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. It is a sequel to prior status reports [1] delivered to RuPAC-2008, -2010, -2012, and outlines the recent machine-related activity and upgrades in run-by-run chronological ordering.

GENERALITIES

Layout of the entire Accelerator Complex U70 of IHEP–Protvino is shown in Fig. 1. It comprises four machines — 2 linear (I100, URAL30) and 2 circular (U1.5, U70) accelerators.

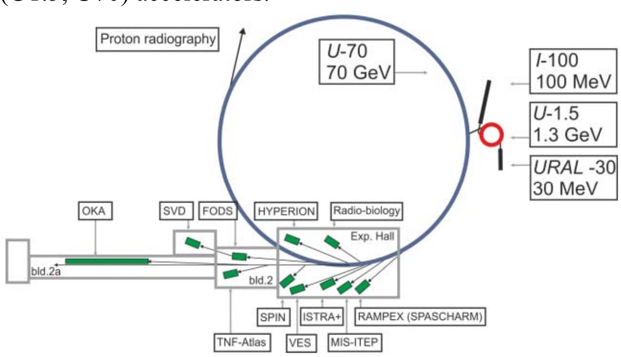

Figure 1: Accelerator Complex U70, beam transfer line network and fixed-target experimental facilities included. Proton mode (default) — cascade of URAL30–U1.5–U70, light-ion (carbon) mode — that of I100–U1.5–U70.

The points of attraction to the efforts spent during the period under report to be spotted in the scheme above are:

- Quality of stochastic slow extraction of 50–60 GeV protons to BTL#21 and the OKA facility;
- Extractions of the top-energy (24.1 GeV/u) carbon ions to BTL#22 (which is also an incidental fragment separator) and the FODS or SVD facilities;
- Stochastic slow extraction of the intermediate-energy (456 MeV/u ca) carbon ions via the new BTL#25 to the Interim Radio-Biological Work-bench;
- Launching beam-commissioning of the new Proton Radiography Facility (along the upward arrow, via a fast extraction);
- Re-equipment of the U-70 ring magnet main power supply plant with the up-to-date static thyristor AC-DC convertors.

The light-ion program proceeds smoothly. Its advances are listed in Table 1.

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
		Slow extraction at 455 MeV/u April 24, 2011
		24.1 GeV/u (300 GeV full) in BTL#22 and the FODS facility April 27, 2012
		Validation tests of all top-energy extractions with the ion beam April 24, 2013

STATISTICS

Since RuPAC-2012, the U70 complex operated for five runs in total. Table 2 lists their calendar data. There were two runs in a row during the spring of 2014, which is uncommon.

Figure 2 shows beam availability data during machine development (MD) and fixed-target experimental physics program (XPh) with averages accumulated over 2002–13. The extracted beam is delivered to experimental facilities with the 82.2% availability, on average.

Runs 2013-2 and 2014-1, 2 are all excluded from the statistics since these were the MD runs entirely, without a pronounced top-energy physical program.

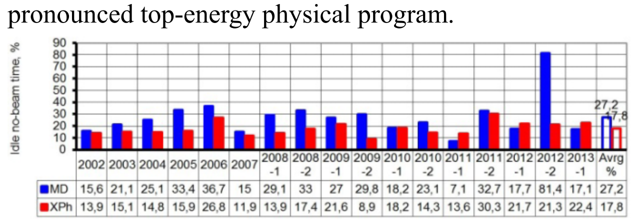

Figure 2: Beam availability statistics.

Details of the routine operation and upgrades are given on a run-by-rum basis in what follows.

RUN 2012-2

As it can be seen from Fig. 2, the unfortunate feature of this run was a failed MD program followed by a squeezed

N. Tyurin, Yu. Fedotov, O. Zyatkov, A. Minchenko, A. Maksimov, A. Afonin, E. Ludmirsky, O. Lebedev, D. Demihovskiy, V. Lapygin, A. Ermolaev, Yu. Milichenko, I. Tsygankov, I. Sulygin, N. Ignashin, S. Sytov, Yu. Antipov, D. Hmaruk, and G. Kuznetsov.

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tuning time for the machines prior to delivering proton beam to the fixed-target physics. (Say, the U70 PS had only 36 hr left for the machine studies and tuning.) The culprit to blame was an ageing HV equipment of RF power supply of the URAL30 linac. Its poor performance was aggravated by a delayed shipment of components and consumables due to adoption of a novel contracting regulation.

Still, all the problems thus involved were absorbed by the MD time thus yielding sustained beam availability for the fixed-target physics that is well commeasurable to the 10-year average expectation value.

Table 2: Five runs of the U70 in between RuPAC-2012 and -2014

Run	2012-2	2013-1	2013-2	2014-1, 2
Launching linac URAL30, booster U1.5 and U70 sequentially	October, 08	February, 25	November, 11	March, 11
Proton beam in the U70 ring since	November, 01	March, 11	November, 26	March, 28
Fixed-target physics program with extracted top-energy beams	November, 08 – December, 14, 35 days	March, 22 – April, 22 31 day	n/a	n/a
No. of multiple beam users (of which the 1st priority ones)	11 (9)	9 (8)	1	2(2)
MD sessions and R&D on beam and accelerator physics, days	8	7	21	21 ½
Light-ion acceleration MD program	December, 14–18, 3½ days	April, 24–27, 3½ days	December, 16–25, 8½ days	April ,08–25, 17½ days

To the final end, state of the entire complex was found to be adequate providing top manageable operational intensity of $1.05{\cdot}10^{13}$ ppp with only 4% beam losses over a cycle, refer to Fig. 3.

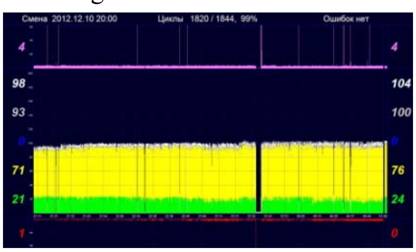

Figure 3: Screenshot of the on-line monitoring over the U70 operation. Time interval (abscissa) extends over 3 hr, or 1000 cycles. Yellow trace slows intensity of slow stochastic extraction, green trace — operation of internal targets and crystal deflectors. The bottom (red) trace indicates spent beam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

The top-energy slow stochastic extraction has fed the OKA facility with $7\text{–}7.6{\cdot}10^{12}$ protons per a low-ripple spill (1.26 s long) at the 1st half of flattop, see Fig. 4.

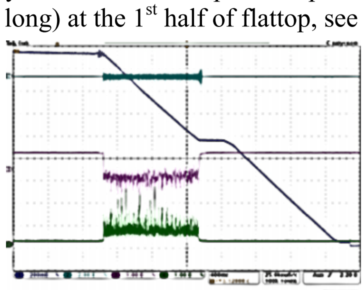

Figure 4: Slow stochastic extraction. The first (top) trace is intensity of waiting beam monitored with a DCCT. The second trace is AM-modulated phase noise of the 200 MHz carrier The third ray is the feedback signal that modulates the noise. The fourth ray shows slowly extracted beam monitored with a BLM at ES-septum.

Still, a persisting critical issue related to the stochastic extraction was left unhandled. The in-out transfer ratio of the extracted beam fraction was as low as 85–87% (occasionally, up to 90%) with a clear trend to lower values at higher beam intensities, above $7{\cdot}10^{12}$ ppp. There was no separation gap observed between the waiting and extracted beams at the upstream deflecting magnet #24 resulting in over-irradiating its septum. This problem was resolved in the run to follow.

Switching over to the carbon nuclei mode went on smoothly.

The I100 linac has provided 12–14 mA of pulsed current. Each emitting point on the graphite block inside the laser ion source survived for 4 300 laser pulses per spot which was equivalent to comfortable 9.5 hr of a non-stop operation, refer to Fig. 5.

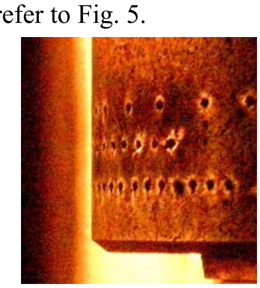

Figure 5: Graphite target of the laser ion source. The lower compact row of spent emitting spots stands for the present, optimised operation.

The booster synchrotron U1.5 operated with 9% overall beam availability and provided up to $6.5{\cdot}10^{9}$ ipp.

The main ring U70 accelerated $5{\cdot}10^{9}$ ipp (cycle period 8.3 s) to 24.1 GeV/u, the beam being extracted to BTL#22 terminated by the FODS facility. Research activity has been focused on the beam diagnostics and extraction procedure conditioning per se. The in-out transparency of the BTL#22 was recorded as 0.82 for test protons and 0.77 for carbon nuclei. These exercises have allowed for acquiring practical experience in handling composite

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multi-nucleon projectiles with an existing inventory adapted to protons by its design.

RUN 2013-1

Prior to this run, the upstream part of the new BTL#25 has been manufactured and assembled, see Fig. 6. The reference top beam rigidity is 6.9 T·m. The beam line is 18 m long and has 3 dipoles, 4 quads and 2 vertical correctors. The line is fed from the septum magnet #34 facing the waiting beam coasting around the U70. The BTL#25 had to transport the beam towards the inner radiation-shielding wall of the ring hall (bld. 1) just upstream of the would-be radio-biological workbench.

Figure 6: Upstream part of the new BTL#25 adjacent to and directed inwards the U70 ring. View along the beam.

To this end, the run was launched in a very uncommon sequence with the U-70 operating, first, in a beam storage and stretcher ring mode with 1.32 GeV protons. Such a beginning pursued the double goal:

1. To condition the URAL30 proton linac under beam in the aftermath of a crash program to restore its functionality during the shutdown.
2. To tune, align and commission with the (more affordable and intense) proton beam the aforesaid BTL#25 so as to ensure its readiness to accept the same-rigidity carbon nuclei beam scheduled by end of the run.

Both these goals were attained. Say, the linac ultimately turned out inoperative for only 8 hr 40 min (of which 6 hr 15 min were spend to replace 3 depleted high power generating tubes) which should be compared to some 320 idle hours during the run 2012-2. The linac had safely provided 35 mA of pulsed current thus enabling a few hours of the U1.5 booster running with $8{\cdot}10^{11}$ ppp, the cruise intensity being 4–$5{\cdot}10^{11}$ ppp. The U70 itself yielded (max) $9.5{\cdot}10^{12}$ and (on average) $4.6{\cdot}10^{12}$ ppp limited by beam user demand.

In course of the U70 machine tune-up, one has spotted and eliminated a malfunction in the $B \propto x^2$ (octupolar) correction system of the magnetic guide field. The outcome was the long sought-for radical improvement of the slow stochastic extraction. It has attained a sustained in-out transfer ratio of 90–94% in the intensity range of 1–$6.5{\cdot}10^{12}$ ppp, see Fig. 7.

With a diffusive (stochastic) actuation of the waiting beam outskirts onto the 3rd order betatron resonance, the spills used to reveal a pronounced DC content and a low-ripple structure free of cut-offs, see Fig. 8. Duty factor of such spills $\langle F\rangle^2/\langle F^2\rangle$ could go as high as to 0.81–0.82.

Both these two features allow for concluding that the U70 has ultimately got the effective low-ripple lasting slow extraction of an intensive proton beam.

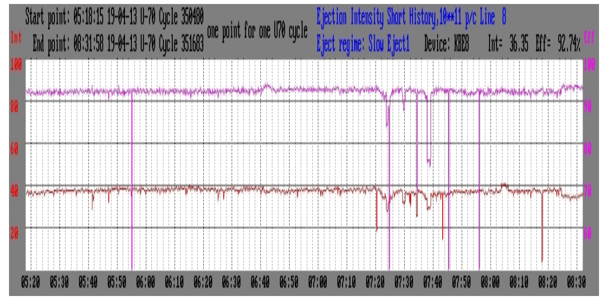

Figure 7: Screenshot of the on-line slow extraction monitor. The upper ray is in-out transfer ratio that safely goes above the 90% grid line intercepting rightmost ordinate axis. The lover ray traces the slowly extracted beam intensity (a bit lower than $4{\cdot}10^{12}$ ppp here).

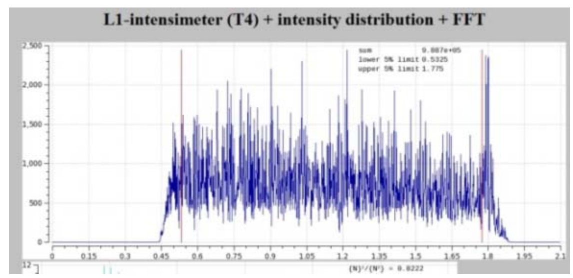

Figure 8: Beam slow spill monitored with head counters of the OKA experimental facility and broadcasted real-time via technological web-network for a control purpose.

During the run, a triple sequential beam splitting at the flattop was also implemented. The regime was found to be operational but not convenient due to an inevitable loss of the valuable flattop time for interfacing in-between the three extraction windows.

There were also the two outcomes of beam slow extractions with bent crystal deflectors worth mentioning:

1. Feeding the TNF-Atlas facility with a proton beam of intensity ranging from $1{\cdot}10^6$ to $4{\cdot}10^{11}$ ppp (i.e., varying by more than 5 orders of magnitude!).
2. Exercises with a new path of 700 ms long extraction of the 24.1 GeV/u carbon beam with the crystal deflector in straight section #22 and minimal spill intensity of $1.5{\cdot}10^7$ ipp. Still, even less intensive spills are demanded for. The work will be continued with a due analysis of the unwanted en-route fragmentation, if any.

The major outcome of the ion program was a successful commissioning of the new BTL#25 (Fig. 6) with a carbon beam, see Fig. 9.

RUN 2013-2

This run, like the run 2014-1 to follow, were the MD runs entirely, without acceleration of protons to the top energy of 50–60 GeV. By the summer of 2013, the former

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out-of-date power supply system (rotating machine generators) of the 1.5 km long U70 ring magnet had been stopped and dismantled. Instead, the new one based on static thyristor AC-DC convertors was being installed thus precluding any conventional operation of the machines.

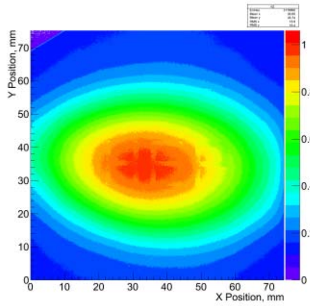

Figure 9: The first-in-record footprint of the slowly extracted carbon beam at the inner wall of the ring hall (bld. 1), i.e., at the end of upstream section of BTL#25.

To this end, the U70 magnet lattice was toggled to a stand-alone DC power supply unit yielding 130 A (field 353.7 Gs) and enabling operating the U70 as a beam storage and stretcher ring for 1.32 GeV (protons) or 455.7 MeV/u (carbon nuclei), which the U1.5 booster serves as the full-energy injector to.

The intermediate-energy runs pursued a double goal:

1. To provide a hot backup run-through and conditioning of all the technological sub-systems except for the top-energy magnet power supply, water-cooling of the U70 ring magnet, and powerful magnetic optics of the top-energy extractions.
2. To provide more time for studies and finer tuning of beam circulation, the new stochastic slow extraction of the intermediate-energy protons (a test beam) and carbon nuclei, and the new BTL#25 terminated by a radio-biological workbench.

The carbon-nuclei mode was turned-on smoothly. Pulsed current form the I100 linac reached 20 mA in 6 μs at base. The U1.5 booster accelerated 10^{10} ipp, the main ring U70 accepting around $5{\cdot}10^{9}$ ipp. In-out transfer ratio of the slow extraction was around 35%, and the external target got up to $1.7{\cdot}10^{9}$ ipp shaped into a tightly focused beam, see Fig. 10.

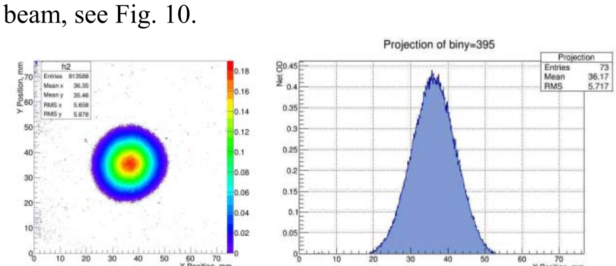

Figure 10: Carbon beam footprint at the entry window through radiation shielding of the workbench. Diameter 3 cm at 90% population level.

Given such a beam, the Interim Radio-Biological Workbench has been for the first time run legally as a self-sufficient experimental setup, short-named the IRBW, having got all the formal permissions thus prescribed. It constituted a noticeable step towards launching the topical applied-research activity there.

RUN 2014-1

The activity proceeded under the same restrictions and along the same guidelines as during the previous run. Finer alignment of the upstream magnets of the BTL#25 backed-up by a horizontal λ/2-bump compensation of the beyond-septum dipole stray field adverse effect on the circulating (waiting) beam has allowed raising the in-out ratio of the slow extraction to

- 8–10% for test protons which constitutes a gain ×2½ w.r.t. outcome of the run 2013-2, top expected limit being around 30% according to calculations;
- 45–50% (occasionally, to 57%) for carbon nuclei with expected calculated limit of around 80%.

Temporal and spatial portraits of the carbon beam extracted from the U70 are summarized in Fig. 11.

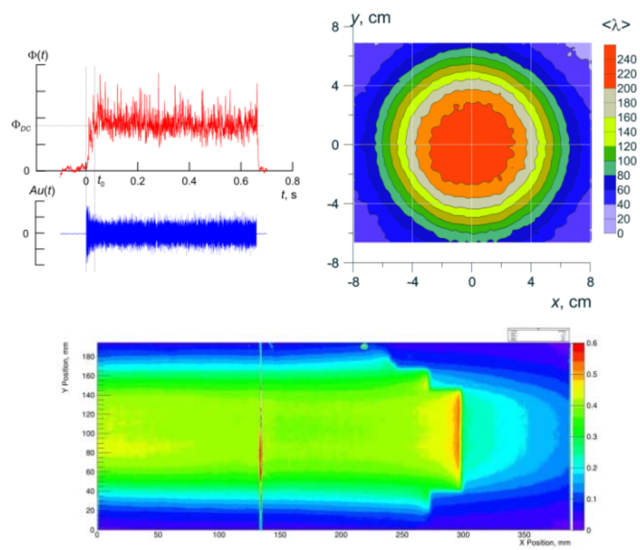

Figure 11: Structure of carbon beam from the U70. Top left — temporal *t*-pattern (0.6 s long low-ripple spill via feedback-controlled slow stochastic extraction). Top right — spatial transverse (*x*, *y*)-pattern (flattened paraxial dose field with a diameter 6 cm of <5% non-uniformity via a PM rotating electromechanical wobbler). Bottom — spatial longitudinal *s*-pattern (30 cm of stopping range in a water phantom with the Bragg's peak visible).

The temporal structure is drawn with a slow stochastic extraction system employing λ/2-phase-advance 2-stage Piccioni-Wright scheme, controlled horizontal noise-induced beam diffusion and dedicated beam fe edback circuit closed over "extraction flux – amplitude of colored-noise random carrier" path, just commissioned. Square-wave spills of 0.6–1.0 s duration are obtained routinely.

Transversally-flat paraxial dose distributions are obtained with a fixed-radius circular sweeping of the primary beam with the purpose-built PM rotating electro-mechanical wobbler. The device employs two third-party

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cylindrical dipole Halbach structures and imposes the net deflection of about 6.5 mrad. Rotation frequency 30–50 Hz is compliant to the spill duration.

Longitudinal dose distribution is governed by the natural Bragg's law for 455.7 MeV/u carbon projectiles in water.

Such beam parameters were found adequate to launch the first-in-U70-record (17.04.2014) radiobiological exercises with biological substances that were accomplished by a team from the Medical Radiological Research Center of the Russian Ministry of Health (Obninsk, Kaluga Region).

RUN 2014-2

It was an extra ad hoc one-month long run dedicated to the two sequential and pressing tasks:

1. The first proof-of-workability ramps to 50 GeV (protons) with the new power supply plant of the U70 ring magnet.
2. Pre-commissioning with the fast-extracted 50 GeV protons of the new Proton-Radiographic Facility.

Both the tasks were accomplished successfully.

Deep upgrading the power supply plant of the U70 ring magnet from rotating machine generators to static thyristor convertors called for 1.5-year long persistent efforts from IHEP and the LLC "NIIEFA–Energo" (St.-Petersburg). These were spent to accomplish design, contracting, manufacturing and shipping the equipment followed by assembly operations on the site.

Figure 12 shows a few pieces of equipment thus acquired.

Figure 12: Direct connecting to an electric power transmission line 220 kV with a commercially available insulating gas (sulfur hexafluoride) electricity distribution switchgear (ABB) followed by a new step-down (10 kV) 108 ton transformer (left). Five sets of (static) thyristor AC-DC convertors designed and manufactured by the LLC "NIIEFA–Energo" (St.-Petersburg) (right).

In despite of quite a new-fangled dynamical and ripple performance of the guide field, the proton beam has been successfully captured at the flat bottom, accelerated to 50 GeV and then transferred to the extraction flattop, see Fig. 13.

Actuating all the control entries foreseen and finer tuning and conditioning of the new power supply plant are planned for the run 2014-3 scheduled for October–December, 2014. Still, quality of the 50 GeV proton beam attained was adequate to deliver fast extracted beam to the Proton Radiographic Facility.

This newly-built 50–70 GeV Proton-Radiographic Facility is a joint venture by IHEP and RFNC–VNIIEF (Sarov, N. Novgorod Region) that was launched in 2010. The facility has been designed to attain a ∅200 mm field-of-view and a sub-mm resolution for > 450 g/cm^2 optical density objects.

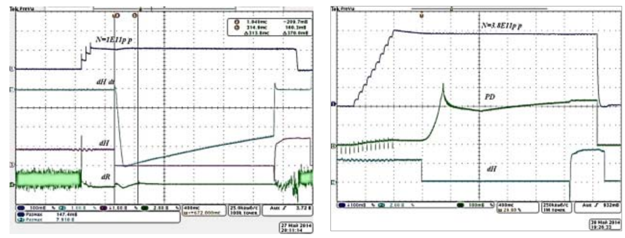

Figure 13: Oscilloscope screenshots of ramping to 50 GeV (protons) with a new power supply plant of the U70 ring magnet. Rays: *N* – beam intensity; *dH*/*dt* – magnetic-field ramping rate; *PD* – read-outs of beam peak-current detector inversely proportional to bunch length (spike at transition crossing); *dR* – radial excursion of rotating beam w.r.t. the reference orbit; *dH* – feedback signal to stabilize flat-bottom and flattop guide fields.

The core of the facility constitutes a triad of 180°FODOFODO quadruplets assembled of 24 paired side-by-side wide-aperture (hole ∅300 mm) quadrupole lenses with the top field gradient 6.7 T/m, see Fig. 14, all the lenses being designed and manufactured by IHEP.

During the run, the fast extracted 50 GeV proton beam from the U70 has been for the first time safely tracked and detected on-axis throughout the entire facility. There were no bottlenecks fond to preclude a further progress.

Figure 14: Wide-aperture quadrupole lenses of the new Proton Radiographic Facility at IHEP.

CONCLUSION

Accelerator Complex U70 of IHEP-Protvino is a subject to an ongoing upgrade program aimed at extending the machine functionality for fixed-target research, both fundamental and applied, with protons and carbon nuclei of high and intermediate energies, slowly or fast extracted.

REFERENCES

[1] S. Ivanov, on behalf of the U70 staff, Proc. of RUPAC-2008, Zvenigorod, 2008, p. 130–133; Proc. of RUPAC-2010, Protvino, 2010, p. 27–31. Proc. of RUPAC-2012, St.-Petersburg, 2012, p. 85–89.

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