ACCELERATOR COMPLEX U70 OF IHEP: PRESENT STATUS AND RECENT UPGRADES

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Abstract

The report overviews status of the U70, accelerator complex 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-2008.

GENERALITIES

Layout and technical specification of the entire Accelerator complex U70 of IHEP-Protvino was specified in the previous status report [1] whose general part remains up-to-date.

On December 30, 2009, the Russian Federal Government issued an executive order enrolling the complex into the national List-Register of Unique Nuclear-Physics Facilities. It constitutes a prerequisite for an awaited revision of a funding scheme to maintain special and general-purpose engineering infrastructure of the IHEP facilities.

Efforts were continued to attain the following goals:

1. to ensure stable operation and high beam availability during the regular machine runs,
2. to improve proton beam quality,
3. to implement a program to accelerate light ions with a charge-to-mass ratio $q/A = 0.4–0.5$, and
4. to put forward a sound long-range option to diversify and develop accelerator and experimental facilities on the IHEP grounds, with a bias towards fixed-target research beyond elementary particle physics.

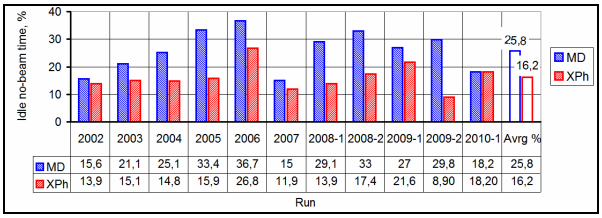
ROUTINE OPERATION

Since RuPAC-2008, the U70 complex worked for four runs in total. Table 1 lists their calendar data (end of the text). The first run of a year is shorter and solves, mainly, developmental and methodological tasks.

Dedicated machine development (MD) activity is split into two sessions per a run. One takes about a week prior to delivering beam to experimental facilities. Another (2-day long) occurs amidst the fixed-target physics program, under conditions of a smooth sustained operation of the machines thus facilitating R&D on beam physics.

Fig. 1 shows beam availability data during MDs and a fixed-target experimental physics program (XPh) with averages over 2002–10. Run 2009-2 has set a record with experimental facilities acquiring the extracted beam with its availability exceeding 90%.

During the runs, all the beam extraction systems available in the U70 were engaged — fast single-turn, slow 3rd-order resonant, internal targets, and deflectors made of bent silicon crystals. Fig. 2 demonstrates a period of smooth operation of the U70. Fig. 3 presents operation of slow extraction system.



	2002	2003	2004	2005	2006	2007	2008-1	2008-2	2009-1	2009-2	2010-1	Avrg %
▨ MD	15,6	21,1	25,1	33,4	36,7	15	29,1	33	27	29,8	18,2	25,8
▨ XPh	13,9	15,1	14,8	15,9	26,8	11,9	13,9	17,4	21,6	8,90	18,20	16,2

Figure 1: Beam availability statistics.

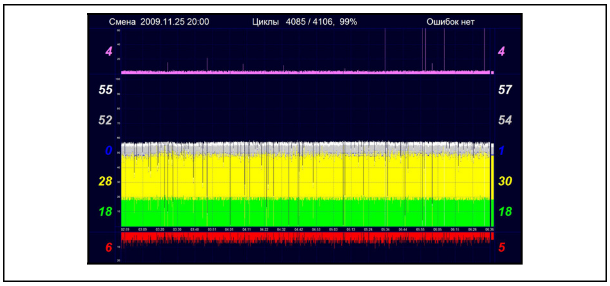

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Figure 2: Screenshot of the on-line monitoring over the U70 operation. Time interval (abscissa) extends over 3 hr, or 1000 cycles of acceleration. Yellow trace slows intensity of stochastic extraction, green trace — operation of internal targets. Red (inverted) trace indicates spent beam remains damped onto internal absorber.

MACHINE DEVELOPMENT

This Section reports on recent updates in equipment.

New Septum Magnet SM26

In 2008, a new septum magnet SM26, manufactured at IHEP workshops, was installed in 4.9 m long straight section SS#26 of the U70 lattice, see Fig. 4. It was a step in upgrade of the slow extraction system aimed at enlarging vertical gap for extracted beam from 25 to 35 mm.

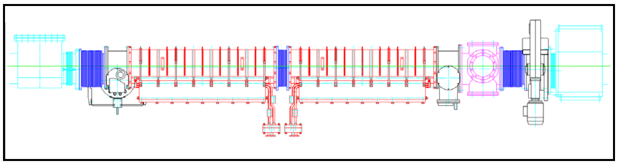

Figure 4: Layout of equipment in SS26 of the U70.

SM26 is sectioned into 2 identical units. Other auxiliary equipment housed in SS#26 (beam diagnostics, vacuum pumps and valves, bellows) was rearranged to a new configuration which also accommodated an universal 3-port docking box (right block in Fig. 4) suitable for inserting diagnostics devices or, say, bent-silicon-crystal deflectors.

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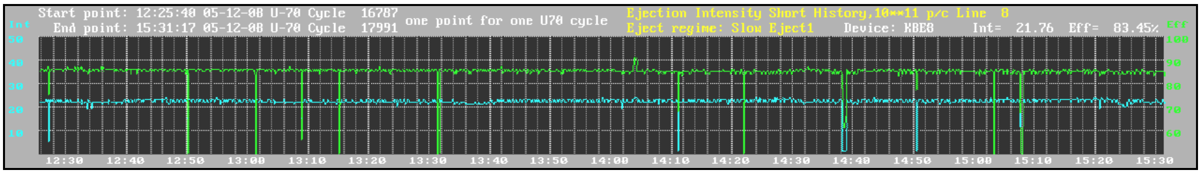


Figure 3: Efficiency factor of slow extraction (90–95%), upper trace. Slowly extracted beam current, lower trace.

Table 1: Four runs of the U70 in between RuPAC-2008 and -2010

Run	2008-2	2009-1	2009-2	2010-1
Launching linac URAL30, booster U1.5 and U70 sequentially	October, 10	March, 10	October, 12	March, 15
Proton beam in the U70 ring since	November, 3	April, 1	November, 5	April, 7
Fixed-target physics program with extracted beams	November, 19 – December, 10, 28 days	April 6–21, 14½ days	November, 12 –December, 9, 25 days	April, 12–22, 10 days
No. of multiple beam users (of which the 1st priority ones)	11 (8)	8 (5)	10 (6)	9 (6)
MD sessions and R&D on beam and accelerator physics, days	9	6 ½	11	7
Light-ion acceleration MD program	December, 10–12, 2 ½ days	April, 21–25, 3 ½ days	December, 11–15, 3 ½ days	April , 24–27, 3 ½ days

Wide-Band Transverse Feedback

It is a fast bunch-by-bunch 1-turn delay feedback employing variable delay line ($\Delta\tau/\tau$ is about –10%) and the "virtual pickup" concept, see Fig. 5. In 2008, the former analogue delay was traded for an up-to-date digital delay clocked at the 16th harmonic of radiofrequency.

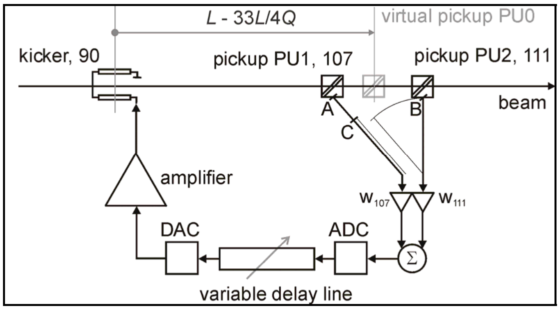


Figure 5: Layout of the wide-band feedback.

A natural byproduct of going to DSP is flexibility in implementation of various feedback algorithms, from linear proportional to nonlinear "bang-bang", sensitive to sign of the beam offset. In practice, an intermediates regime constituting a combination of the two was found most effective with its factor of 50 in shortening decay time of coherent transverse oscillations. Details of the technical solutions adopted by now are reported in [2].

Our intent is to continue efforts in this direction and test a promising one-pickup 3-turn digital delay feedback solution that behaves as a 3-tap periodical notch FIR filter and imposes a purely imaginary coherent tune shift [3].

Intensity of Proton Beam

For the first time in many years, we have run the U70 complex with a high intensity and 29 bunches injected. Here is a summary of beam parameters in the run 2009-1.

Proton synchrotron U70 has achieved operating intensity of 0.7–1.1·10^{13} protons per pulse. Beam top energy is 50 GeV (kinetic). Beam losses over cycle are 2–3%. Bunch length through a cycle is 96 ns (injection) – 17 ns (transition) – 20 ns (extraction). Horizontal beam size is 9–11 mm at 50 GeV. Slow stochastic extraction to beamline #21 to the OKA experimental facility (study of rare kaon decays) yielded 6–9.5·10^{12} protons per a low-ripple 1.4–1.85 s long spill. Booster synchrotron U1.5 has attained top intensity of 5.3·10^{11} protons per a (single) bunch under a very reliable operation (relative idle time 6%). Fig. 6 illustrates operation of the U70.

On going to higher beam intensities, mainly, due to uniform orbit filling patterns involved, we have encountered problems with transition crossing. They were tentatively evaded by switching back the 200 MHz spill cavity that dilutes longitudinal phase volume (notice a kink in the peak-current trace of Fig. 6). Still, efforts were and are being spent to better understand transition crossing with compact bunches (high local density) and work out appropriate working point, betatron resonance- and chromaticity-correction scenarios close to γ_t.

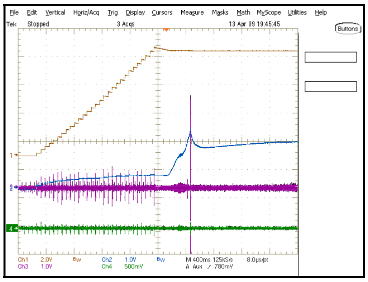


Figure 6: Aaccumulated beam intensity (upper trace, DCCT monitor, 29 bunches) and peak current of beam (second trace). Lower traces show transverse beam offset signals (H/V injection errors).

Slow Stochastic Extraction

Fig. 7 illustrates operation of slow extraction system delivering beam to the OKA experimental facility. It shows both, technological signals acquired in the U70 ring and readouts of front-end counters in the OKA setup proper (courtesy of the OKA team). Distance between these two data acquisition points is around 1 km.

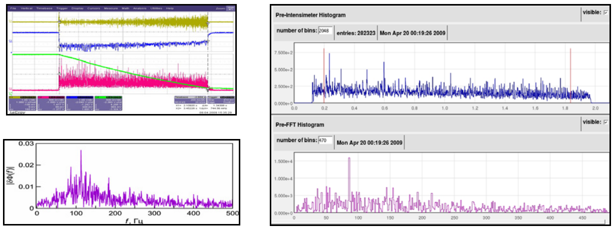


Figure 7: Left, signals from the U70. (1, brown) AM-modulated extraction noise. (2, blue) Feedback signal to modulate noise amplitude. (3, green) Population of waiting beam stack monitored with a DCCT. (4, red) Spill current measured with a BLM in SS#106. (5, purple) Amplitude Fourier spectrum of spill. Right, slowly extracted beam seen at the OKA facility. (1, blue) Spill current. (2, purple) Amplitude Fourier spectrum of spill.

Left-side spill trace (4) in Fig. 7 originates from the beam loss monitor in the ring hall that sees secondary particles emerging due to interception of extracted beam halo by a wire septum of electro-static deflector ESD106. Right-side signal shows intensity of the slowly extracted beam core delivered to the terminal beam consumer.

The data confirms that the U70 now possesses a high-intensity low-ripple long-spill slow extraction system.

Fast Extraction below Flattop

To meet the demand of beam users, we have successfully tested a fast 1-turn extraction of bunches at 50 GeV (B-field 0.8590 T) during a ramp with $dB/dt \neq 0$ and flattop 1.0331 T corresponding to beam energy 60 GeV.

To this end, new cable traces in the ring hall of the U70 were laid that allowed reshaping horizontal closed-orbit bump near deflecting magnets DM62, 64 from a half- to a full-wavelength (cancellation of electromotive force due to $dB/dt \neq 0$ at bump-coil power supply outlets). Beam trace angle at entry to transfer line has required adjusting with a dipole corrector DCH66 (switched polarity).

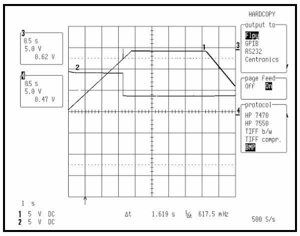


Figure 8: Fast extraction from the U70 during B-field ramp (trace 1). Intensity of circulating bean is shown by trace 2

Fig. 8 shows experimental data. Stability of operation of fast-extraction synchronization (especially, in its updated configuration) and reproducibility of the extracted beam energy was confirmed in runs 2009-1 and 2009-2.

The similar goal — to diversify extracted beams available in a given magnetic cycle of the U70 — was pursued during tests of acceleration with an intermediate plateau of the B-field. The first plateau (flat bottom) at .0.03537 T corresponds to injection energy 1.32 GeV. The second (new) plateau at 0.8590 T accepts 50 GeV beam, while the third plateau (flattop) is at 1.0330 T and 60 GeV.

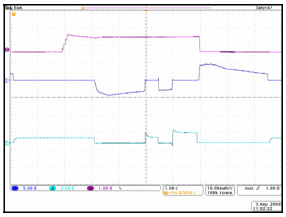


Figure 9: Here and on the right, traces are listed from top to bottom. (1) Beam current (DCCT). (2) Derivative dB/dt, inverted. (3) Feedback signal to stabilize level of plateau.

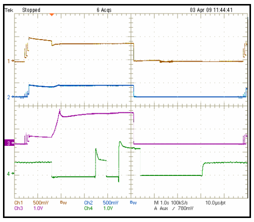


Figure 10: (1) Beam intensity (pickup). (2) Beam current (DCCT). (3) Peak current of bunches. (4) Feedback signal to stabilize level of plateau.

On the one hand, this task constitutes a backup alternative to the on-the-fly fast extraction mentioned above. On the other hand, it set a sound work-pad to Department of Power Engineering Facilities of the U70 to develop and test a new set of tools to control, synchronize and stabilize magnetic cycle, with both 3 and 2 (routine) plateaus.

This regime was safely implemented in the run 2009-1. There were no beam loss observed in course of (a well adiabatic) traversal of the intermediate plateau. Experimental signals acquired from ring magnet supplies and beam monitors are shown in Fig. 9 and 10.

Both the tasks in question related to fast extraction below flattop put forward new options for a more flexible operation of the U70 in the future.

Proton Linear Accelerator URAL30

This machine stands in the start position in the Accelerator complex U70. Its stable operation is crucial to maintain high overall beam availability.

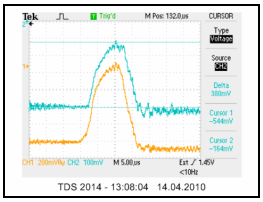


Figure 11: Beam pulse in the URAL30. Pulse current is 25–40 mA.

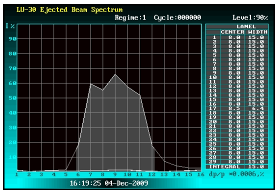


Figure 12: Bunch distribution over momentum at exit from the URAL30.

To maintain stable operation of the proton ion source (duoplasmatron), its vacuum pumping system was renovated. To this end, a pair of new high-tech turbo molecular pumps SHIMADZU 3203LM (speed 3200 l/s (in N_2), 2400 l/s (in H_2)) was mounted. Since then, no failures of ion source due to vacuum conditions were observed. Reproducibility of bunches has improved, witch can ne noticed, say, as a linear slope of the upper, beam accumulation trace in Fig. 6. Fig. 11, 12 show other beam data.

The upgrade plans foresee renewal of pulsed power supplies in the ion gun, of RF powering scheme of the fist two sections, and installing a commercially available subsystem to stabilize temperature of cooling water.

Digital Master Oscillator

A new DDS master oscillator for the U70 proton synchrotron was developed and tested in the run 2010-1. This activity pursues many goals. These are (in priority order):

1. To attain more flexibility in generating "B-field–radiofrequency" law allowing acceleration of protons and light ions with charge-to-mass ratio about ½.
2. To provide a tool for coordinated variation through cycle of gains in radial and phase-frequency feedback loops around the maser oscillator.
3. To introduce, as a routine, bunch-rotation RF gymnastics prior to de-bunching at flattop for prompt control over momentum spread in circulating beam.
4. To introduce a straightforward procedure of bunch smoothing and lengthening with an off-line digitally synthesized and uploaded phase noise samples of accelerating voltage.

All items of this list were beam-tested successfully. The capabilities of the DDS master oscillator are very promising, though an in-depth study of the newly opened options is yet to be completed. Figs. 13–15 present a few experimental results on the items in question.

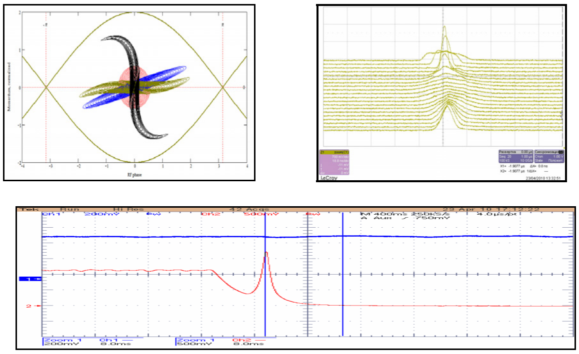


Figure 13: Bunch rotation in the longitudinal phase-plane. Top left – calculation, right– observed "mountain range" display, bottom – peak current of beam. Notice a fast 1.5 ms de-bunching with no symptoms of a spurious re-bunching due to a widened $\pm\Delta p/p_0$.

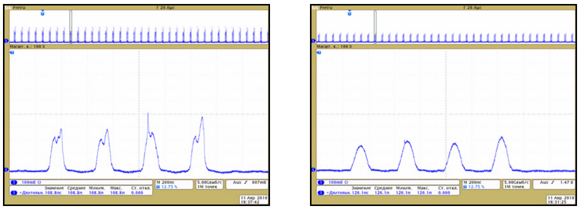


Figure 14: Bunch smoothing and lengthening with external phase noise.

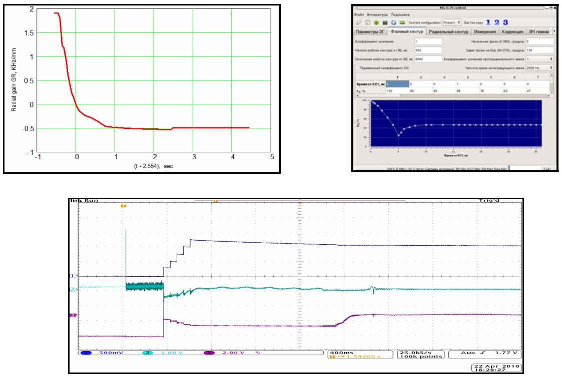


Figure 15: Variable gains in feedback loops. Top left – calculated optimal gain in radial loop for a fixed gain 0.15 kHz/deg in phase-frequency loop, right– its view in a control screen of the DDS MO, sign reversal at transition is implied. Bottom – traces of beam intensity, radial position, and beam phase about RF voltage.

Light-Ion Program

This program proceeds at a steady pace. By the last run 2010-1, deuterons were accelerated to 23.6 GeV per nucleon (kinetic) through a chain of the Г100, U1.5, and U70 proper. Chronology of the progress is reported in [4].

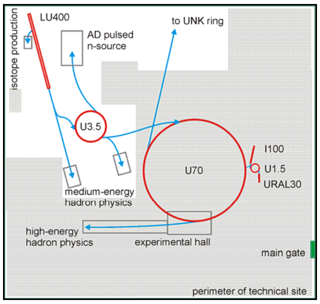
Crystal Deflectors

These types of beam transverse deflectors are extensively employed for routine technological purposes and in a dedicated R&D program accomplished with beams of the U70. Ref. [5] reports on details of this activity.

AC-IHB

Generalities

This acronym stands for Accelerator Complex of Intense Hadron Beams. It is a multi-purpose mega-project discussed at IHEP now [6]; refer to Fig. 16. The proposal offers a long-range plan to develop accelerator and experimental facilities on the IHEP grounds for fixed-target research, within and beyond elementary particle physics.



Area of a dense civil engineering and utility infrastructure existing is shadowed. Blue arrows show directions of beam transfer.

Figure 16: Layout of the AC-IHB facility.

The base-line design foresees construction of a pulsed facility having more than 1 MW of proton beam average power, a pulse rate of 25 Hz, pulse width ≤ 1.5 µs, clear staging, site-specific integration and upgrade plans, and a reduced technical risk (use of proven technologies).

The facility comprises a non-SC 400 MeV linear accelerator LU400 followed by a 3.5 GeV rapid cycled proton synchrotron (RC PS) U3.5.

Staging

A particular stage of the project addresses either applied or fundamental science (see Fig. 16).

Stage-1 assumes construction of a short-pulse accelerator-driven 1 MW neutron source for applied research (material and life sciences).

Goal of the next stage-2 is to develop the second direction of fast extraction from the U3.5 to feed a new experimental zone dedicated to intense-beam medium-energy hadron physics.

At a later stage, the U3.5 is engaged as a new injector to the existing U70 PS, or its updated successor. To this end, orbit length and RF harmonic number of the U3.5 amount to 3/10 of those in the U70. It facilitates, at most, a 3-train bunch-to-bucket transfer from U3.5 to the U70 ring thus yielding a beam pattern 3 × (9 filled + 1 empty) bunches there. Apart from the lower-energy mode of a 3.5 GeV proton beam stretcher delivering slow spills, the U70 will accelerate intense beam to higher energies.

This staging does not intervene drastically into the present operation of the URAL30(I100)/U1.5/U70 chain. Even more, at stage-0, the existing machines will be beam test benches and pilot consumers of the key project-related technologies (like source of H^- ions, RFQ linac, stripping-foil insertion, ferrite-loaded RF cavities, etc).

RC PS U3.5

Core of the AC-IHB project constitutes a new 3.5 GeV rapid cycled proton synchrotron U3.5 ramped at 25 Hz (sinusoidal) and yielding $7.5{\cdot}10^{13}$ ppp. Other specifications of the machine are listed in Table 2.

Table 2: Specifications of U3.5 (project)

Energy (kinetic), E	0.4–3.5	GeV
Orbit length, L	445.11	m
Curvature radius, ρ	15.28	m
Magnetic rigidity, $B\rho$	3.18–14.47	T·m
Compaction factor, α	0.0173	
Transition gamma, γ_t	7.60	
Intensity, N	$7.5{\cdot}10^{13}$	ppp
Ramping time, t_R	0.020	s
Cycle period, T	0.040	s
Average beam current	300	μA
Beam power, P	>1	MW
RF harmonic, h	9	
Radio frequency, f_{RF}	4.322–5.925	MHz
Net RF voltage, V_{RF}	720	kV/turn
Lattice period	FODO(90°)	
No. of periods	36	
No. of super periods	6	
Betatron tune (H/V)	9.15/7.20	

A multi-turn (145 turns around) charge-exchange injection into the RC PS U3.5 is performed at 400 MeV from a new linear accelerator LU400 (H^-, 40 mA).

Lattice of the U3.5 is based on a synthesis of a plain FODO stricture, “missing dipole” and “quadruple-bent achromat” (QBA) concepts with 6 dispersion-free straights half-the-ring long totally, Fig. 17.

The lattice has 24 dipole magnets (length 4 m, field 0.95 T, and gap 150 mm). There are 72 identical quadrupole lenses (length 0.6 m, gradient < 5.6 T/m, and bore radius 102.8 mm). The quads are arranged into three families (36 QF, 30 QD, and 6 QD1 at arc mid-points).

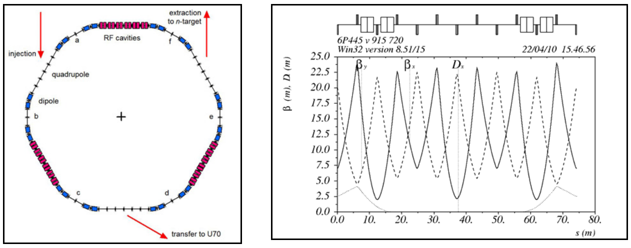


Figure 17: Backbone equipment and optical functions of the U3.5 RC PS ring.

Aperture margin is set at a conservative ±4σ level. The betatron acceptance is about 660/160 π·mm·mrad (horizontal/vertical). Momentum acceptance is ±3.1% (pencil beam), or ±1.6% (full beam).

Coulomb tune shift at injection is –0.08/–0.15 (horizontal/vertical).

Protons are accelerated by 36 two-gap ferrite-loaded cavities yielding 20 kV peak voltage each. An RF station occupies < 2.5 m of a dispersion-free straight flange-to-flange. Stable phase angle is ≥ 55–56° (cosine convention). Estimated power consumption is around 130 kW per a cavity. Beam loading factor (ratio of beam fundamental RF harmonic to peak current through shunting resistance) is 3.8 ca, which is manageable.

Outline for other subsystems is being elaborated, [6].

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. To maintain and develop expertise available at IHEP in hadron beam accelerators and experimental physics, a new AC-IHB project is put forward and is under development.

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