ADVANCES OF LIGHT-ION ACCELERATION PROGRAM IN THE U70

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Abstract

The paper reports on the recent progress in implementing the program of accelerating light ions in the Accelerator Complex U70 of IHEP-Protvino. The list of milestones achieved since RuPAC-2010 includes: (1) Proof-of-principle acceleration of carbon-12 to the top available 34.1 GeV/u (specific kinetic energy). (2) Circulation and slow extraction from the U70 of the carbon beam at flat-bottom 453–455 MeV/u. (3) The first ever successful extraction of carbon nuclei at 24.1 GeV/u to the existing beam transfer line #22 followed by feeding the FODS experimental facility with carbon beam for fixed-target high-energy nuclear physics start-up.

INTRODUCTION

The program to accelerate light ions (deuterons, carbon nuclei) 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 the accelerator facilities. The ion mode of operation involves a sequence of Alvarez DTL I100 (2 tanks of 3, 4π mode), rapid cycled synchrotron U1.5, and the main synchrotron U70 itself.

This program is fulfilled incrementally, each recent machine run constituting a noticeable step in accomplishing the task.

This report overviews chronologically the progress achieved since the previous conference RuPAC-2010.

The starting point is acceleration in the U70 of deuterons to the specific kinetic energy 23.6 GeV/u (flattop 8441 Gs) with $5\cdot10^{10}$ dpp, see Ref. [1], RuPAC-2010.

Since then, the cascade of I100, U1.5, and U70 involved was switched to the **carbon-beam mode.** The procedure implies re-assembly of the solid-state laser (CO_2, 5 J) ion source, acceleration of ions $^{12}C^{5+}$ in the I100, thin-foil (Mylar, 4 μm) stripping to bare ions (nuclei) $^{12}C^{6+}$, and their subsequent acceleration in the synchrotrons U1.5 (6.9 T·m) and U70 (233 T·m).

RUN 2010-2

During this run, on Dec 8, 2010, the fully stripped carbon ions $^{12}C^{6+}$ were **first accelerated** to 455.4 MeV/u (kinetic) **in the U1.5**. Beam intensity varied between 5.3–$3.5\cdot10^9$ ipp through 26 ms ramp (once in 8 s), Fig. 1.

There were, at least, two prerequisites for this success:

1. Operational experience gained earlier with the more intensive deuteron beam.
2. Abundance of ions delivered by the I100, Fig. 2.

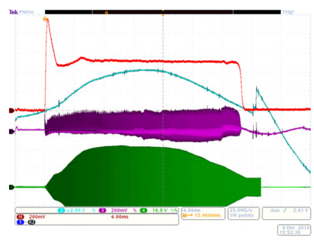

Figure 1: Carbon ($^{12}C^{6+}$) beam intensity monitored with a DCCT (upper (red) trace) and ramping rate of the U1.5 guide field (lower (blue) trace). In-out transfer is 65%.

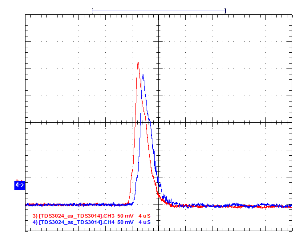

Figure 2: Beam at exits from the I100 (red) and BTL I100–U1.5 (blue). Pulsed current 21 mA, max. Pulse length 5 μs. In-out transfer through the BTL is 90%.

The first turns of carbon beam **in the U70** at flat-bottom 353.1 Gs were committed on Dec 10, 2010, Fig. 3. Bunch length is 80 ns FW at base. The lattice behaves as a magnetic ion separator, and 149.70 kHz beam rotation frequency is a signature of the particular $^{12}C^{6+}$ ion species due to mass defect in a bound system of nucleons (Table 1).

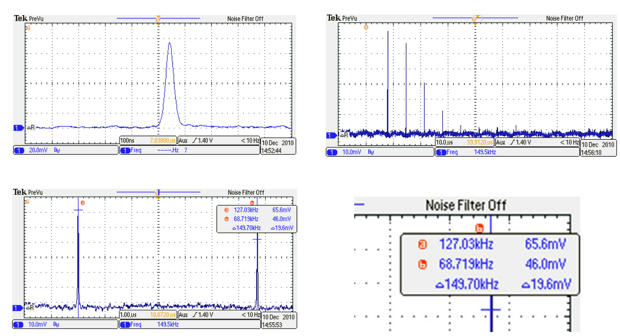

Figure 3: The first turns of carbon beam in the U70.

Table 1: Rotation frequency at 353.1 Gs flattop in the U70

Ion species	Rotation frequency, kHz
Carbon $^{12}C^{6+}$	149.70
Deuterons $^{2}H^{1+}$	149.24
Protons $^{1}H^{1+}$ (p)	183.80

RUN 2011-1

During this run, on Apr 24, 2011, carbon beam (single bunch) was **first accelerated in the U70 to the ultimate** available **energy** of 34.1 GeV/u (flattop 12 kGs) with max $5\cdot10^9$ ipp (8 s), design figure being $3\cdot10^9$ ipp.

Organizationally, the ion-mode MD was very challenging with the use of a low-intensity pilot proton beam and

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multiple switching lattice power supply from rotor machine generators (RMG) to a stand-alone DC PSU (130 A, 20 kW) and back, refer to Table 2.

Table 2: Flow chart of regimes in Apr 21–27, 2011

Field, Gs	8590	352	12000	352
PSU	RMG	DC PSU	RMG	DC PSU
p-beam				
C-beam				

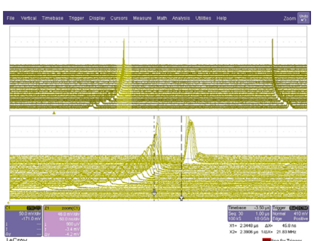
The I100 linac yielded some 12–14 mA (occasionally, up to 17 mA) of pulsed current.

A remotely controlled tool to shift out spent emitting spot on the graphite cylinder surface inside the laser ion source was set in operation to ease in-run maintenance. That time, spot sustainability was some 800 cycles, or just >1½ hr, a new spot requiring about 2 min of pre-training.

The U1.5 machine run smoothly and effectively.

A single bunch of ions was accelerated once per 8 s. Its parameters complied with the best performance data for a proton mode: injected bunch length at base ±60 ns, fractional momentum spread $\pm 2{\cdot}10^{-3}$. Lifetime at flat-bottom is about 40 s. Evolution of bunch length through cycle ±60 ns (flat-bottom), ±10 ns (transition crossing at 7.9 GeV/u kinetic), and ±25 ns (flattop).

Figure 4 shows transition crossing as a "mountain range" display.



Scan period is 5000 turns. Scans are locked to the RF phase, and apparent jump of the bunch is, thus, virtual.

Figure 4: Transition crossing with C beam in the U70.

During end of the run 2011-1, the U70 operated in a storage-stretcher mode for a 453 MeV/u beam of $^{12}C^{6+}$ at 352 Gs flat-bottom.

On Apr 25, 2011 this intermediate-energy beam was for the **first time slowly extracted** from the U70 (0.6 s long spills of $1.5{\cdot}10^9$ ipp). Both bunched (single bunch) and un-bunched circulating beam options were tried.

Thus, the new slow extraction system was successfully beam-tested. This system is based on a compact cascade scheme "internal energy-degrader target IT#28 — deflecting septum magnet SM#34".

The beam is extracted inwards the U70 lattice from SS#34 pointing to the existing BTL#6. This beam-line and its shielding are now dismounted. Instead, the new BTL#25 is assembled there to deliver carbon beam for applied research (radiobiology, medicine, etc).

Physically, the extraction system at issue employs the well-known scheme by Piccioni-Wright, Ref. [2], adapted for the strong-focusing synchrotron U70. In the latter case, a localized & compact (1/20 of orbit length) layout with 180° betatron phase advances (horizontal and vertical) between IT and SM is feasible and suits the case.

It is the advantageous trade-off between ionisation losses and hampering multiple Coulomb scattering (MCS) across IT that opens a 'feasibility slot' for an effective (tens % of in-out ratio) extraction of multi-charged $^{12}C^{6+}$ at flat-bottom of the U70, see Table 3. A test proton beam was also extracted with the scheme.

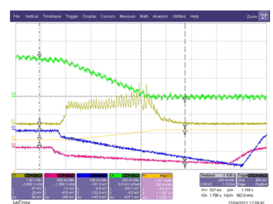
Table 3: Internal energy-degrader targets

Ion species	Carbon $^{12}C^{6+}$	Protons *p*
Kinetic energy, MeV/u	353–355	1320
Target material	Beryllium	Graphite
Target thickness, mm	4.0	30
Target height, mm	10	10
Ionisation loss, $\Delta p/p_0$	–0.0069	–0.0069
R.m.s. MCS scattering, mrad	0.96	2.93

The new flat-bottom extraction system was proposed, manufactured, installed and beam-tested (proton and carbon ions) within a tight schedule starting in Jan 2010. Beam spot size observed at exit flange of SM#34 well fits to the design figures — around 20 × 10 mm^2 (h × v) for azimuthally uniform and 10 × 10 mm^2 for bunched beams.

In course of beam tests, two ways of pushing the waiting beam onto the IT#28 for slow extraction were tested.

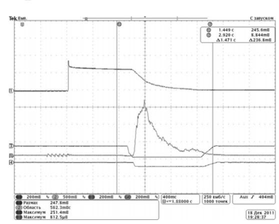
The first one applies varying (dynamical) closed-orbit bumps near IT#28 and SM#34, Fig. 5.



Traces from top to bottom: (1) circulating C beam intensity; (2) slow spill (a saturated signal); (3, 4) coil currents for closed-orbit bumps near IT#28 and SM#34, resp.

Figure 5: Slow spill under bumps of closed orbit.

The second way is to apply horizontal betatron noise causing controlled beam diffusion towards IT#28. To this end, the existing electrostatic deflector ESD#2, otherwise servicing the transverse feedback, is driven by a noise with flat (within 1.5–70 kHz) power spectrum, Fig. 6 and Ref. [3]. This option looks more promising for future routine operation due to inherent stationarity of beam traces.



Traces from top to bottom: (1) circulating C beam intensity; (2) slow spill (a proportional signal); (3, 4) coil currents for steady closed-orbit bumps near IT#28 and SM#34, resp.

Figure 6: Stochastic slow spill.

RUN 2011-2

During this ion-beam run, the U70 operated in a storage-stretcher mode for a 455 MeV/u C beam at 353 Gs flat-bottom. Top beam intensity gained was $10{\cdot}10^9$ ipp, design figure being $3{\cdot}10^9$ ipp. Efforts were spent to get more experience with the new slow extraction, the **first observations of Bragg's range** being recorded.

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Two experimental shots are shown in Figs. 7, 8. Fig. 9 confirms the expected performance of the slow extraction.

Figure 7: Finite range (30 cm ca) of extracted carbon beam through a plastic scintillator at 455 MeV/u.

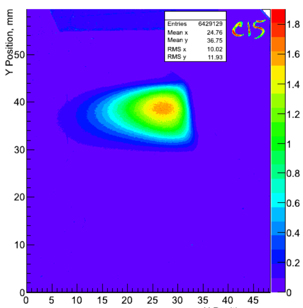
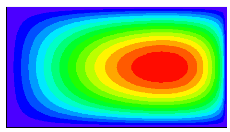


Figure 8: Bunched C beam spot at exit from SM#34 under stochastic slow extraction. Convolution over 3 cycles 8 s long each.



Surface contour plot of

$$F(x,y) = C\cdot x\cdot\sqrt{1-x^2}\times$$
$$\times\left(1-y^2\right),\ |x,y|\le 1$$

Figure 9: Calculated beam spot profile for a parabolic bunched beam under stochastic slow extraction.

RUN 2012-1

During the latest run 2011-2, carbon beam was accelerated to 24.1 GeV/u (flattop 8590 Gs) with $5\cdot10^9$ ipp (8 s).

The I100 team has managed to improve drastically the performance of the laser ion source. Thorough choice of gas mixture composition and laser pulse energy now allows to operate with 10–12 mA of pulsed current for 4000 cycles (instead of the former 800), i.e. for >8 hr.

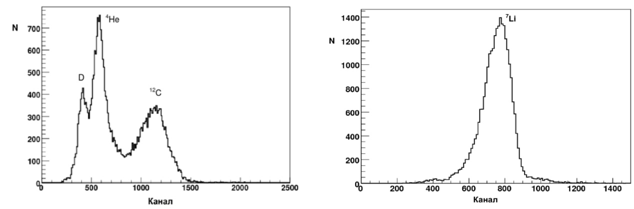
All the high-energy beam extraction systems available in the U70 — fast single-turn, slow resonant (both, via lens Q38 and stochastic), slow with a bent Si-crystal deflector — were readily tested with a carbon beam.

The beam thus extracted was transferred through the existing 190 m long BTL#22 to the FODS experimental facility (the FOcussing Double-arm Spectrometer). The primary beam and its fragments were detected with the FODS scintillator counters, calorimeter, monitor and data acquisition systems. The counters and calorimeter were pre-calibrated with a 49.1 GeV (kinetic) pilot proton beam.

To start with, the BTL#22 was tuned to 50 GeV/c central momentum (protons). In this case, it accepts 25 GeV/c/u beam of ion species with charge-to-mass ratio q/A = ½ as well ($^2H^{1+}$, $^4He^{2+}$, $^6Li^{3+}$, $^{10}B^{5+}$). Indeed, the hadron calorimeter saw peaks in energy spectrum at 300 GeV (12 nucleons × 25 GeV/u (full energy) in ^{12}C), 100 GeV (^4He) and 50 GeV (^2H), refer to Fig. 10 (left).

Then, to detect fragments with q/A < ½, the BTL#22 was re-tuned to a higher momentum 60 GeV/c (protons) and fractional momentum acceptance ±1%. In this case, of all ^{12}C fragments, it can accommodate and transfer ^7Li nuclei only. Those indeed show themselves up as 175 GeV peak in the calorimeter readouts, Fig. 10 (right).

Fragmentation of ^{12}C occurs, presumably, due to an unattended presence of substances across the beam path (foils, air gaps, beam monitors, septa, etc).



BTL#22 @ 50 GeV/c (p) BTL#22 @ 60 GeV/c (p)

Figure 10: Amplitude spectra from the FODS hadron calorimeter. Abscissa division value is 3.2 bins per a GeV.

Thus, operational retuning of optics (central momentum and acceptance) of the BTL#22 allowed to use this beamline as an 'ad hoc' Fragment Separator yielding the **first ever experimental observations of high-energy nuclear-physics events** obtained with a 300 GeV (full energy) carbon beam delivered by the U70 (Apr 27, 2012).

CONCLUSION

In course of the four recent machine runs (2010–12) reported, important milestones of the program to accelerate beams of bare carbon ions in the Accelerator Complex U70 of IHEP-Protvino were achieved. Every run had its specific **highlight** boldfaced in the text above.

The light-ion (carbon) program pursues two goals:

1. To accelerate, extract and deliver high-energy (24.1–34.1 GeV/u, kinetic) carbon beam for fixed-target experiments in relativistic nuclear physics.
2. To accelerate, extract and deliver intermediate-energy (453–455 MeV/u and less) carbon beam for experimental applied research, including radiobiology and radiation medicine.

Steps are taken in either direction. Still, some advances have a flavor of a feasibility 'proof-of-principle' experiment yet. More efforts are planned to elaborate the techniques and attain a reliable routine operation with the better light-ion beam performance data.

REFERENCES

[1] S. Ivanov and the U70 light-ion task team, Proc. of RUPAC-2010, Protvino, 2010, p. 130–2.

[2] O. Piccioni et al., Rev. Sci. Instrum., 26, p. 232–3, 1955; B. Wright et al., Rev. Sci. Instrum., 25, p. 429–31, 1954.

[3] S. Ivanov, O. Lebedev, Preprint IHEP 2012–10, Protvino, 2012.

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