, transverse non-linear resonances, interaction with charge-exchange target and residual gas, transverse instabilities and so on. A possible way of suppressing these phenomena is the introduction of an electron cooling system [2], which allows us to increase the six-dimensional beam density.

2. Design project of TWAC electron cooler

The small length of the straight TWAC section of 2.35 m available for the electron cooler (Fig. 2, Table II) together with steering magnets is the main peculiarity of the cooler.

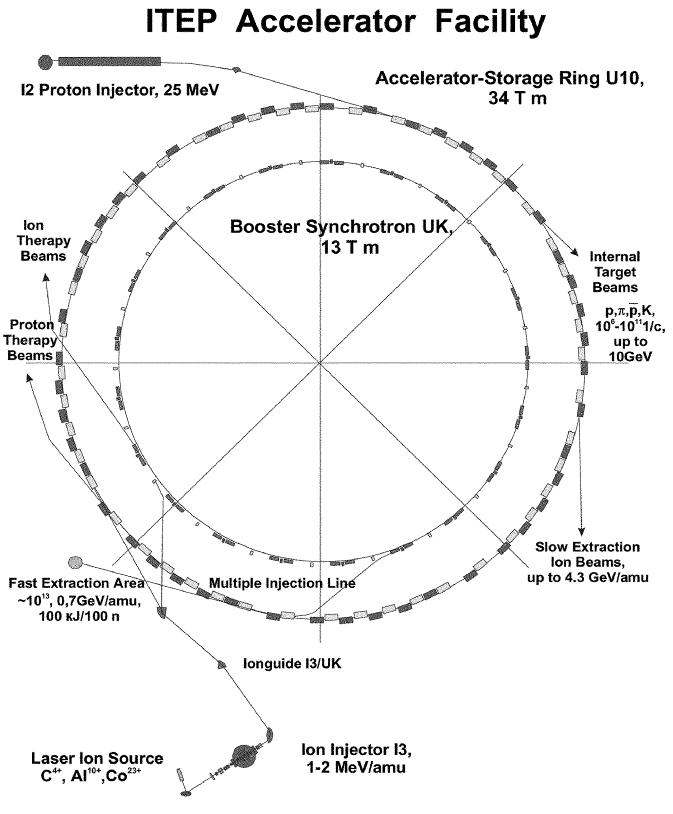

Fig. 1. Schematic layout of ITEP Accelerator Facility after reconstruction.

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Table I. *Project parameters of the TWAC.*

Stacked beam energy, kJ	100
Stacked beam power, TW	1
Beam pulse length, ns	100
Beam power density, TW/cm^2	120
Electron temperature in matter, eV	10
Electron density in matter, cm^{-3}	10^{23}
Internal pressure in mater, Mb	10–100

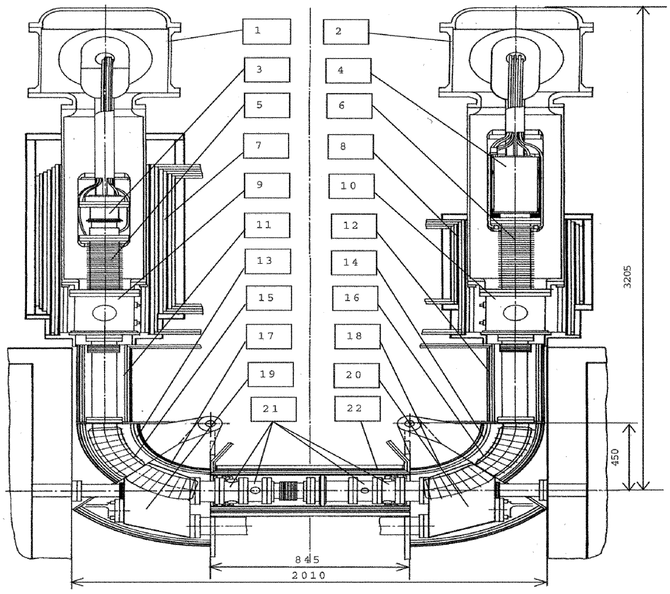

Fig. 2. TWAC electron cooling system.

The following limitations determine the special features of the designed system: small curvature radius of the electron beam of 45 cm in the toroid bending magnet; short cooling section of 84 cm and small effective cooler length of 55 cm with high quality of magnetic field.

The relative transverse magnetic field in the straight cooling section is $2 \cdot 10^{-4}$, the corresponding effective longitudinal electron temperature is about 10–20 meV. However the field region with non-uniformity of order 10^{-3} appears in junction of straight and toroidal solenoids with 15 cm length. The application of additional 6 dipole-correcting coils permits to reduce the transverse magnetic field on the beam axis. The length of the cooling section with non-uniformity of magnetic field less than $2 \cdot 10^{-4}$ is 55 cm in accordance to OPERA and SAM codes simulations [2].

The developed electron cooling system (Fig. 1) consists of the following main subsystems: 1) system of electron beam formation including the electron gun (p. 3) and accelerating tube (p. 5); 2) recuperation system consisting of decelerating tube (p. 6) and electron collector (p. 4); 3) magnetic system including straight solenoids (p. 7, 8, 11, 12, 22), toroidal solenoids (p. 13, 14, 17,18), coils for drift compensation in bending toroides (p. 15, 16) and correction coils; 4) vacuum system, which consists of vacuum chambers and vacuum getter pumps (p. 9, 10, 19, 20), as well as of devices for vacuum chamber heating and for pressure control; 5) diagnostics system including two pairs of pickup stations at the entrance and the exit of the cooling section (p. 9, 10 and 21); 6) water cooling system providing cooling of the solenoids, collector, gun anode and the radiators of air cooling and distillate cleaning system; 7) system of elegas isolation in tanks (p. 1, 2); 8) high voltage power supplies; 9) mechanical supports.

A magnetic expansion scheme is used for formation of an electron beam with current of 3 A and transverse energy of 200 meV for boundary electrons and 50 meV for axis electrons [2]. The feature of the TWAC electron cooler is a collector with low flux of secondary electrons. Almost all secondary electrons that escape the collector are lost due to a large drift displacement of 13 cm in the toroid bending magnets.

Table II. *Main parameters of TWAC electron cooler.*

Maximum energy, keV	380
Beam current, A	0–3
Beta functions in cooling system, m	3/7.3
Dispersion function, m	~0.5
Length of cooling section, m	0.8
Effective length of the cooling section, m	0.55
Magnetic field in the cooling section, kG	1–1.2
Field non-uniformity in the cooling section	$2 \cdot 10^{-4}$
Beam radius in the cooling section, cm	1.1–1.5
Relative current losses	$2 \cdot 10^{-4}$
Transverse electron temperature, meV	200–300
Longitudinal electron temperature, meV	10–20

3. Ion accumulation with electron cooler

For multiple charge exchange injection the number of ions N in the ring is defined by the equation

$$\frac{dN}{dt} = \frac{N_{inj}\eta_{target}}{\tau_0} - \frac{N}{\tau_{life}},$$

where t is the time, τ_0 is the interval between injection cycles, N_{inj} is the number of injected ions per pulse, η_{target} is the target efficiency. Simultaneously we have the following equations for the beam emittance and momentum spread:

$$\frac{1}{\varepsilon_{x,y}}\frac{d\varepsilon_{x,y}}{dt} = \Lambda_{x,y} - \lambda_{x,y}, \qquad \frac{1}{\sigma_p}\frac{d\sigma_p}{dt} = \Lambda_p - \lambda_p,$$

where the terms $\Lambda_{x,y,p}$ describe the heating terms, $\lambda_{x,y,p}$ describe the electron cooling. Numerical investigation of the beam accumulation process (Tables III–IV) with

Table III. *Simulation TWAC parameters.*

Kind of ions	$^{27}Al^{+13}$
Kinetic energy, MeV/u	600
Electron beam radius, cm	1
Effective length of cooling system, cm	55
Injected beam r.m.s. $\varepsilon_x = \varepsilon_y$, mm · mrad	2.4
Injected beam r.m.s. momentum spread, $\Delta p/p$	$6 \cdot 10^{-4}$
Number of injected particles per cycle	$1 \cdot 10^{10}$
Time interval between injection cycles, s	1.0
Material of charge exchange target	$^{197}Au^{79}$
Thickness of charge exchange target, g/cm^2	$6 \cdot 10^{-4}$

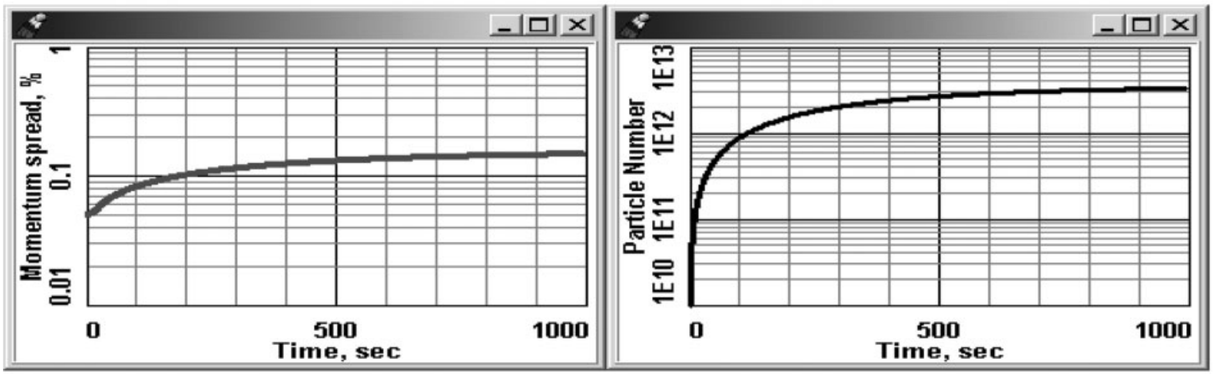

Fig. 3. Dynamic of ion parameters at charge–exchange injection for Al^{13+} for target density of $n_{target} = 0.5\,\mathrm{mg/cm^2}$, $N_{inj} = 10^{10}$ and $I_e = 0.6\,\mathrm{A}$.

Table IV. *Accumulated beam parameters.*

Option	without cooler	with cooler
Injected beam intensity, 10^{10}	1	1
Kicker instability, mrad/cycle	0.3	0.3
Number of injected cycles	300	112
Accumulated beam intensity, 10^{12}	1.9	1.1
Capture coefficient	0.65	0.96
R.m.s. horizontal emittance, mm · mrad	27.2	15.2
R.m.s. vertical emittance, mm · mrad	5.9	2.2
R.m.s. momentum spread, 10^{-4}	8.8	4
Incoherent tune shift	0.11	0.15
Stored energy, kJ	5.05	2.8
Beam size at the target, mm	1.1	0.6
Maximal compression degree	5.7	10.4
Beam power, GW	22.4	33.2
Specific energy deposition, kJ/g	1.8	3
Specific power TW/g	8.1	35.0
Plasma temperature, eV	1.5	2.4

account of both effects has been made using two simulation codes: "BETACOOL" considering analytically evolution of a Gaussian beam [5] (Fig. 3) and code "MOCAC" based on Monte-Carlo method (Table IV) [6]. During accumulation the longitudinal momentum spread increases due to the following processes: intra-beam scattering (IBS) and interaction with target (straggling and random target interactions). The beam emittance can increase due to the following phenomena: noise of kicker magnets, transverse non-linear resonances, transverse instability and interaction with charge exchange target and residual gas.

The high temperature plasma target experiments in TWAC are characterised by several parameters (Table IV): E_{sp} is the specific energy deposition in the target, τ is the ion beam pulse duration on the target after compression and T_{p} is the plasma temperature:

$$E_{sp} \approx \frac{N_t}{2\pi a_x a_y}\frac{\mathrm{d}E}{\mathrm{d}x}, \quad \tau \approx T_{rev}\frac{\sigma_p}{\sigma_p^{\max}},$$

$$T_p \propto P^{1/2} \propto \sqrt{\frac{N_t}{\varepsilon^{2/3}\sigma_p}},$$

where N_t is the number of ions on target, $a_{x,y}$ is the horizontal and vertical beam size on the target, $\mathrm{d}E/\mathrm{d}x$ is the ionisation losses, T_{rev} is the ion revolution time in the storage ring, σ_p and $\sigma_p^{\max}$ is the ion momentum spread before and after compression, $P = E_{sp}/\tau$ is the power of the extracted beam on the target. The power of the extracted beam is equal to

$$P = \frac{eNAE}{T_{rev}} D_{long}\frac{\sigma_p^{\max}}{\sigma_p},$$

where E is the ion energy in MeV/u, $D_{long} = N_t/N = 0.8$ is the compression efficiency, A is the atomic number. The maximum number of accumulated ions is determined by the betatron tune shift ΔQ. In calculations we use the following assumptions: the maximal incoherent tune shift is equal to 0.15; the beam is heated due to kicker noise (r.m.s. kick is equal to 0.3 mrad per injection cycle). We see that the plasma temperature can decrease because of transverse heating, which results in an increase of the beam emittance ε. The second possible reason for diminishment of specific energy is enhancement of longitudinal momentum spread due to intra-beam scattering. In absence of electron cooling the momentum spread is increased as

$$\sigma_p \propto \sqrt{\varepsilon}$$

caused by the IBS.

The electron cooling gives significant advantage (Table IV): 1.5 times increase in the specific energy, 1.5 times in

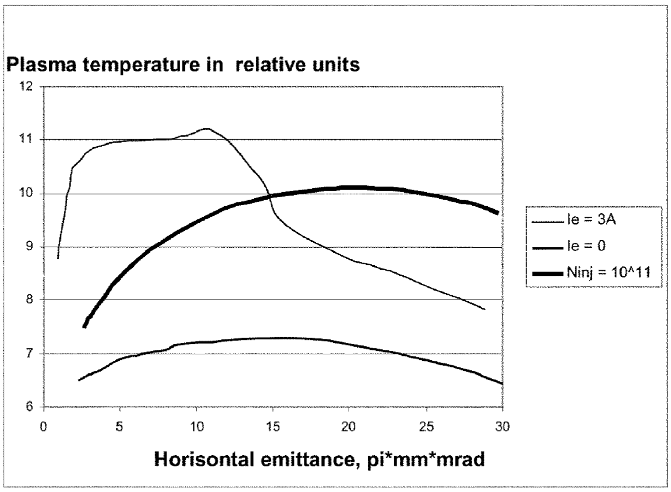

Fig. 4. Dependence of plasma target temperature on horizontal beam emittance.

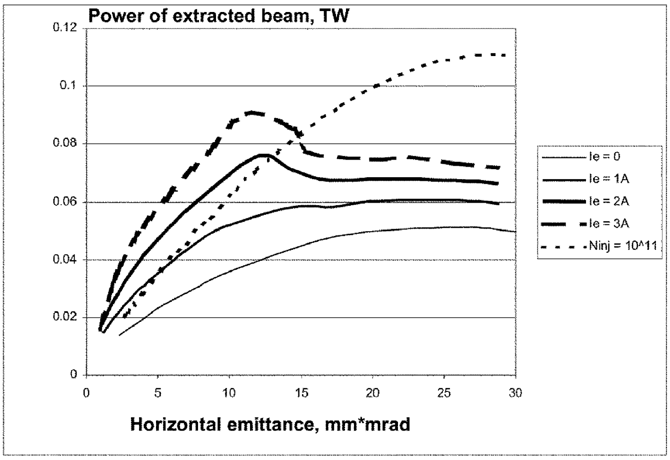

Fig. *5*. Dependence of extracted Al^{13+} ion beam power on horizontal emittance.

the plasma temperature (Fig. 4) and 3 times in specific power (Fig. 5). But the most important advantage is 10 times reduction of beam losses.

4. Conclusion

The design of an electron cooler for TWAC short length straight section of 2.35 m was realised at an electron energy of 380 keV and beam current of 3A. The application of electron cooling allows an increase of the power of the extracted beam on the plasma target by a factor 2–3 and to reach a level of 60–100 GW for a new laser injector.

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