STATUS OF U70

S. Ivanov, on behalf of the U70 staff#
Institute for High Energy Physics (IHEP) of NRC "Kurchatov Institute"
Protvino, Moscow Region, 142281, Russia

Abstract

The report overviews present status of the Accelerator Complex U70 at IHEP of NRC "Kurchatov Institute". The emphasis is put on the recent activity and upgrades implemented since the previous conference RuPAC-2014, in a run-by-run chronological ordering.

History of the foregoing activity and upgrades is recorded sequentially in Refs. [1].

GENERALITIES

Layout of the entire Accelerator Complex U70 is shown in Fig. 1. It comprises four machines — 2 linear (I100, URAL30) and 2 circular (U1.5, U70) accelerators. Proton mode (default) employs a cascade of URAL30–U1.5–U70, while the light-ion (carbon) one — that of I100–U1.5–U70.

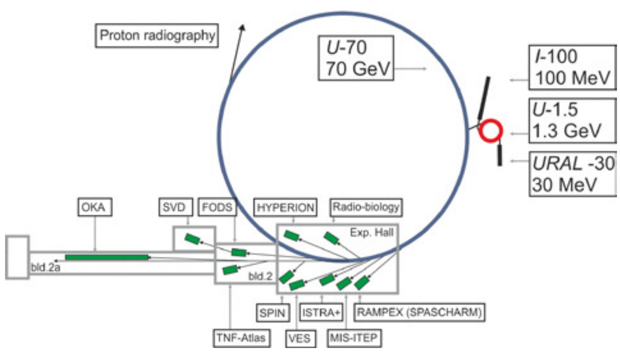

Figure 1: Accelerator Complex U70, beam transfer line network and fixed-target experimental facilities included.

Since the previous conference RuPAC-2014, the U70 complex operated for four runs in total. Table 1 lists their calendar data. The second run of 2016 was being launched during compiling this report.

Details of the routine operation and upgrades through 2014–2016 are reported in what follows run by run.

RUN 2014-3

It was the 3rd run per year of 2014 which has broken the long-term tradition of two annual (spring and autumn) runs of U70. The run had its specific features:

On the one hand, it was the 1st run of U70 for fixed-target physics when the machine was operated under the upgraded 1.5 km ring magnet main power supply plant equipped with the up-to-date static thyristor AC-DC convertors. The relevant upgrade activity took 1½ years.

The *B*-field ramping quality attained ensured safe acceleration (at least, in the single-particle limit) which is illustrated by Fig. 2.

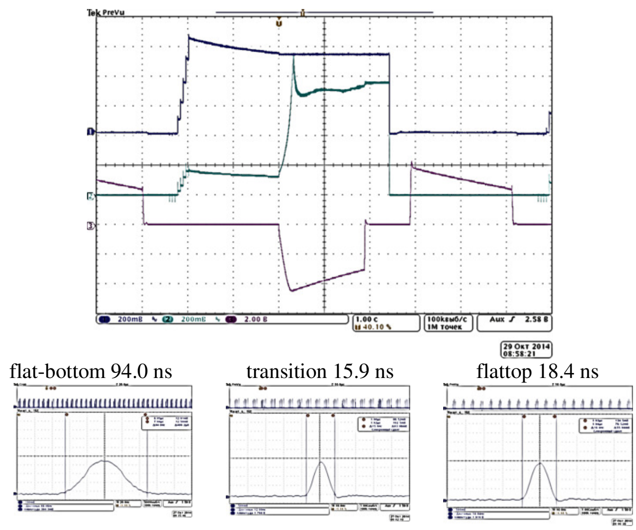

Figure 2: Acceleration in U70 with a new ring magnet power supply plant. Traces from top to bottom: beam DC current (5 bunches injected); bunch peak current (spike occurs at transition); *B*-field ramp rate (0.82 T/s max); bunch evolution through a cycle.

On the other hand, it was the 1st ever run when the 50 GeV proton beam was directed with the highest priority to the topical applied fixed-target research. It was ejected to the full-scale Proton-Radiographic Facility, named PRGK-100, operated jointly with RFNC–VNIIEF (Sarov, N. Novgorod Region).

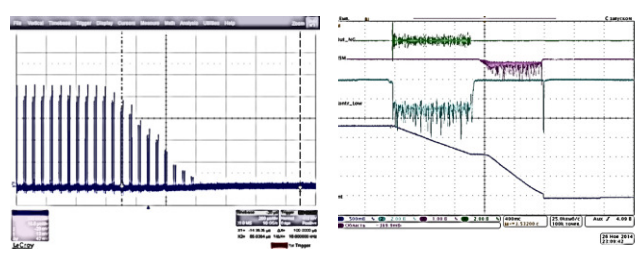

Figure 3: Beam extractions from U70. Left: 10-turm fast extraction of a short train of bunches. Right: Sequential beam sharing at flattop with slow extractions. Traces from top to bottom: AM-modulated feeding noise, spill to internal target IT35, stochastic slow spill, and waiting beam DC current decay (piecewise-linear).

To this end, the beam was extracted either with the conventional 1-turn fast (in 5 μs) or with the multi-turn (3–10 turns) fast extractions (refer to Fig. 3, left). The

N. Tyurin, A. Zaitsev, O. Lebedev, V. Kalinin, V. Lapygin, D. Demihovskiy, Yu. Milichenko, I. Tsygankov, I. Sulygin, N. Ignashin, S. Sytov, Yu. Fedotov, A. Minchenko, A. Maksimov, A. Afonin, Yu. Antipov, and D. Khmaruk.

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latter was due to the new FE scheme implemented that involves fast dipole magnet deflectors to drive a rising lumped horizontal orbit bump around the thin-wire electrostatic deflector for incremental beam shaving.

In course of operation for particle physics, U70 has delivered $3{\cdot}10^{12}$ ppp (average), $3.8{\cdot}10^{12}$ ppp (max) to 7 experimental facilities. Stochastic slow extraction (refer to Fig. 3, right) has attained 80–85% in-out transfer ratio for the beam fraction extracted. Fractional beam availability was about 83.8% which figure complies with the 10-year-long operational statistics.

By end of the run, the machine was switched to carbon-beam mode at intermediate energy 456 MeV/u (specific kinetic). The beam of bare carbon nuclei was stretched in and then extracted from the U-70 ring at flat-bottom. The intensity stored was $1–2.8{\cdot}10^{9}$ ipp of which $1.2–1.9{\cdot}10^{9}$ ipp were extracted for applied methodical and radio-biology research. Pulse-to-pulse period was 8.2 s.

The beam was extracted slowly with a stochastic extraction scheme capable of yielding 0.6–1 s long square-wave spills. The in-out transfer ratio amounted 55-57%, close the top expected value of around 68%.

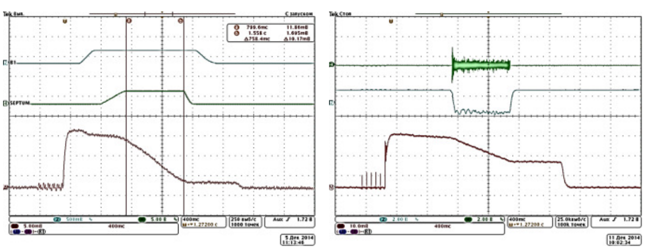

Figure 4: Stochastic slow extraction of carbon beam at flat-bottom of U70.

Fig. 4, left, illustrates the attractive, quasi-static nature of the stochastic slow extraction involved. Indeed, the linear decay of circulating beam DC current (bottom trace; 90% extracted, ca) is maintained under steady-state currents through closed-orbit bump coils and the 1st (upstream) deflecting magnet windings (two top traces).

Fig. 4, right, plots the feeding noise AM-modulated with a dedicated beam feedback (top trace), resultant square-wave spill monitored with a smoothing ionization chamber (central trace), and circulating beam DC current (bottom trace; about 50% of beam extracted in this case).

It is the adequate quality of carbon beam extracted that allowed a team from the Medical Radiological Research Center of the Russian Ministry of Health (MRRC, Obninsk, Kaluga Region) to accomplish the 2nd round of carbon-beam radio-biology studies with biological objects and structures at U70.

RUN 2015-1

While planning this run, the U70 personnel had encountered a noticeable competition between divergent demands of beam users. The compromise was settled with a complicated operational schedule composing various machine regimes overloaded by interfacing periods in between.

First, the machine was operated with the proton beam at 25 GeV. Such a routine regime was the first in U70 record. Still, in despite of complications in tuning the hardware, the beam was ultimately accelerated to the non-standard 25 GeV flattop and extracted successfully to the experimental facilities. Use was made of the stochastic slow extraction (up to 90% in-out), of internal targets and bent-crystal deflectors. The average beam intensity was not high, $2{\cdot}10^{12}$ ppp in 10–12 bunches (of 29 max available).

Second, the machine was operated at the conventional 50 GeV (protons). The beam has fed up to 7 experimental facilities (refer to Fig. 5) and, under the top priority, the Proton-Radiographic Facility. Beam intensity was $3–6{\cdot}10^{12}$ ppp, which was not so high due to troubles at the proton linac URAL30 at front end of the accelerating cascade in the proton mode. There is definitely a room for improvement left since occasionally the machine has yielded promising values of intensities per bunch amounting at max to 4.5 (U1.5), 3.8 (U70)$\cdot10^{11}$ ppb.

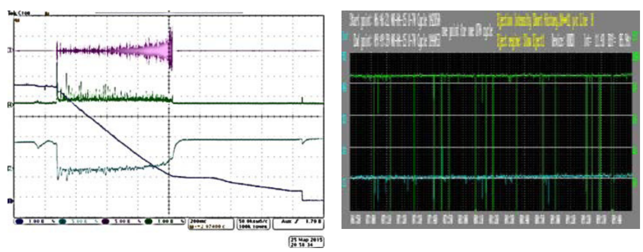

Figure 5: Stochastic slow extraction of protons from U70. Left, traces from top to bottom: AM-modulated feeding noise, low-ripple stochastic slow spill, waiting beam DC current, and beam feedback signal to modulate amplitude of noise. Right, monitor of slow extraction: bottom trace is spill intensity in relative units; top trace is in-out transfer ratio varying from 80 to 93% (at this plot).

Third, U70 was switched to high-energy carbon-beam mode at 25 GeV/u (the same magnetic rigidity and compliable kinematics as those for 50 GeV protons for future complementary hadron-nuclei and nuclei-hadron experiments). In course of a very short MD session the three issued extraction systems available were re-tuned to service carbon nuclei — (i) fast extraction to beam transfer line BTL#8, (ii) stochastic slow extraction to BTL#22, and (iii) slow extraction via bent-crystal deflectors to BTLs#22 and #8. Beam intensity varied in between $3–6.5{\cdot}10^{9}$ ipp.

There were two beam observations reported that are crucial for further advance of light-ion experimental program at U70. These are high quality (purity) of the high-energy carbon beam at the exit faces of beam transfer lines and negligible fragmentation the carbon nuclei in and after bent-crystal deflectors.

Fourth and finally, U70 was switched over to 456 MeV/u carbon beam storage and stretcher mode feeding BTL#25 ended by Interim Radio-Biological Workbench. Stored beam intensity amounted to $3–6.5{\cdot}10^{9}$ ipp. The end-user off-site experimentalist community at U70 has been joined by a new member — a

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team from Institute for Theoretical and Experimental Biophysics the Russian Academy of Science (ITEB, Pushchino, Moscow Region). The intermediate-energy slowly-extracted carbon beam is thus well in-demand.

RUN 2015-2

In course of this run, U70 was again employed in two modes — proton (50 GeV) and carbon (456 MeV/u) ones.

To meet beam user demand, proton part of the run was broken into 3 segments with different priorities assigned either to fundamental or to applied fixed-target research. These used to call for a non-compliant set of beam structure, extractions and the BTLs involved.

During the shutdown, a crush program to improve functionality of proton source and URAL30 linac had been accomplished to attain reliable operation with $4{\cdot}10^{11}$ ppb in a variable number of bunches (up to 29).

Major bulk of fixed-target fundamental research was arranged, as usual, with sequential and parallel beam sharing at flattop. Occasionally, 5 experimental facilities were fed by the beam simultaneously in a cycle which constitutes a clear example of an efficient multi-user regime.

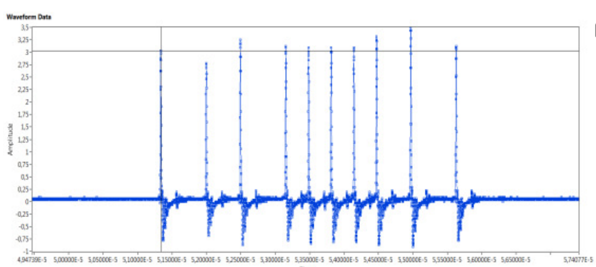

Figure 6: Beam train of 10 bunches in U70 for fast single-turn extraction for applied research. Bunch intensity is $3{\cdot}10^{11}$ ppb (marked with horizontal line).

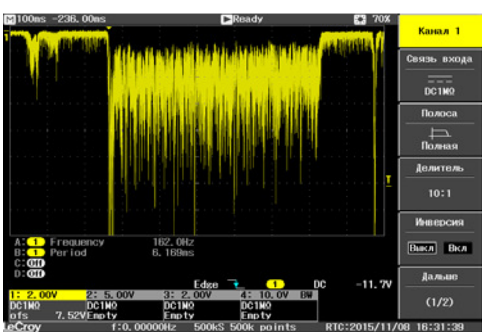

Figure 7: Stochastic slow spill of 50 GeV protons to the OKA experimental facility (study of rare kaon decays). Spill intensity $4{\cdot}10^{12}$ ppp.

In total, the 50 GeV proton beam was consumed by 6–8 beam users. Beam intensities were $3{\cdot}10^{12}$ ppp (average), $8.2{\cdot}10^{12}$ ppp (max), $5.3{\cdot}10^{12}$ ppp (stochastic slow extraction @ max 91% in-out transfer).

In the 456 MэB/u carbon beam mode, U70 accepted 3–$5{\cdot}10^{9}$ ipp and delivered beam to radio-biological research. The two off-site research teams engaged in this activity were already mentioned (MRRC and ITEB).

Figures 6–9 illustrate a few milestones of the run at issue. Its tasks were accomplished.

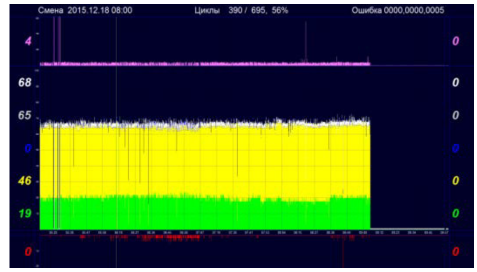

Figure 8: End of run 2015-2. Numerical data at the intensity monitor screenshot: $1.9{\cdot}10^{12}$ ppp to internal targets (green), $4.6{\cdot}10^{12}$ ppp to stochastic slow extraction (yellow), $6.5{\cdot}10^{12}$ ppp of total extracted intensity, 4% of integral start-to-end beam losses, transition crossing included (purple). Notice smooth sustained operation of U70 prior to scheduled shutdown at 09:00 of December 18, 2015.

RUN 2016-1

In course of this run, U70 was employed in two modes and with four beam energies — proton (40 and 50 GeV) and carbon (20 GeV/u and 456 MeV/u).

The machine was launched and tuned with 40 GeV proton beam at 3 s long flattop. Essentially, it was a test pilot beam to adjust injection systems and beamlines to the non-standard energy. The goal was to accommodate the machine to accept the much-less-intensive 20 GeV/u carbon-nuclei beam of the same magnetic rigidity.

In the aftermath of such a pre-tuning, the machine was switched to carbon mode. Thus, the 1st in record lengthy (23 days) run of U70 for fixed-target physical program with high-energy carbon beam had started. Peak intensity observed was $7{\cdot}10^{9}$ ipp (one bunch).

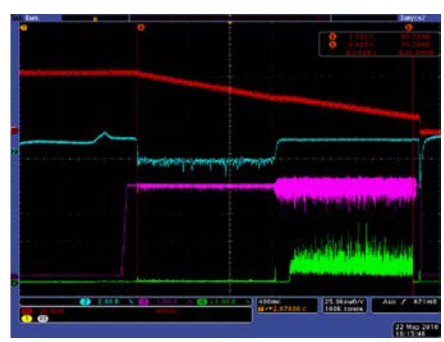

Figure 9: Sequential slow extraction of high-energy (20 GeV/u) carbon nuclei to FODS (via bent-crystal deflectors) and VES (stochastic) experimental facilities at the 1st and 2nd halves of the U70 flattop, respectively. Net intensity is $6.7{\cdot}10^{9}$ ipp.

Upon acceleration, the beam was de-bunched at flattop and extracted to existing FODS, SPIN and VES experimental facilities. To this end, two extraction schemes were employed — via noise-diffusive feeding the 3rd order horizontal resonance (stochastic slow extraction) or via bump-translational feeding bent-crystal

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Table 1: Four runs of the U70 in between RuPAC-2014 and -2016

Run	2014-3	2015-1	2015-2	2016-1
Launching linac URAL30, booster U1.5 and U70 sequentially (I100 in parallel with a delay)	October, 06	February, 09	September, 29	February, 15
Beam in the U70 ring since	October, 23	March, 03	October, 29	February, 29
Fixed-target physics program with extracted top-energy beams (either of protons or of carbon nuclei)	November, 06 – December, 01, 25 days	March, 10 – April, 20 32 days	November, 09 – December, 18, 39 days	March, 03 – April, 11, 31 day
No. of multiple beam users (of which the 1st priority ones)	9 (7)	9 (8)	9(9)	6(6)
MD sessions and R&D on beam and accelerator physics, days	14	12	14	11
Light-ion acceleration program, intermediate energy only	December, 12–22, 11½ days	April, 20–24, 4½ days	December, 18–25, 7½ days	April ,14–25, 11 days

deflectors. Both the extractions succeeded which is confirmed by Fig. 9.

By end of the high-energy part of the run, U70 was again re-tuned to standard 50 GeV protons to yield the beam for other fixed-target research: proton radiography (daytime); TNF-ATLAS and ISTRA (nights).

Traditionally now, the run had ended with the 456 MeV/u carbon beam mode for radio-biological studies. Still, it is worth noting that one more off-site team of experimentalists had applied for and got the intermediate-energy carbon beam from U70 — the scientists from Joint Institute for Nuclear Research (JINR, Dubna, Moscow Region) irradiated nuclear emulsions thereby.

This run deserves a dedicated comment from the standpoint of experimental physics.

Indeed, it has launched a systematic experimental fixed-target research in the field of relativistic nuclear physics with the formerly entirely-proton machine. It was its first-in-record run when experimental facilities where fed mostly by high-energy beams of carbon nuclei. There were three major physical facilities involved – FODS, SPIN and VES. Beam energy was 20 GeV/u or 240 GeV in total. (To remind, the top magnetic rigidity of the U70 synchrotron allows gaining proven 35 GeV/u or 420 GeV total). Beam intensity varied from 10^5 to $4\cdot10^9$ nuclei per cycle (9.5 s), on demand of experimentalists.

The FODS facility was engaged in observation of fragmentation processes of high-energy carbon nuclei projectiles impacting other fixed-nuclei and studies of generating secondary particles in a deep cumulative region.

The SPIN facility studied spectra of secondary particles with large transverse momenta in course of impact of the high-energy carbon nuclei against nuclear (hydrogen included) fixed targets. Implementation of hydrogen target allows acquiring carbon-proton interaction data for subsequent cross-analysis with the complementary inversed-kinematics proton-carbon interaction data recorded in the earlier proton runs of U70.

The VES facility was engaged in a survey hadron-spectroscopy experiment to study specifics of meson states showing up in carbon-carbon interactions. Another topic was a search for bounded meson-nuclei states

Thus, run 2016-1 has de-facto opened a new direction of experimental research in IHEP of NRC “Kurchatov Institute”.

CONCLUSION

Accelerator Complex U70 at IHEP of NRC “Kurchatov Institute” is maintained in a healthy functional status, have noticeably improved its functionality due to recent upgrades and provides beams for ongoing topical 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; Proc. of RUPAC-2014, Obninsk, 2014, p. 1–5.

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