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# STATUS OF U70

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## *Abstract*

The report overviews present status of the Accelerator Complex U70 at IHEP of NRC "Kurchatov Institute" (Protvino). The emphasis is put on the recent activity and upgrades implemented since the previous conference RuPAC-2016, in a run-by-run chronological ordering.

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

## GENERALITIES

The entire Accelerator Complex U70 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.

Since the previous conference RuPAC-2016, the U70 complex operated for four runs in total. Table 1 lists their calendar data. The second run of 2018 is being planned for October–November of 2018.

Details of the routine operation and upgrades through years 2016–18 are reported in what follows, run by run.

## RUN 2016-2

The run lasted from October 03 till December 27 2016 in the two modes sequentially: with 50 GeV protons (see Fig. 1), and 455 MeV/u carbon beams.

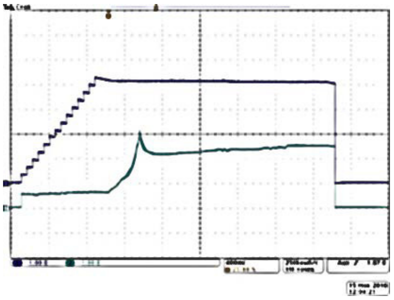

Figure 1: Acceleration of protons in U70. Traces from top to bottom: beam DC current (14 bunches (of 29 feasible) injected); bunch peak current (spike occurs at $\gamma$-transition 7.96 GeV).

During the 1st half of the run, 50 GeV proton beam was directed to applied research at the radiographic facility.

To this end, the facility was fed with the fast-extracted bunched beam with equal bunches of $3–4{\cdot}10^{11}$ ppb. To attain electric energy conserving operation, the flattop length was cut short to 0.6 sec.

During the 2nd half of the run, the azimuthally uniform (de-bunched) 50 GeV proton beam was used for 672 hr for fundamental physics at seven experimental facilities. Typically, slow extraction took 2.5 sec with $7.7{\cdot}10^{12}$ protons per a spill, refer to Figs. 2, 3.

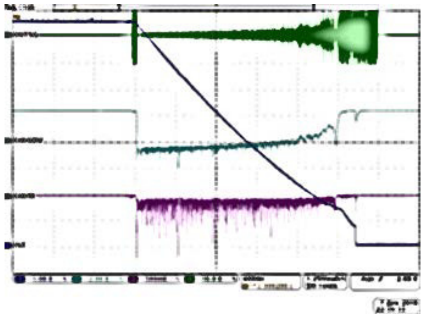

Figure 2: Slow stochastic extraction of protons from U70. Traces from top to bottom: waiting beam DC current, AM-modulated noise, beam feedback signal to modulate amplitude of noise, and a slow stochastic spill as such.

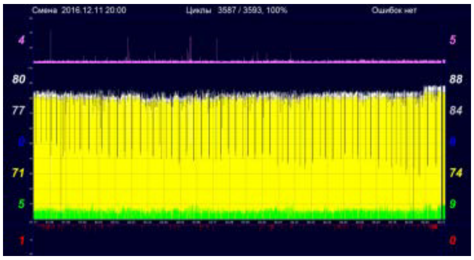

Figure 3: Numerical data at the intensity monitor screen during run 2016-2 for physics: The upper trace is overall beam loss during the cycle (5%). Beam intensity delivered is $8.0{\cdot}10^{12}$ ppp (average), or $8.8{\cdot}10^{12}$ ppp (instantaneous).

Some of the fixed-target experiments were run with secondary particles from internal targets under a parallel beam splitting see Fig. 4.

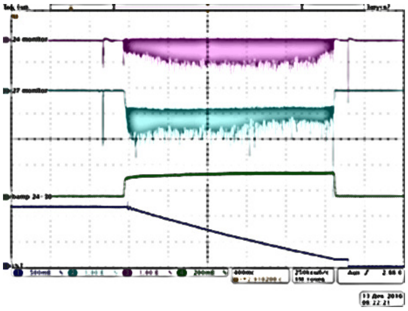

Figure 4: Traces from top to bottom. Spill of secondary particles beam from internal targets ## 24 and 27. Driving current of the enclosing orbit bump between straight sections ## 24 and 30, DC current of the waiting circulating beam.

Closer to end of the run, the U70 complex was turned to the carbon-beam mode at 455 MeV/u, the main ring being operated as a beam storage and stretcher ring at flat-bottom DC magnetic field. The beam was used for applied radiobiological and biophysical research by teams from institutes listed in the 2nd row of Table 1.

During preparation to the run, due efforts were spent to better understand and employ specific features of the just commissioned new power supply plant (PSP) of the U70 ring magnet. This system implements solid-state AC-DC convertors and step-down transformers net-worked to the incoming 220 kV power transmission line directly. One of useful developments was to derive reference to synchronize the PSP trigger from the stepped-down 220/0.1 kV parent voltage directly via home-made electronics. The outcome observed is a noticeable improvement in reproducibility of magnetic field cycles and suppression of their ripples.

## RUN 2017-1

The run went on from February 27 till April 27, 2017. The complex was engaged in a variety of regimes.

First, 1.3 GeV proton beam from the RC PS booster U1.5 was employed to irradiate electronics and scintillators in frames of the upgrade activity for the TileCal calorimeter of the CERN LHC ATLAS experiment. Later, this proton beam was used to pre-tune injection to and beam capture in the U70 ring in a flat-bottom beam storage and stretcher ring mode for the subsequent running with the same-rigidity 455 MeV/u carbon ion beam.

Second, during nominal carbon-beam operation, up to $8.5\cdot10^{9}$ ipp were delivered by stochastic slow extraction for applied research, see Fig. 5, that was accomplished by teams from 5 institutions listed in the 3rd row of Table 1. The research capabilities opened by availability of medium-energy carbon beam are well in demand.

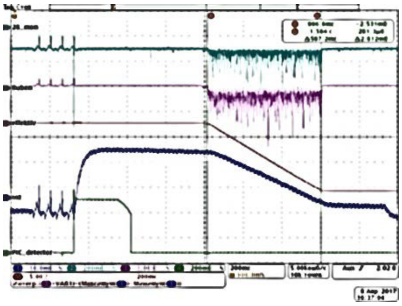

Figure 5: Slow extraction (about 0.6 sec) of 455 MeV/u azimuthally uniform carbon beam. Traces from top to bottom. Beam loss monitor #28 close to thin energy-degrader internal target, the 1st upstream element at the extraction path. Read-out from ionization chamber traversed by extracted beam fraction in the destination BTL#25 followed by the running integral over the signal at issue. Waiting beam intensity measured with a DC CT. Bunch peak current to monitor de-bunching of the beam.

Third, the U70 was set to yield 50 GeV protons. This mode was launched with exploration of operational capabilities of the new U70 power supply plant commissioned recently. Major emphasis was put onto study of temperature margins of the down-step transformers under various flattop lengths proceeding from 2.5 to 3.2 sec at the most.

The top-priority beam consumer was the proton radiographic facility (50 GeV, flattop 0.6 sec) that called for beam intensity of $3.0\cdot10^{11}$ ppb (max $4.5\cdot10^{11}$ ppb with 60 mA from linac). Beam structure was either single-bunch or multi-bunch with an arbitrary orbit filling with equal bunches, on demand. In total, U70 has delivered 5722 spills with integrated intensity of about $1.17\cdot10^{15}$ protons. To this end, a few extractions were used: single-turn fast, 3rd order resonant fast and double-turn fast on-the-flight during ramping at the intermediate 30 GeV.

Program of fundamental research of the run 2017-1 was accomplished in a conventional multi-user way illustrated by Figs. 6 and 7. In their captions and in what follows, BTL is a Beam Transfer Line, IT is an Internal Target, CD is a bent-Crystal Deflector, all numbered by the # of the relevant (host) straight section (SS) in the U70 lattice.

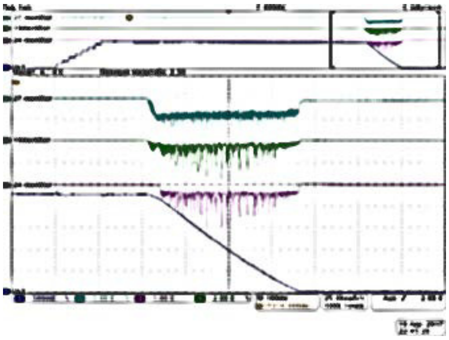

Figure 6: Parallel beam sharing (50 GeV, $2.25\cdot10^{12}$ ppp net) towards 3 experiments: FODS @ BTL #22 via CD#19; SPASCHARM @ BTL #14 via IT#24/3B; ISTRA–CRYSTALL @BTL #4A via CD#27.

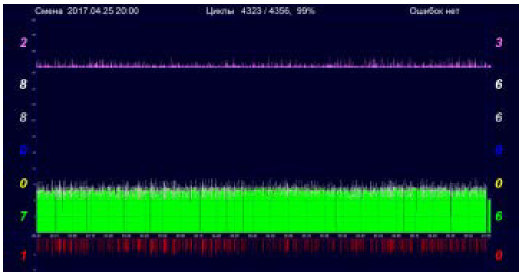

Figure 7: Screenshot of the U70 intensity monitor during run 2017-1 for physics in a sustained regime, (5–20)$\cdot10^{11}$ ppp. Three experiments: TNF–ATLAS, SPASCHARM, and ISTRA–CRYSTALL.

## RUN 2017-2

Prior to the run, on October 14, 2017 Accelerator Complex U70 has marked the 50th anniversary since launching into operation. The run itself took place from November 17 till December 29, 2017.

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First, the 50–60 GeV proton beam was used for both, applied and fundamental research.

Radiographic facility consumed bunched beam (1–10 equal bunches, on demand) with intensity 3–4·$10^{11}$ ppb, see, Fig. 8.

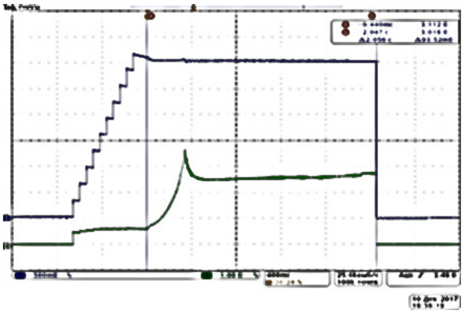

Figure 8: Typical operation of U70. Traces from top to bottom: beam DC current (10 bunches); bunch peak current (spike occurs at γ-transition).

Fundamental research was carried out (though, under a lowered priority) with 50 GeV azimuthally uniform proton beam at the two experimental facilities. These were HYPERION @ BTL#18 via IT#35, and ISTRA–CRYSTALL @ BTL#4A via CD#27 and IT#27. Spill duration varied from 0.4 to 0.53 sec, subject to availability of the time slot. The regime is illustrated at Figs. 9, 10.

During run 2017-2, the new flying-wire beam profilometer (transverse) was put into test operation. The 1st records of beam shapes acquired are shown in Fig. 11.

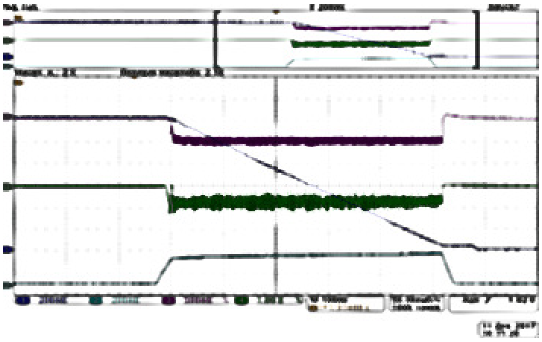

Figure 9: Traces from top to bottom. DC current of circulating beam. Spill of secondary particles beam from IT ## 27, 35. Driving current of the enclosing orbit bump between SS ## 24 and 30.

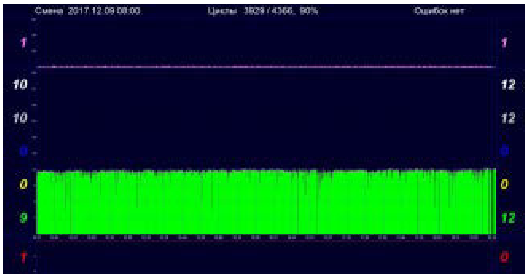

Figure 10: Screenshot of the U70 intensity monitor during run 2017-2 for physics. Beam intensity (10–14)·$10^{11}$ ppp.

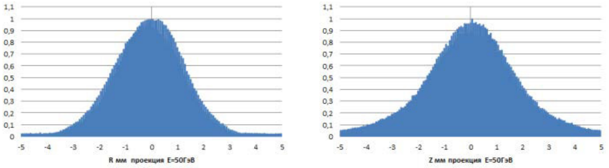

Figure 11: Transverse profiles of the proton beam (left – horizontal, right – vertical), 50 GeV and 1·$10^{12}$ ppp.

On completing the proton sub-run, the U70 machine was again set to the intermediate-energy (455 MeV/u) carbon-beam mode (a storage and stretcher ring). A few operational signals are plotted in Figs. 12, 13.

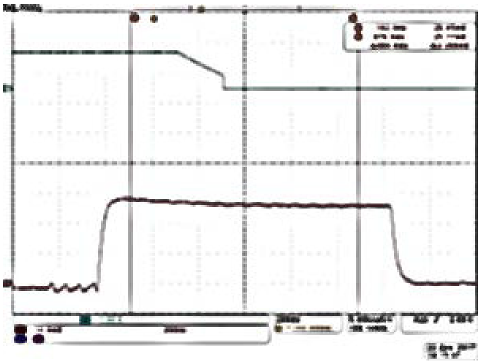

Figure 12: Circulation and de-bunching of carbon beam in U70.. Top trace – envelope of RF electric field. Bottom trace – DC current of the beam, 4.6·$10^9$ ipp, 455 MeV/u.

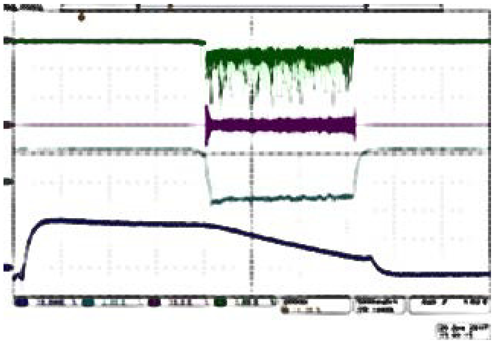

Figure 13: Slow stochastic extraction of the carbon beam (0.6 sec). Traces from top to bottom: ionization chamber in the head of BTL#25, deflecting noise, feedback signal for noise AM modulation, waiting beam DC current.

Significant efforts were spent for beam-based experimental activity with appropriate diagnostic tools — ionization chambers (calibration, voltage-current characteristics, non-standard (4-way mosaic), semiconductor option included), beam shape meters with scintillator strips and SiPM, flattening doze deposition, etc.

Beam composition (carbon nuclei species versus fragments) and energy was studied with two techniques — time-of-flight and Bragg's peak position measurement. Outcome is shown in Fig. 14 that confirms high quality of the beam in question.

The carbon beam was used by a team from Institute of Biomedical Problems (IBMP RAS, Moscow) in compliance with its in-house research program, see Fig. 15.

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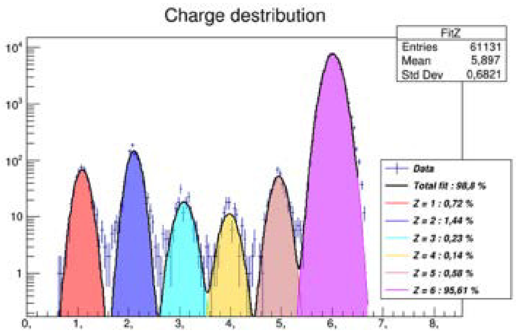

Figure 14: Composition of extracted beam vs. charge number $Z$ of constituents. Fractional weight of (target) carbon nuclei is 95.6%.

Figure 15: Test animal (a monkey) facing the carbon beam. Through passage of beam across the head with 1 Gydose deposed.

## RUN 2018-1

The run was accomplished in between February 05 and April 27, 2018.

During the run, 1.3 GeV proton beam from the booster U1.5 was again used for applied research — radiation sustainability tests of electronics and scintillators, similar to that accomplished in course the previous run 2017-1.

The U70 ring itself was operated under various ramping cycles with flattops 0.38 sec (machine tuning and conditioning), 0.77 sec (proton radiography and physics @ the 2nd priority), and 3.0–3.2 sec (for the physics alone).

In the latter case, the flattop accommodated two sequential slots for slow extraction? either 1.05 and 1.35 or 1.3 and 1.4 sec, refer to Figs. 16–18.

The 1st slot was serviced by the stochastic slow extraction system, while the 2nd one — by internal targets (IT) and bent-crystal deflectors (CD), up to 3–4 experiments in parallel.

For an applied research with the proton radiographic facility, the U70 was operated in single- and multi-bunch modes with (3–4.5)·$10^{11}$ ppb.

In total, ten experimental facilities were fed by the accelerated proton beam during the run, which confirms U70 being really a multi-user machine.

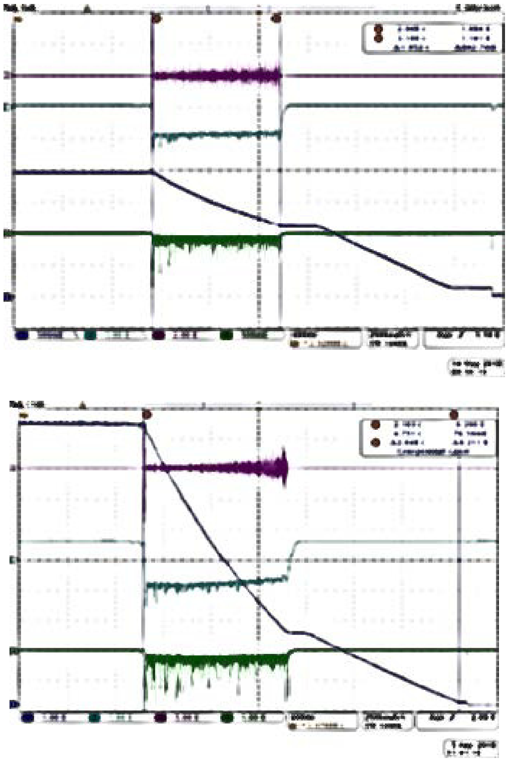

Figure 16: Slow stochastic extraction at the 1st half of flattop. Beam intensities prior to extraction: 2.0·$10^{12}$ ppp (top plot, 1.05 sec spill), 9.2·$10^{12}$ ppp (bottom plot, 1.3 sec spill). Traces from top to bottom: phase noise, beam feedback signal for AM-modulation of the noise, slow spill, and intensity of the waiting beam (descending trace).

The complementary carbon-beam mode was not turned on for users during run 2018-1 due to a deficit in beam time affordable.

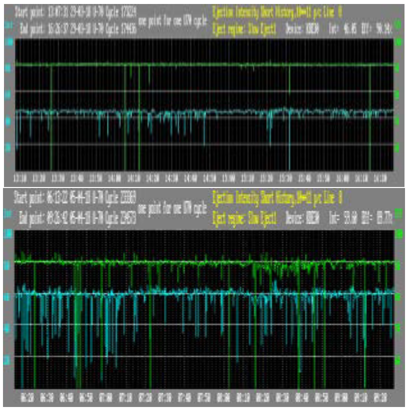

Figure 17: On-line monitoring of intensity of beam extracted to BTL #8 (lower trace) and in-out transfer efficacy along the extraction beam path (upper trace).

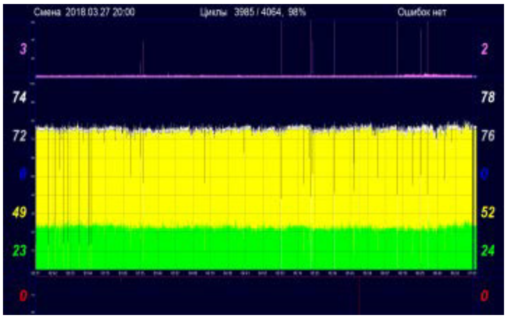

Figure 18: Screenshot of the U70 intensity monitor during run 2018-1 for physics. Beam intensity $(5–10)\cdot 10^{12}$ ppp.

Table 1: Engagement of the Off-Site Institutions in Carbon-Beam Sub-Runs

| Institution | 2016-2 | 2017-1 | 2107-2 | 2018-1 |
|---|---|---|---|---|
| MRRC of NMRCR,<br>http://mrrc.nmicr.ru | + | + | | |
| ITEB of RAS,<br>web.iteb.psn.ru | + | + | | |
| IBMP of RAS,<br>www.imbp.ru | | + | + | |
| FMBC of FMBA,<br>fmbafmbc.ru | | + | | |
| JINR, www.jinr.ru | + | + | | |

Table 2: Four Runs of the U70 in between RuPAC-2016 and -2018

| Run | 2016-2 | 2017-1 | 2017-2 | 2018-1 |
|---|---|---|---|---|
| Launching linac URAL30, booster U1.5 and U70 sequentially (I100 in parallel with a delay) | October, 03 | February, 27 | October, 30 | February, 05 |
| Beam in the U70 ring since | November, 03 | March, 27 | November, 27 | March, 06 |
| Fixed-target physics program with extracted top-energy beams (either of protons or of carbon nuclei) | November, 07 – December, 19, 42 days | April, 14 –29, 15½ days | December, 04 – 18, 14 days | March, 12 – April, 26, 45 day |
| No. of multiple beam users (of which the 1st priority ones) | 8 (7) | 5 (3) | 3(1) | 10(9) |
| MD sessions and R&D on beam and accelerator physics, days | 12 | 17 | 25 | 7 |
| Light-ion acceleration program, intermediate energy only | December, 19–27, 8½ days | March, 27–April 09, 13½ days | December, 18–29, 11½ days | April, 26–27, 1 day |

## CONCLUSION

Accelerator Complex U70 at IHEP of NRC “Kurchatov Institute” continues its routine operation for fixed-target physics and applications and has accomplished four regular machine runs since the previous conference RuPAC-2016, refer to Table 2.

## REFERENCES

[1] S. Ivanov *et al.*, *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; *Proc. of RUPAC-2016*, St.-Petersburg, 2016, p. 44–47.