ACCELERATION OF DEUTERONS UP TO 23.6 GEV PER NUCLEON THROUGH I100, U1.5, AND U70 OF IHEP

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Abstract

The paper reports on the recent progress en route of implementing the program of accelerating light ions in the Accelerator Complex U70 of IHEP-Protvino. The crucial milestone of guiding the deuteron beam through entire cascade of three accelerators available to a specific kinetic energy of 23.6 GeV per nucleon was accomplished in April 2010, which confirms feasibility of the project goal to diversify our main proton machine U70 to a light-ion synchrotron as well.

INTRODUCTION

The program to accelerate light ions with a charge-to-mass ratio q/A = 0.4–0.5 in the Accelerator complex U70 of IHEP-Protvino aims at diversification and development of our accelerator facilities. The ion mode of operation involves a sequence of Alvarez DTL I100, rapid cycled synchrotron U1.5, and the main synchrotron U70 proper.

Refs. [1, 2] reported on the first attempts of operation with a deuteron beam of a yet truncated cascade comprising I100 and U1.5. Since then, consisted efforts were continued to adapt and upgrade technological systems of the proton machines to better accommodate the ion beam. This report chronologically overviews the progress achieved since the previous conference RuPAC-2008.

RUN 2008-2

During this run, in the period of 10–12.12.08, acceleration of deuterons from 16.7 to 455 MeV per nucleon was accomplished for the second time in the U1.5 record of service (Fig. 1). Achieving this goal was hampered by improper vector adding at beam of RF voltages from 8 accelerating ferrite-loaded cavities whose start frequency is lowered from 0.747 (design value) to 0.563 MHz.

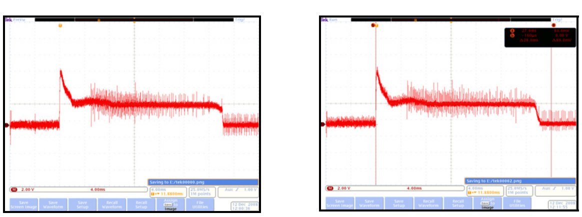

Figure 1: Deuteron beam in the U1.5 seen by a DCCT.

A bit earlier, while being in a proton mode, the U70 was trained to accept the ions. To this end, 1.32 GeV proton beam accumulation and circulation on flat-bottom was studied. The lattice magnets were powered a stand-alone DC power supply (131.1 A, 354 G). Coasting beam circulation (with RF off) and injection of bunches populated by as small as $3 \cdot 10^{10}$ ppb (imitation of a low-intensity deuteron bunch) were tried.

Attempts to transfer a full deuteron beam to the U70 ring and get a circulation there were not successful. Still, first deuterons in the U70 were observed with scintillating screen in straight section #10 indicating beam traversal through at least 4 of 120 combined-function magnets.

RUN 2009-1

In the closing days of this run (on April 25, 2010), the first ever stable circulation of a light-ion beam (ions of deuterium) at flat-bottom values of magnetic guide field of the main synchrotron U70 was obtained.

To start with, the Alvarez DTL I100 safely accelerated deuterons to 16.7 MeV per nucleon at the 4π-mode. The gas ion source yielded 16–17 mA of pulsed current at 40 μs pulse width with chopper off, and 15 mA; 5 μs with chopper on.

Specific kinetic energy was then ramped in the U1.5 ring from 16.7 to 448.6 MeV per nucleon. Overall in-out transfer efficiency through the machine amounted to 50%. The output intensity of $4.5 \cdot 10^{10}$ dpb complies with design expectations. Beam observation over the regime is shown in Fig. 2.

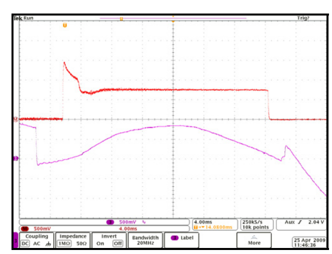

Figure 2: Ramping rate of the U1.5 guide field (lower trace) and deuteron beam intensity monitored with a DCCT (upper trace). Acceleration is accomplished in 26 ms. Compare with Fig. 1 to notice much improved performance of beam diagnostics made free of EM interferences.

Finally, the deuterons at 448.6 MeV per nucleon were transferred onto the waiting flat-bottom of the U70 ring (field 350.9 G, DC PSU current 128.4 A).

As a result, the U70 got a stable circulation of a coasting deuteron beam for about 7.5 s. This limit was imposed by an operational constraint in the existing timing system rather than by any physical reason. Momentum spread of the bunch injected is equal to $\pm 3.6 \cdot 10^{-3}$, bunch full length at base is about 100 ns, intensity is $4.5 \cdot 10^{10}$ dpb.

O. Lebedev, A. Ermolaev, G. Hitev, V. Lapygin, Yu. Milichenko, V. Bezkrovnyy, V. Stolpovsky, I. Sulygin, E. Nelipovich, A. Bulychev, Yu. Antipov, S. Pilipenko, N. Anferov, D. Khmaruk, S. Semin, V. Dan'shin, N. Ignashin, S. Sytov, and G. Kuznetsov.

Estimated decay time of de-bunched beam (RF field off) is about 30–40 s.

Beam signals observed are shown in Figs. 3, 4.

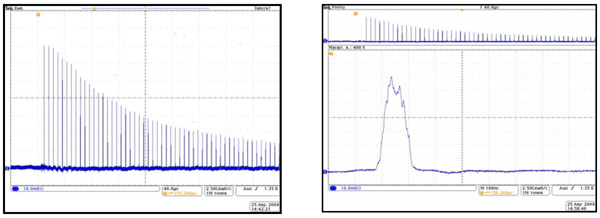

Figure 3: Circulation of a deuteron beam in the U70. (Left) AC beam current acquired by a pickup electrode. Rotation period is 6.72 µs. The same guide field would have forced lighter and faster protons rotate with 5.44 µs recurrence. The signal decays due to de-bunching given RF accelerating field switched off. Envelope of this signal bears data about beam momentum spread. (Right) First-turn shape of a deuteron bunch injected.

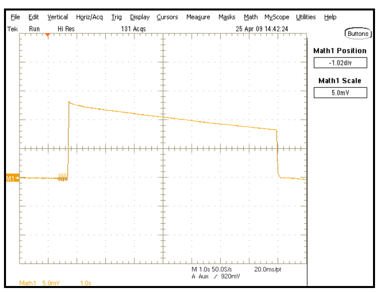

Figure 4: Deuteron beam intensity monitored with a DCCT. It dyes out much slower than beam peak current shown in Fig. 3. Scan tome base is 10 s.

RUN 2009-2

In course of maintenance activity for this run, 8 (of 40 available) ferrite-loaded RF cavities in the U70 ring were accommodated to an extended band of radiofrequency 2.6–6.1 MHz (essentially, reset to the factory default). These and only these cavities were fit to operate with the light-ion beam. To this end, they were driven to the top gap voltages feasible to compensate for a deficit in an overall number of cavities adapted.

This group of cavities had lower frequency sufficient to capture light-ion beam longitudinally at the flat-bottom guide field of the U70.

A new digital (DDS) RF master oscillator was put into service and coded to start from a lower RF of 4.46 MHz.

On taking full advantage of these hardware updates, we have continued with light-ion acceleration program during closing days of the run (December 11–15, 2010).

The injector cascade comprising ion source, Alvarez DTL I100 and transfer line to the booster ring U1.5 operated reliably, as is shown in Figs. 5, 6.

Troubles with vector summing of RF voltages in accelerating system of the U1.5 persisted. They were even aggravated by a certain misbalance of performances of a renovated Automated Frequency Control (in 8 cavities of 8), well adapted for light-ion program, and an out-dated wide-band intermediate amplifiers (in 7 of 8) that stayed yet beyond the upgrade activity by the run in question.

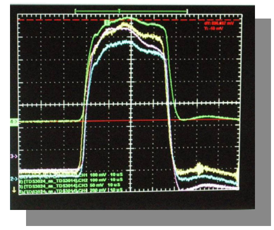

Figure 5: Deuterons in the DTL I100. Pulsed current 19 mA, pulse width 40 µs. Beam chopper is off.

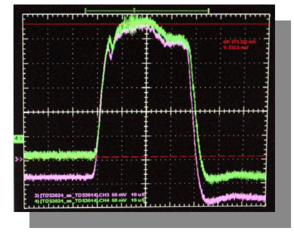

Figure 6: Beam current at entry to and exit from beam transfer line from I100 to U1.5. In-out transfer efficiency is 90% ca.

In spite of the obstacles encountered, we have managed to get circulation of both, an azimuthally uniform beam (like in run 2009-1) and capture deuterons into RF buckets to get circulation of deuteron bunches in the U70.

Then, after a smooth ramp of RF by +10 kHz in 3 s we have safely tried the fixed-field mode of acceleration of a deuteron bunch (the so called phasotron regime). This way, kinetic energy was ramped by +3.8 MeV per nucleon unless deuterons had been lost at the outer wall of the vacuum chamber (Fig. 7).

Formally, this exercise might be recorded as the first ever attempt of *acceleration of light ions* in the U70.

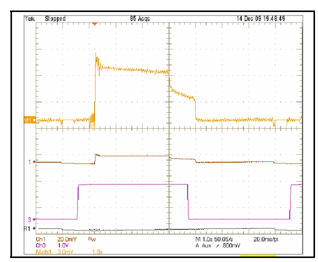

Figure 7: Acceleration of deuterons in the U70, fixed-field regime. Upper trace is beam intensity. First step down occurs when the captured beam fraction goes to outer radii and impacts horizontal aperture limitation. The surviving residual is azimuthally continuous fraction that is intercepted later on by internal beam dump target. Meander shows RF voltage amplitude program.

RUN 2010-1

This run succeeded on April 27, 2010 in the first acceleration to specific kinetic energy 23.6 GeV per nucleon of a light-ion beam (deuterons) in the main ring U70.

Booster U1.5 ramped the beam energy, as usual, from 16.7 to 448.6 MeV per nucleon. Top intensity observed amounted to $2 \cdot 10^{11}$ and $1.2 \cdot 10^{11}$ dpb at start and end of a cycle, respectively. In-out transfer efficiency improved to 60% thus exceeding that of the previous runs.

Lattice magnets of the U70 were powered via the conventional scheme, by rotor machine generators (guide field 351–8441 G, cycle period (shortened) 7.5 s). Ultimately, the transition energy (at 8.0 GeV per nucleon) was safely crossed, and U70 accelerated deuterons to 23.6 GeV per nucleon. Maximum beam intensity observed was $7{\cdot}10^{10}$ and $5{\cdot}10^{10}$ dpb at start and end of a cycle, respectively.

The top energy of 23.6 GeV per nucleon was imposed by the particular magnet cycle inherited from a preceding regular 50 GeV proton mode of the U70. Going to the top magnetic field of 12 kG would have resulted in a deuteron beam having 34.1 GeV per nucleon which energy now seems surely attainable from the technical viewpoint.

Figs. 8, 9 and 10 present beam observations along the cascade of machines engaged.

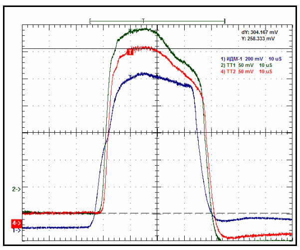

Figure 8: Acceleration of deuterons in the Alvarez DTL I100. Lower trace — beam pulse at exit from the fore injector. First and second traces from top — beam current at entry to and exit from beam transfer line I100/U1.5, respectively. In-out transfer factor is 91%. Top-pulsed current at exit from I100 amounted to 21 mA. All the pulses are 40 µs wide.

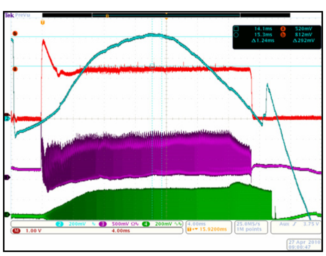

Figure 9: Acceleration of deuterons in the booster U1.5. Traces are listed from top to bottom. First (blue) signal is ramp rate of guide field. Second (red) signal is beam intensity monitored with a DCCT. It stands for $1.4{\cdot}10^{11}$dpb at start and $8.6{\cdot}10^{10}$ dpb at end of acceleration. Third (purple) ray is a signal from pickup electrode that sees combination of longitudinal and transverse beam motions. Fourth (green) trace is envelope of the net accelerating field. Ramping time is 26 ms, cycle period is 60 ms long.

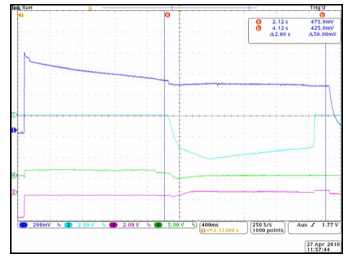

Figure 10: Acceleration of a deuteron bunch in the main ring U70. Traces are listed from top to bottom. First (blue) signal is acquired from an electrostatic pickup. It stands for $4{\cdot}10^{10}$ dpb at start and $2.5{\cdot}10^{10}$ dpb at end of acceleration. Second (cyan) trace shows ramping rate of magnetic field. Third (green) ray is a technological signal from beam radial position detector. Fourth (purple) ray is a technological signal from beam phase detector. Phase jump occurs at transition crossing (at 8 GeV per nucleon).

CONCLUSION

The important milestone of the program to accelerate beams of light ions in the Accelerator complex U70 of IHEP-Protvino was achieved in April of 2010 by accelerating deuterons to 23.6 GeV per nucleon in the U70 ring.

The main accelerator faculty of IHEP— its proton synchrotron U70 can now be substantially referred to as an ion (to be more precise, a light-ion) synchrotron as well.

Next step planned for the end of 2010, or beginning of 2011, is to accumulate and accelerate carbon ions and to put on trial a new slow extraction system delivering spills at the flat-bottom energies of the U70.

REFERENCES

[1] S. Ivanov and the U70 staff, Proc. of RUPAC-2008, Zvenigorod, 2008, p. 130–133.
[2] Yu. Antipov et al, ibid, p. 104–106.