DEUTERON BEAM ACCELERATION AT LINAC I-100 AND IHEP BOOSTER

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Abstract

Light ion acceleration program is being pursued in IHEP, Protvino. Light ion beams are planned to be used both for fundamental and applied research. Currently, the scope of activity extends over an ion source, the 100 MeV Alvarez linac I100, new beam transfer line from I100 to the 1.3 GeV rapid-cycled Booster proton synchrotron U1.5, beam injection system, and the U1.5 machine itself. In the first run of 2008, $3{\cdot}10^{10}$ deuterons were successfully accelerated up to 450 MeV/u and extracted to an external beam absorber. The report outlines technical milestone passed, up-to-date status of these works and experimental results achieved.

I100 LINAC

The 100 MeV Alvarez DTL linac I100 was used formerly as the proton-injector to the U70 synchrotron of IHEP from early days up to 1985. Substantial efforts were made since year 2000 to modify it for light ion acceleration.

Such an operation is possible only in the 4π-mode, when light ion has exactly one half of proton velocity. It was found experimentally [1] that *d*-beam (charge-to-mass ratio $q/A = 0.5$) is safely captured and then accelerated in I100 starting from the 5th gap, on having passed through a 570 keV HV electrostatic fore-injector.

When the I100 is working as a Booster injector, only 2 out of 3 its resonator tanks are used for acceleration. Third tank is working in a beam-transport mode with only the DT-lenses powered. In such a layout, the facility can yield either 72.7 MeV protons (at the standard 2π-mode), or 16.7 MeV/nucleon light ions with $q/A = 0.5$ (the 4π-mode). The first option is treated as a backup proton injector supplying a test proton (*p*) beam with magnetic rigidity 1.26 T·m that is close to $B\rho = 1.19$–1.18 T·m of the reference ions (*d* and $_{12}C^{6+}$).

Many efforts are spent for a routine maintenance of technological subsystems of the aged I100, its beam diagnostic and control equipment is being gradually renewed. Recently, a fast-rise-time chopper was integrated into fore-injector ion gun. A 3 m long base available between the gun and a Faraday cup allowed for TOF mass spectrometry to monitor technical status of duoplasmatron by measuring the amount of heavier ion impurities in beam ejected from the fore-injector. As a pay-off, in the 1st run of 2008, the facility yielded a 16.7 MeV per nucleon beam of *d* with pulsed current 15 мA in 5 μs long pulses.

BEAM TRANSFER LINE

New beam transfer line (BTL) from the I100 to the Booster synchrotron U1.5 provides ion beam transportation from the I100 linac exit to septum-magnet located in the long straight section of the period #9 in the U1.5 lattice. The beam transfer line includes 8 quadrupole lenses L1F–L8D, 4 horizontally bending magnets MH1/2–MH2/2, and 3 combined corrector-magnets MHV1–MHV3 which could provide both horizontal and vertical beam steering.

The horizontal and vertical beam envelopes A_r, A_z and dispersion function D_r. are shown in Fig. 1. Beam envelopes were calculated for invariant beam emittances equal to 8π mm·mrad in both planes.

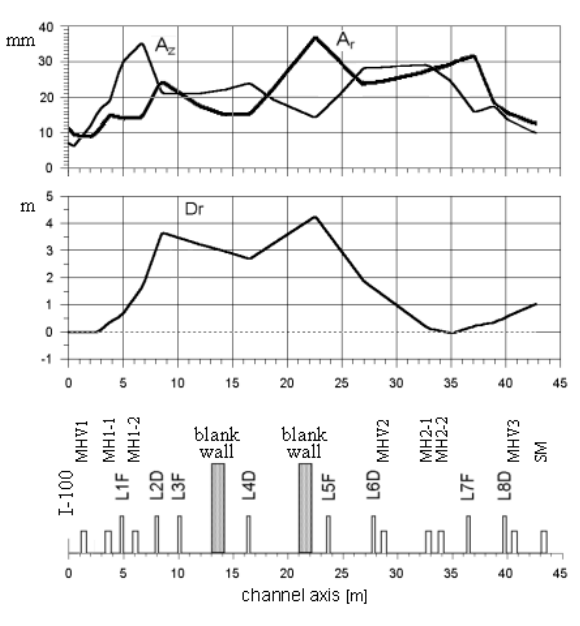

Figure 1: Envelopes A_r, A_z and dispersion function D_r in the beam transfer line.

BTL magnetic elements power supply is provided by the purpose-built units that provide current accuracy of ±0.1% for bending magnets and ±0.5% for quadrupoles and corrector-magnets.

BTL magnetic element currents are controlled through the U70 Main Control System.

The BTL also includes beam diagnostic equipment which comprises 8 scintillation screens, 2 profilometers, and 2 beam current transformers.

BEAM INJECTION SYSTEM

The BTL ends at a long straight section of the period #9 of the U1.5 Booster synchrotron lattice. Single-turn injection scheme is shown in Fig. 2. Beam injection is provided by a septum magnet positioned in the straight section and a kicker magnet located between the Booster quadrupoles 9D and 9F2.

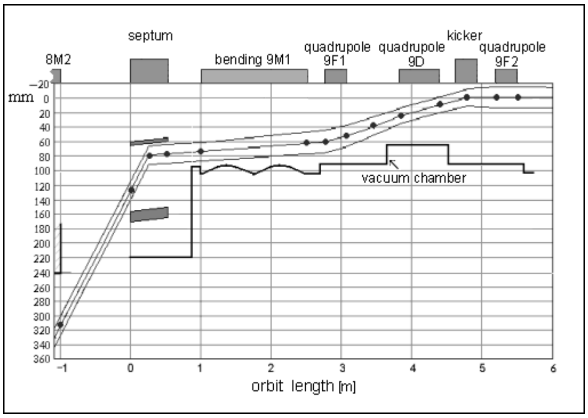

Figure 2: Injected beam trajectory.

To install a new ion beam injection system one of the Booster accelerating RF station was removed.

Septum magnet length is 0.5 m, septum thickness is 3 mm. Input septum aperture (92×50 mm^2) is sufficient with about a 15% safety margin to accept the beam with invariant emittance 8π mm·mrad and $\pm 5\cdot 10^{-3}$ fractional momentum spread. Septum magnetic field strength is 0.42 T. Sinusoidal current pulse width is 12 ms.

Kicker is a one-turn coil magnet with a ferrite core. Kicker magnet length is 0.5 m, aperture is 130×100 mm^2, magnetic field strength is 0.054 T, pulse flat-top ripple is ±0.2%. Pulse trailing edge time does not exceed 180 ns.

Top feasible repetition rate of power supply units feeding the septum and kicker magnets is 1 Hz. Mutual positions of kicker and septum magnets allows for both, single-turn and two-turn injection schemes.

ACCELERATION AND EXTRACTION OF ION BEAM FROM THE U1.5

The Booster operation mode for light ion acceleration is significantly different from that for a usual proton acceleration with initial proton energy T = 30 MeV [2]. Table 1 specifies magnetic rigidity $B\rho$, magnetic field strength B, accelerating frequency f_{RF} for proton and deuteron injection, respectively.

Magnetic Guide Field

Adjustments of magnetic guide field during beam injection were foreseen during the Booster design. These could be achieved by changing the time program for power switches [3], and such an option was used for the deuteron acceleration.

Table 1: Injection conditions for *p* and *d*

Particles	Energy *T*	$B\rho$, T·m	B, T	f_{RF}, MHz
proton, *p*	30.00 MeV	0.7977	0.1392	0.7467
deuteron, *d*	16.69 MeV/u	1.1856	0.2069	0.5629

RF System

As the former RF system master oscillator had the lower operational frequency of around 0.7 MHz, the new master oscillator for ion acceleration was developed and manufactured. It is a direct digital frequency synthesizing (DDS) device that uses information about magnetic guide field with a possibility to correct the frequency program by using feedback signals. Frequency range is 0.4–2.9 MHz, nonlinear distortions being < 3%.

Since one of the 9 accelerating RF stations was removed to free the space along orbit for new injection septum magnet, the number of available Booster RF stations had reduced to 8. To increase the RF frequency range by factor of 1.3 ca, the additional capacitors were connected in parallel to each accelerating cavity gap. Maximal RF cavity ferrite bias current is increased by some 10%. These changes demanded for increasing the output power of RF amplifiers that are now working in a new mode, close to their power limit.

Beam Diagnostics

To control ion beam having a lower intensity than protons, an additional amplifying units for Booster beam diagnostics were made. These units give a possibility to provide an additional remotely-controlled signal amplification by factors k = 1, 10, and 50. During deuteron acceleration, the k = 10 option was used.

Beam Extraction

Table 2 specifies the accelerator parameters for protons and deuterons at the end of accelerator cycle.

Table 2: Extraction conditions for *p* and *d*

Particles	Energy *T*	$B\rho$, T·m	B, T	f_{RF}, MHz
proton, p	1323.8 MeV	6.866	1.1982	2.7510
deuteron, d	454.6 MeV/u	6.866	1.1982	2.2347

As the top deuteron magnetic rigidity $B\rho$ is exactly equal to the proton one, the conventional Booster extraction schemes and devices [4] were used.

EXPERIMENTAL RESULTS

For the first time, the deuteron beam was accelerated in Booster up to energy 454.6 MeV/u on March, 2008. Deuteron beam current at the exit from I100 (TT1) was 15 mA and 9.6 mA at the end of BTL (TT2). These signals are shown in Fig. 3.

Tuning of the elements of BTL, septum and kicker-magnets, level of the Booster magnetic field at the injection time were made by measuring the deuteron beam current after the first turn in the Booster. To measure this current, the Faraday cup positioned before the septum edge in the septum magnet vacuum box, not obscuring the magnet input aperture, was used.

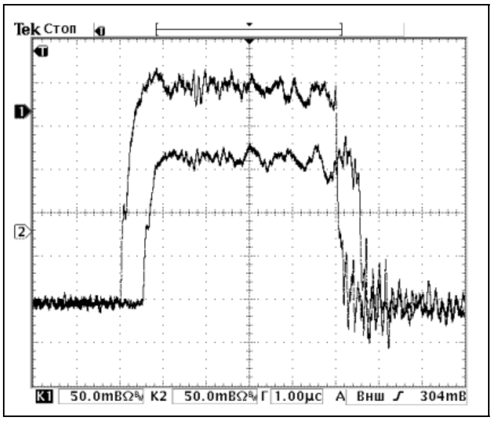

Figure 3: Ray 1 – TT1 signal, 2 – TT2 signal.

After optimization, the deuteron beam current measured by this Faraday cup reached 8 mA. On removing the Faraday cup, .beam readily circulated in the Booster during 1 ms. The relevant signals are shown in Fig. 4.

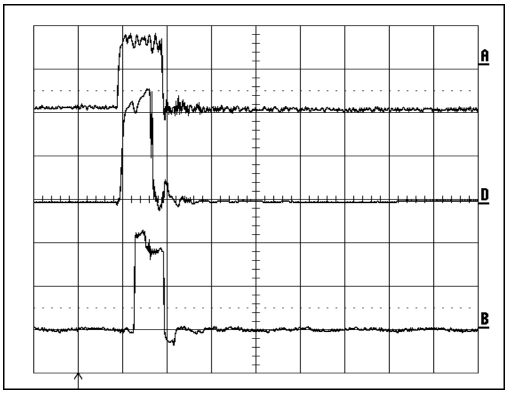

Figure 4: Ray A – TT2 signal, B – Faraday cup signal, D – kicker current signal (5 µs/division).

In order to obtain the maximal deuteron beam intensity at the end of accelerating cycle, corrections were introduced to the initial frequency program of the master RF oscillator. The optimal value of initial radiofrequency was set to f_{RF} = 570.5 kHz, which corresponds to initial deuteron energy T = 17.16 MeV/u.

After adjustment of initial betatron tune and proper orbit corrections, $3.0 \cdot 10^{10}$ deuterons were accelerated and extracted to the Booster beam absorber (see Fig. 5). In-out acceleration efficiency attained was about 35%.

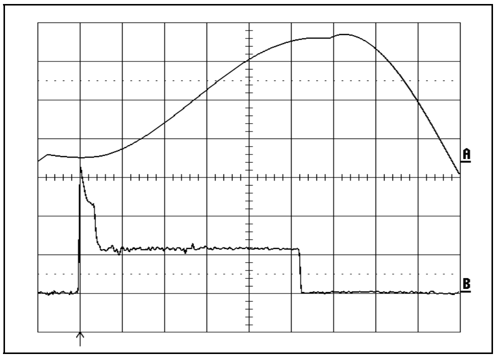

Figure 5: Ray A – magnetic guide field, B – deuteron beam intensity (5 ms/division).

CONCLUSION

Light ion acceleration program is being pursued in IHEP, Protvino. Deuteron beam with a plausible intensity was successfully accelerated in the I100 linac, transferred through BTL to the Booster, injected onto the ring orbit, and subsequently accelerated through the Booster with a decent efficiency.

Initial results thus obtained provide us with a confidence in feasibility of the light ion program for the IHEP acceleration complex.

Light ion beams at IHEP could be used both for fundamental and applied research.

REFERENCES

[1] Yu. Antipov, N. Anferov, V. Batarin et al, Preprint IHEP 2003-14, Protvino, 2003.

[2] V. Bezkrovney et al., “Operational Experience and Further Development of the IHEP Booster”, Proc. of the 19th RuPAC-2004, Dubna, 2004, report THCP13, p. 269; http://www.JACoW.org

[3] O. Gusev et al., Proc. of the 4th All-Union Conference on Charged Particle Accelerators, Moscow, 1974, v. 2, p. 151.

[4] V. Bezkrovney et al., Proc. of the 17th National Conf. on Particle Accelerators, Protvino, 2000, v. 2, p. 390.