ACCELERATOR COMPLEX U70 OF IHEP: STATUS AND UPGRADES

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Abstract

The report overviews present status of the Accelerator Complex U70 of IHEP-Protvino comprising four machines (2 linear accelerators and 2 synchrotrons). Particular emphasis is put on the recent upgrades implemented since the previous conference RuPAC-2010.

GENERALITIES

Layout and technical specification of the entire Accelerator Complex U70 of IHEP-Protvino were specified in the status report of 2008, Ref. [1]. Since October 2007, the complex comprises four facilities — 2 linear (I100, URAL30) and 2 circular (U1.5, U70), Fig. 1.

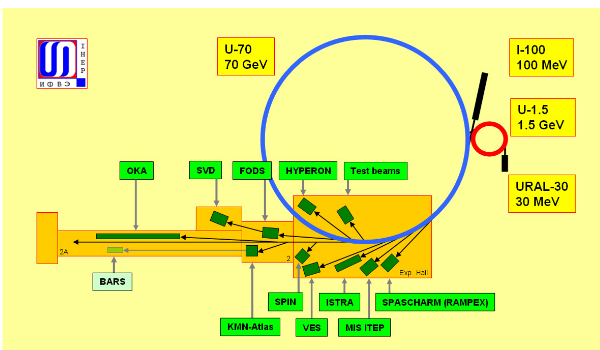

Figure 1: Accelerator Complex U70, beam transfer line network and fixed-target experimental facilities included. Proton mode (default) — cascade of URAL30–U1.5–U70, light-ion mode — I100–U1.5–U70.

Due to recent advances of the light-ion acceleration program, refer to Table 1, former proton synchrotrons U1.5 and U70 can be attributed to the (light-) ion synchrotron category as well.

Table 1: Light-ion program milestones

	Deuterons $^{2}H^{1+}$	Carbon $^{12}C^{6+}$
U1.5	16.7–448.6 MeV/u March 30, 2008	16.7–455.4 MeV/u December 08, 2010
U70	23.6 GeV/u April 27, 2010	34.1 GeV/u April 24, 2011

In the mid-April 2012, IHEP was reorganised into Federal State Budgetary Enterprise and moved under the auspices of the National Research Centre (NRC) “Kurchatov Institute”, which implies a revision of funding schemes to perform R&D and maintain special and general-purpose engineering infrastructure of the IHEP facilities.

N. Tyurin, Yu. Fedotov, O. Zyatkov, A. Minchenko, A. Afonin, E. Ludmirsky, O. Lebedev, D. Demihovskiy, V. Lapygin, A. Ermolaev, Yu. Milichenko, I. Tsygankov, I. Sulygin, N. Ignashin, S. Sytov, $\boxed{\text{V. Zenin}}$, Yu. Antipov, D. Khmaruk, and G. Kuznetsov.

ROUTINE OPERATION

Since RuPAC-2010, the U70 complex operated for four runs in total. Table 2 lists their calendar data. The first run of a year is shorter and solves, mainly, R&D and methodological tasks.

Figure 2 shows beam availability data during machine development (MD) and fixed-target experimental physics program (XPh) with averages over 2002–12. The extracted beam is delivered to experimental facilities with 82.8% availability, on average.

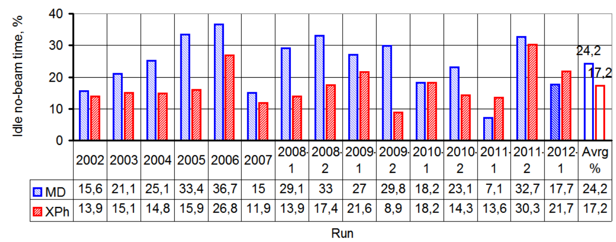

Figure 2: Beam availability statistics.

Figure 3 is a screenshot of the on-line statistics monitor that is an example (December 2011) of a long-term sustained operation of the complex. The large ring (i.e., the U70 PS itself) delivers $0.98{\cdot}10^{13}$ ppp. Beam losses through a cycle amount to 4%. Slow stochastic extraction spills some $6.7{\cdot}10^{12}$ ppp, while internal targets and Si-crystal deflectors consume the allowed $2.5{\cdot}10^{12}$ ppp.

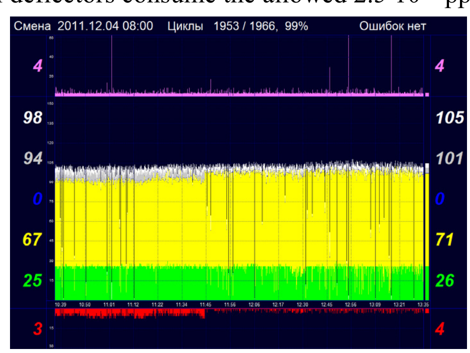

Figure 3: Screenshot of the on-line monitoring over the U70 operation. Time interval (abscissa) extends over 3 hr, or 1000 ramping cycles. Yellow trace slows intensity of slow stochastic extraction, green trace — operation of internal targets and crystal deflectors. Red (inverted) trace indicates spent beam remains dumped onto internal absorber.

Fixed-target experimental setups (from 6 to 10 per a run) acquire the beam via sequential and parallel sharing of the U70 magnetic field flattop (about 3.2 s at 50 GeV).

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Table 2: Four runs of the U70 in between RuPAC-2010 and -2012

Run	2010-2	2011-1	2011-2	2012-1
Launching linac URAL30, booster U1.5 and U70 sequentially	October, 04	March, 14	October, 10	March, 12
Proton beam in the U70 ring since	October, 27	April, 06	November, 02	April, 04
Fixed-target physics program with extracted beams	November, 03 – December, 06, 31 days	April 11–21, 10 days	November, 09 –December, 13, 32 ½ days	April, 09–21, 12 days
No. of multiple beam users (of which the 1^{st} priority ones)	11 (8)	9 (7)	9 (6)	9 (6)
MD sessions and R&D on beam and accelerator physics, days	7	5	9 ½	5
Light-ion acceleration MD program	December, 06–10, 4 days	April, 21–27, 6 ½ days	December, 14–18, 4 ½ days	April , 21–27, 6 ½ days

Typically, internal targets (IT) and crystal deflectors (CD) are engaged during the 2^{nd} half of the flattop at 8590 Gs (50 GeV). Fig. 4 shows oscillograms of beam splitting between users. The traces are specified from top to bottom. The first (olive) trace shows beam extraction with CD#19 and IT#24. The next, purple (blue) traces show extraction with IT#27 (IT#35), respectively. The fourth (green) trace is intensity of waiting beam monitored with a DCCT ($2.8{\cdot}10^{12}$ ppp extracted).

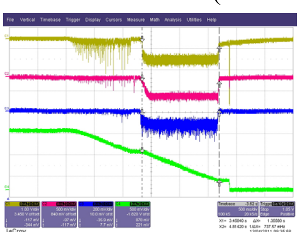

Figure 4: Beam splitting at the 2^{nd} half of the flattop.

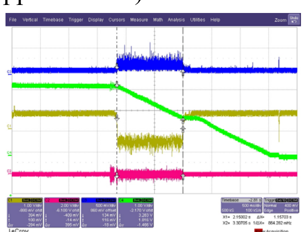

Figure 5: Slow stochastic extraction at the 1^{st} half of the flattop.

Slow stochastic extraction (SSE) operates at the 1^{st} half of the flattop. Fig. 5 shows the SSE technological signals. Again, the traces are specified from top to bottom. The first (blue) trace shows signal from beam loss monitor BLM#106 fed to spill-rate feedback. The second (green) trace is intensity of waiting beam monitored with a DCCT ($1.1{\cdot}10^{13}$ ppp max of which up to $8.4{\cdot}10^{12}$ ppp may be slowly extracted, cruise rates being $3–7.4{\cdot}10^{12}$ ppp). The third (olive) trace is feedback signal that AM modulates the phase noise of the 200 MHz carrier (the fourth (purple) trace). A short pre-pulse of noise has another power spectrum. It is used to cure beam self-bunching by means of controlled reshaping beam distribution over momentu.

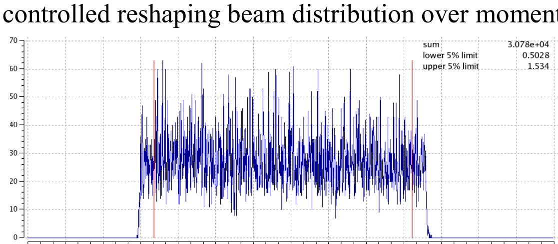

Figure 6: A slow spill delivered to the OKA facility.

Quality of the slow spills (up to 1.6–1.8 s long) seen with headcounters of the OKA experimental facility (rare kaon decays) is shown in Fig. 6. The spill Φ exhibits low ripples, no mains harmonics, no cut-offs and a flat DC spill rate $\langle\Phi\rangle$. Occasionally, spill duty factor $\langle\Phi\rangle^2/\langle\Phi^2\rangle$ rises to comfortable values near 0.95.

Figure 7 presents attainable spill-to-spill sustainability of the SSE. The upper trace is an in-out transfer efficiency ratio for the extracted beam fraction (90%). Slowly extracted beam current is shown by the lower trace ($3{\cdot}10^{12}$ ppp). Still, given higher beam intensities, the top attainable in-out extraction ratio has a tendency to drop to about 85% causing over-irradiation of the septum magnet SM#24. The nature of this deterioration effect is not yet fully understood and cured.

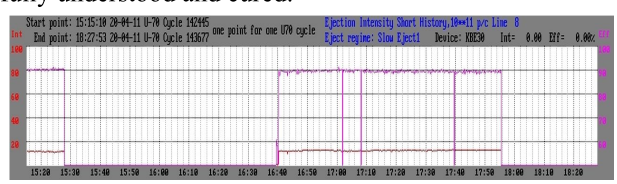

Figure 7: Spill-to-spill sustainability of the SSE.

Occasionally, for applied research, the fast single-turn extraction is employed. Its operation is shown in Fig. 8. At the 50 GeV flattop, the proton bunch extracted has a length of 15 ns at 0.5-level and population of $4{\cdot}10^{11}$ ppb.

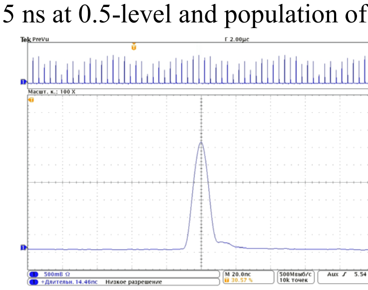

Figure 8: Fast single-turn extraction.

Proton Radiography

Until the run 2011-2, the fast single-turn multi-bunch extraction has fed 50 GeV Proton-Radiographic Facility mounted around two 90°FODO cells in a spare BTL channel, Ref. [2]. This facility with a 60 mm field-of-view and 0.25 mm resolution for > 300 g/cm^2 optical density objects is a successful joint venture of IHEP and RFNC–VNIIEF (Sarov, N. Novgorod Region).

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MACHINE DEVELOPMENT

Digital Master Oscillator

Both the synchrotrons, U1.5 and U70, now employ unified DDS master oscillators based on COTS digital processing boards XDSP-3PCM equipped with the Xilinx FPGA and plugged into an industrial PC iROBO.

For the time being, the U1.5 (booster) utilizes only part of the new functionality now available — extended flexibility in generating "B-field–radiofrequency" law allowing acceleration of protons and light ions with charge-to-mass ratio about ½. Other options available are still waiting (and planned) to be implemented.

On the contrary, in the main ring U70, the DDS master oscillator now:

1. routinely introduces embedded bunch-rotation RF gymnastics prior to de-bunching at flattop for prompt control over momentum spread in a circulating beam;
2. provides coordinated variation through a ramping cycle, transition crossing included, of gains in phase-frequency and radial feedback loops around the maser oscillator.

The latter option called for a dedicated study Ref. [3] of the closed-loop configuration (Fig. 9) and locus of complex roots of the characteristic equation (Fig. 10) to attain optimal and balanced tune-up. Experiments with 1.3–50 GeV proton beam have shown promising results.

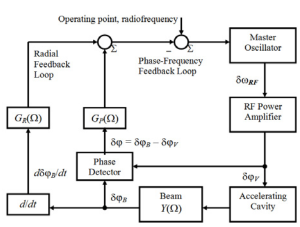


Figure 9: Block diagram of RF control in the U70.

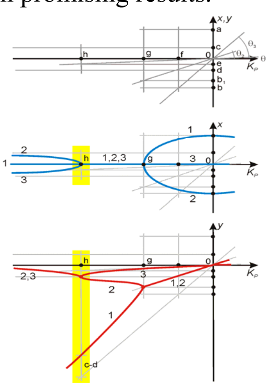


Figure 10: Characteristic equation root map.

Wide-Band Transverse Feedback

The former topology of this network is discussed in the status report of 2010 Ref. [1]. Since then, a novel architecture of the digital feedback circuit, see Fig. 11, was successfully beam-tested in the U70.

It employs a finite-time impulse response (FIR) non-recursive filter layout based on 3 variable (–10%) digital delay lines. Apart of using these natural-to-DSP components, the configuration involved has three operational advantages:

1. A single beam pickup layout (saves room on the orbit and ensures acceptability of an arbitrary betatron phase advance between pickup and kicker).
2. Accessibility of the purely imaginary coherent tune shift.
3. A built-in rejection of DC and higher rotation frequency harmonic signals persisting in raw beam-position readouts.

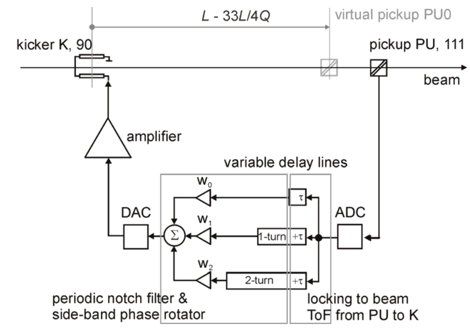
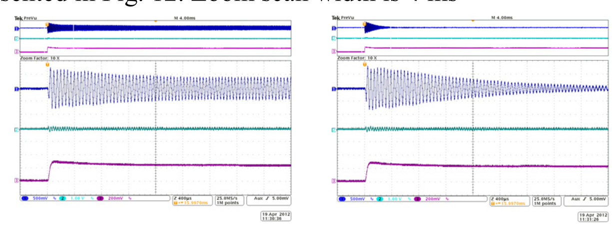


Figure 11: Updated layout of the wide-band feedback.

The latter occurs due to a periodic notch nature inherent in the amplitude-frequency in-out open-loop feedback transfer function.

Beam observations with the updated feedback are presented in Fig. 12. Zoom scan width is 4 ms



Feedback OFF Feedback ON

Figure 12: Damping of radial oscillations at injection (upper traces). Lower trace is beam intensity (DCCT).

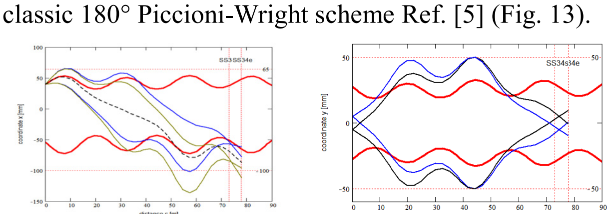
Technically, the circuit implements the similar XDSP board as the RF master oscillators in the U1.5 and U70. Detailed report on the subject can be found in Ref. [4].

Slow Extraction at Flat-Bottom

At its 352–353 Gs flat-bottom, the U70 ring serves in a storage-stretcher mode. To this end, the entire 1.5 km lattice is fed by a stand-alone DC PSU (130 A, 20 kW).

The regime accommodates either a test proton beam (1.32 GeV kinetic), or a carbon $^{12}C^{6+}$ ion beam (453–455 MeV/u).

The challenge of squeezing a new slow extraction system into the densely packed U70 lattice was met with a classic 180° Piccioni-Wright scheme Ref. [5] (Fig. 13).



Horizontal Vertical

Figure 13: Waiting beam envelope ($\delta p/p_0 = \pm 3{\cdot}10^{-3}$) and representative traces for extracted fraction (ionization loss $\Delta p/p_0 = -0.69\%$ and $\pm 2\sigma'_{MCS}$ in slope over IT#28).

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The scheme uses a thin energy-degrader internal target IT#28 (Fig. 14) followed by a newly-build deflecting septum magnet SM#34 (Fig. 15). The extracted (perturbed) beam fraction travels between IT#28 and SM#34, i.e. via 6 CF magnets of 120 available (1/20 of orbit length only).

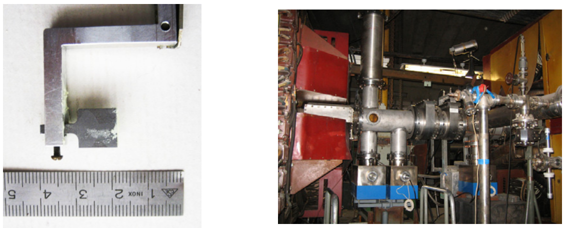


Figure 14: Energy-degrader inner target IT#28 (beryllium, thickness 4.0 mm, height 10 mm) for carbon beam and the IT outer assembly at SS#28.

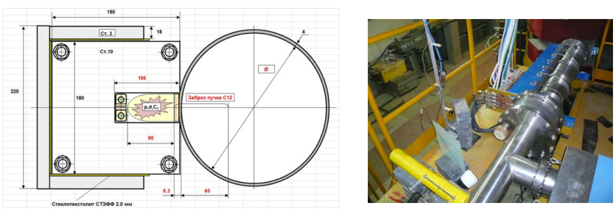


Figure 15: Deflecting septum magnet SM#34 (80 mrad, 0.42 T, 1.3 m, 80×40 mm^2 (h×v)).

In the runs 2011-1,-2, the system was beam-tested and attained the design performance (see Figs. 16, 17) with beam extracted towards the new BTL#25 being mounted.

Figure 16: Finite range (30 cm ca) and stopping point of carbon beam in a plastic scintillator at 455 MeV/u.

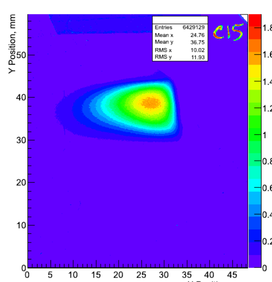
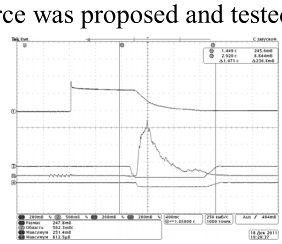


Figure 17: Carbon beam spot at exit from SM#34. Convolution over 3 cycles 8 s long each.

A dedicated scheme to point the beam outskirts to IT#28 for subsequent extraction with a random deflecting force was proposed and tested; see Fig. 18 and Ref. [6].



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

Figure 18: Slow spill under a stochastic horizontal betatron excitation with a fixed noise power.

Intensity-Related Effects

The major goal pursued during MDs for the proton mode of the U70 is to operate with higher intensities $> 1{\cdot}10^{13}$ ppp in 29 bunches (of 30 RF buckets) and small phase-space volumes. The consumer of the high intensity is slow extraction (SSE) for the OKA experiment.

For the time being, the challenging effect is spurious self-bunching of beam seeing longitudinal coupling impedance of 40 idle RF cavities at their fundamental mode.

The situation has been aggravated recently with the advance of the light-ion program, which has necessitated the comeback to the extended (factory default) bandwidth 2.7–6.1 MHz of the RF cavities.

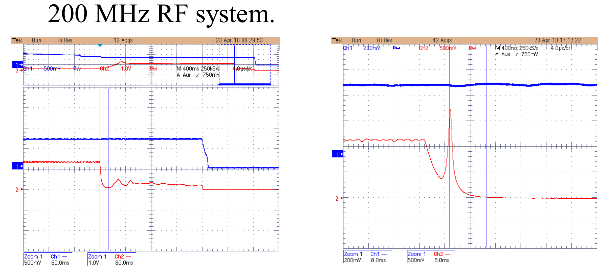
Due to the well-known E. Keil–W. Schnell criterion, to ensure the coasting beam stability, one has to obey

$$\left|\frac{Z(k\omega_0)}{k}\right| < \frac{1}{\Lambda}\frac{\beta^2|\eta|E}{eJ_0}\left(\frac{\delta p}{p_0}\right)^2 \qquad (1)$$

where $2\delta p/p_0$ is full fractional momentum spread at base; Λ is form-factor depending on beam distribution function $F_0(\delta p)$; other notations are conventional.

To increase the r. h. s. of Eq. 1, two cures are now optionally applied to in the U70:

1. Blow-up of $\delta p/p_0$ from $\pm 4{\cdot}10^{-4}$ to $\pm 1{\cdot}10^{-3}$ by means of bunch rotation (8 ms long coherent 6 MHz RF gymnastics) prior to de-bunching at flattop using the extended functionality of the new DDS RF master oscillator. Factor Λ is kept unvaried meanwhile.
2. Smooth blow-up of $\delta p/p_0$ accompanied by re-shaping (flattening) $F_0(\delta p)$ and, thus, affecting factor Λ, with a 100 ms long low-pass (2.3–4.2 kHz) phase noise carried by 300 kV voltage driven by the auxiliary 200 MHz RF system.



Self-bunching seen as oscillation and slow decay of peak curve (bottom).

Damping out with bunch compression (surge) accompanied by momentum spread blow-up.

Figure 19: Suppression of self-bunching at 50 GeV flattop and $7{\cdot}10^{11}$ ppp with RF gymnastics. Upper (blue) trace is beam intensity (DCCT). Lower (red) trace is beam peak current signal.

Beam observations over self-bunching and effect of the two cures against are shown in Figs. 19 and 20.

A supplementary measure against self-bunching, when applicable, is injection of even bunch patterns that reduce beam de-bunching time.

Another cure possible is to close dedicated longitudinal beam feedback (digital) whose actuator might be a spare 6 MHz RF cavity. This option is under study now.

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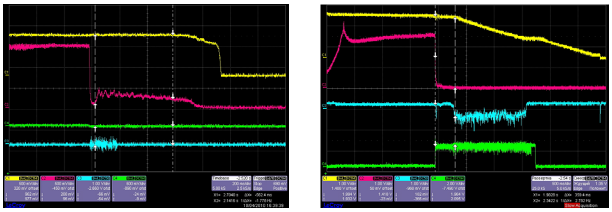

Self-bunching seen as oscillation and slow decay of peak curve (2nd from top).

Suppression of self-bunching with noise pre-pulse followed by a transition to the SSE.

Figure 20: Suppression of self-bunching at 50 GeV flattop with 200 MHz phase noise. Upper (yellow) trace is beam intensity (DCCT). Next (red) trace is beam peak current monitor signal. Lower (green) trace is phase noise injected (1st quarter is band-pass 2.3–4.2 kHz, while remainder is low-pass 0–4.2 kHz random signal).

Still, other intensity-related effects in the U70 are waiting to be understood and cured.

The shortest bunches available in the machine cannot cross transition loss-free when injected in a dense one-by-one train of > 6–10 bunches. One has to resort to preliminary longitudinal blow-up with the 200 MHz (spill) RF system. Effect of some short-range wakes is suspected.

Transverse coherent motion of proton beam is well cured with the narrow-band low-pass (analog) and wide-band band-pass (digital) beam feedback circuits installed. Still, in the open-loop configuration, one cannot identify the source of an apparent asymmetry between thresholds of vertical and horizontal instabilities. Threshold of vertical instability is by a factor-of-2 higher than that for horizontal motion, while the opposite ratio is expected for the elliptic resistive steel vacuum chamber with 10×5 mm^2 aperture (inner half-axes, horizontal × vertical).

These and other effects are scheduled for future studies.

Crystal Deflectors

These types of beam transverse deflectors are extensively employed for routine technological purposes and in a dedicated R&D program accomplished with the beams of the U70. Ref. [9] reports on details of this activity.

Light-Ion Program

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

Acceleration in the U70 of deuterons to a specific kinetic energy 23.6 GeV/u (flattop 8441 Gs) with $5{\cdot}10^{10}$ dpp was reported in Ref. [8] of RuPAC-2010. Since then, the cascade of I100, U1.5, and U70 involved was switched to the carbon-beam mode.

During the run 2010-2, fully stripped ions (nuclei) $^{12}C^{6+}$ were first accelerated to 455.4 MeV/u in the small ring U1.5. Beam intensity varied between 5.3–$3.5{\cdot}10^9$ ipp through 26 ms ramp (once in 8 s). The first turns of the C beam around the U70 ring at flat-bottom were committed.

During the run 2011-1, carbon beam (a single bunch) was accelerated in the U70 to the ultimate available energy of 34.1 GeV/u (flattop 12 kGs) with max $5{\cdot}10^9$ ipp (8 s).

During the runs 2011-1, -2, the U70 also operated in a storage-stretcher mode for a 453–455 MeV/u carbon beam at 352–353 Gs flat-bottom. Top beam intensity observed was 5–$10{\cdot}10^9$ ipp, which exceeds the design figure of $3{\cdot}10^9$ ipp. New direction for the slow extraction of the intermediate-energy carbon beam via IT#28 and SM#34 inwards the U70 ring was safely beam-tested. In the aftermath, a new BTL#25 is assembled in the Experimental Hall to transfer the carbon beam for applied research.

During the latest run 2011-2, carbon beam was accelerated to 24.1 GeV/u (flattop 8590 Gs) with $5{\cdot}10^9$ ipp (8 s). All the high-energy beam extraction systems available — fast single-turn, slow resonant (including stochastic), slow with a bent Si-crystal deflector — were readily tested with a carbon beam. The carbon beam extracted was transferred through the existing 190 m long BTL#22 to the FODS (a FOcussing Double-arm Spectrometer) experimental facility and detected there. Operational retuning of optics (momentum acceptance) of the BTL#22 allowed to use this beam-line as an 'ad hoc' Fragment Separator yielding the first ever experimental observations of high-energy nuclear-physics events with a 300 GeV (full energy) carbon beam delivered by the U70.

Further physical and technical details of the light-ion acceleration program progress are reported in Ref. [9].

CONCLUSION

Accelerator Complex U70 of IHEP-Protvino is the sole national proton facility running for the fixed-target research in high-energy physics. It is a subject of an ongoing upgrade program affecting the key technological systems and promising still better beam quality. Functionality of the machine for fundamental and applied research is being enhanced with the advent and adoption of its light-ion beam mode.

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