ACCELERATOR COMPLEX U70 OF IHEP-PROTVINO: STATUS AND UPGRADE PLANS

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Abstract

Accelerator complex U70 of IHEP-Protvino now comprises four machines cascaded plus one operated in a stand-alone mode. These are 30 MeV RFQ DTL proton linac URAL30 – the standard proton injector, Alvarez DTL linac I100 – the 16.7 MeV/nucleon light-ion and/or backup 72.7 MeV proton injector, the 6.9 T·m rapid cycled booster synchrotron U1.5, and the 233 T·m main ring synchrotron U70 proper. The new 30 MeV proton linac URAL30M, the would-be modernized successor to the URAL30, is being pre-commissioned on a separate technical site. This report outlines current status of the entire accelerator complex and ongoing upgrade activity which is aimed at improving proton beam quality and step-by-step accomplishing the program to accelerate light-ion beams for applied and fundamental research.

GENERALITIES

Layout of accelerators is shown schematically in Fig. 1, their parameters being listed in Tables 1 and 2. Alvarez linac I100, the former proton-injector to the U70 since its early days till 1985, is engaged back in service since December 2007. Now, it runs as either a backup proton-, or a light-ion-injector feeding the U1.5 ring.

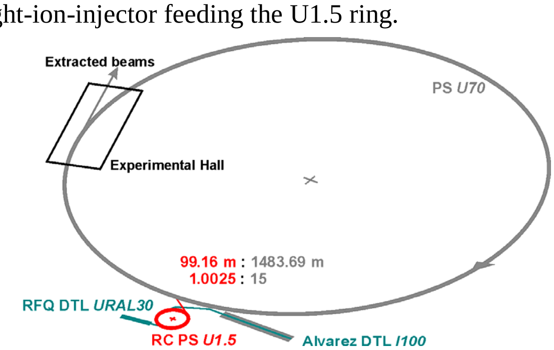

Figure 1: Schematic view of the IHEP accelerators.

Major efforts are invested to attain the three goals:

1. to ensure stable operation and high beam availability during the regular machine runs,
2. to improve proton beam quality (by going to lower emittances and higher intensities, up to $3{\cdot}10^{13}$ protons per cycle, ultimately), and
3. to implement gradually a program to accelerate light ions with a charge-to-mass ratio q/A = 0.4–0.5 ca.

Generally, the trend is to convert the largest national facility U70 into a universal hadron accelerator fit for ongoing applied and basic fixed-target research.

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Table 1: Specification of proton synchrotrons

	U1.5	U70	
Energy, E	0.030–1.32	1.32–69	GeV
Orbit length, L	99.16	1483.699	m
Curvature radius, ρ	5.73	194.125	m
Magnet rigidity, $B\rho$	0.80–6.87	6.87–233	T·m
Compaction factor, α	0.07235	0.011120	
Intensity, N	$2–9{\cdot}10^{11}$	$1.4{\cdot}10^{13}$	ppp
Ramping time, t_R	0.030	2.75	s
Cycle period, T	0.060	9.77	s
RF harmonic, h	1	30	
Radio frequency, f_{RF}	0.75–2.75	5.52–6.06	MHz
RF voltage, V_{RF}	6–60	190–300	kV
Lattice period	MFDFM	FODO	
No. of periods	12	120	
No. of super periods	12	12	
Betatron tune (H/V)	3.85/3.80	9.9/9.8	

Table 2: Specification of proton linear accelerators

	URAL30	I100	
Type	RFQ DTL	Alvarez DTL	
Energy, E	0.1–30	0.7–100	MeV
Length, L	25.3	79.4	m
Radio frequency, f_{RF}	148.5	148.5	MHz
Pulsed current, I	70	100	mA
Pulse length, t_P	1–10	12–40	µs
Cycle period, T	0.060	1–5	s
Sectioning	5	3	tanks

ROUTINE OPERATION

The U70 complex is used to run once/twice a year for 1000–1500 hr per a run. Dedicated machine development (MD) activity takes a week prior to delivering beam to experimental facilities. For the time being, top energy is compromised to 50 GeV. It is still acceptable to beam users but noticeably minimises overall electrical power consumption (–20% ca) thus making the runs affordable.

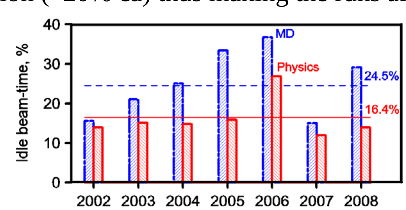

Figure 2: Beam availability statistics.

Fig. 2 shows beam availability data during the MDs and runs for a fixed-target physics with averages over 2002–7. Experimental facilities acquire the beam with availability 83–84% which is an outcome of an extensive routine maintenance carried out between the runs. Surge of idle beam-time during MD of the 1st run in 2008 is due to efforts diverted for the first successful attempt to accelerate deuterons (q/A = 0.5) through the I100 and U1.5.

PROTON BEAM

The top priority was set to improving longitudinal and transverse feedback circuits already available in the U70.

Longitudinal

The scope of feedback circuitry around the RF system is shown in Fig. 3, [1]. In 2006–7, all the 40 RF ferrite-loaded cavities installed got their voltage amplitude loop *A* and resonant-frequency tuning loop *T* modernized. Up-to-date circuit and hardware solutions were implemented so as to ensure a more robust control over voltage and frequency programs through a cycle, extend accessible dynamic tuning ranges, eliminate loop-to-loop cross-talk, and improve reliability of electronics. To this end, say, amplitude control path got closed-loop bandwidth extended from 3 to 50 kHz (at –3 dB) and 0.2–10 kV dynamic tuning range, instead of the former 1–10 kV span.

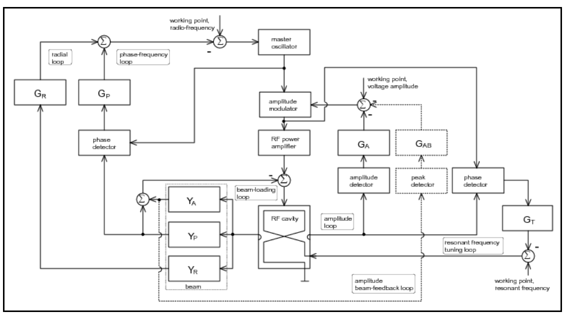

Figure 3: Feedback circuits in RF system of U70.

Since frequency of unwanted coherent bunch-length oscillations in the U70 varies from 2.8 to 0.2 kHz, extended bandwidth of voltage control now offers a straightforward way to close the amplitude beam-feedback loop *AB*, see Fig. 3. This circuit was readily tested with beam in the 1st run of 2008. By the 2nd run, a 2-channel option of the *AB* feedback (servicing beam below and above transition distinctively) will be put into test operation.

During beam dynamics studies in 2007, harmful interference of bunch peak-current signals into phase-detector readouts in the phase-frequency loop *P* was cured by toughening the front-end signal filtering.

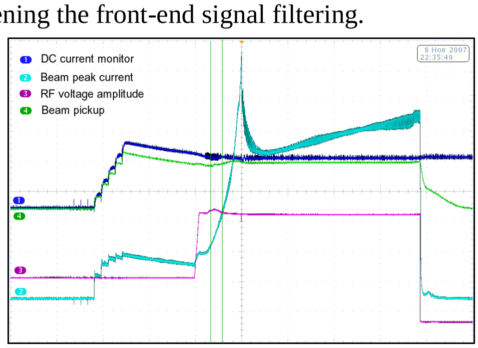

Figure 4: Experimental oscillograms. Horizontal scale is 400 ms/div.

All the efforts mentioned have drastically improved robustness of control over beam longitudinal motion. Bunch-length evolution is now close to a perfect adiabatic law (see ray *2* in Fig. 4). Bunch data at top energy 50 GeV is listed in Table 3. Unjustified longitudinal dilution through cycle was restrained resulting in an apparent (virtual) 5-fold squeezing of bunch longitudinal phase area.

Table 3: Bunch data at 50 GeV

	≤ 2006	2007–8	
Bunch length, τ_B (FW@0.9)	36	12–15	ns
Momentum spread, $\Delta p/p$	±1	±0.4–0.5	$\cdot 10^{-3}$

It is worth mentioning that peak power *P* transported by such a (matched) bunch reaches the Tera-Watt range. Indeed, assuming a parabolic longitudinal distribution,

$$P = 3N_B E/2\tau_B = 0.4-1\ \text{TW} \qquad (1)$$

for N_B = 5–9·10^{11} ppb and *E* = 50–70 GeV.

Given a shortened bunch, a 165 ns long RF bucket at 50 GeV flattop offers enough room for exercising coherent beam RF gymnastics to compress the bunches further. In 2008, this scheme was beam-tested and is about to be implemented in a new VCO design. Effect of RF voltage on beam is "toggled off/on" by a fast jump to an offset RF value, +40 kHz to the nominal 6.06 MHz value, and back. Computed and observed results for synchrotron frequency 100 Hz, τ_{B0} = 30 ns, drift = 5 ms, rotation_1 = 0.5 ms, rotation_2 = 3 ms are plotted in Fig. 5. Extremes of the phase ellipse vary in the course of 5.5–8 ms within

$$\tau_B = (K - 1/K)\tau_{B0}\,; \qquad \Delta p/p = (1/K - K)\Delta p/p_0 \qquad (2)$$

with a feasible compression factor *K* = 3 for τ_{B0} = 15 ns. Thus, peak power *P* from Eq. 1 can at least be tripled for a mismatched bunch, Eq. 2. A prompt control over $\Delta p/p$ of the coasting beam at flattop is can be gained as well.

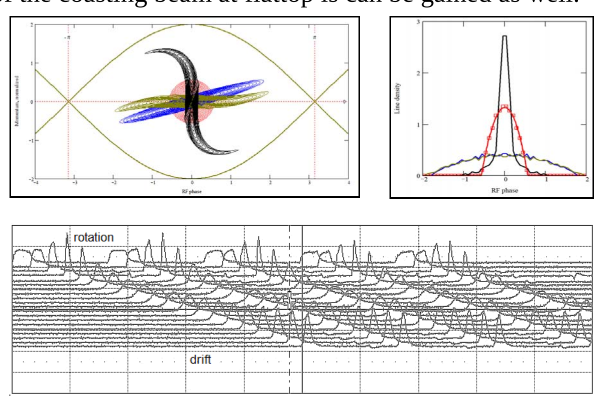

Figure 5: Bunch rotation in the longitudinal phase-plane. Top – calculation, bottom – observed "mountain range" display with a scan-to-scan delay 0.5 ms.

Transverse

The former narrow-band low-pass transverse feedback system [2] was initially tailored to compensate for a resistive thin-wall deflecting impedance $Z(\omega) \propto 1/\omega$ near DC (wall thickness Δ = 0.3 mm). By now, the thin vacuum chamber in the U70 ring was replaced with a thick-wall one (Δ = 3 mm). It hampered the prescribed operation of the circuit as the thick-wall's $Z(\omega)$ turns out $\propto -i/(-i\omega)^{1/2}$.

In 2007, the feedback circuit was renovated, its actuator part comprising HV electrostatic kicker (*E*-field integral ± 35 kV) and high-power low-pass amplifier (bandwidth

0–0.2 MHz) being left intact. Design goal was to dampen out the 10th azimuthal harmonic of resistive-wall instability as strong as possible.

Advantage was taken of the amplifier being housed close to kicker and one of two beam pickup electrodes involved sharing the same period #2 of the lattice. Given such a local layout, inherent time delay for signal processing is very short and spatial dispersion is negligible. Quadrature phase shift between pickup beam-coordinate readout and kicker beam-angular correction is imposed with a cascade of two integrators (cut-off frequency 35 kHz at –3 dB). Rejection of a DC signal due to closed-orbit distortions is performed with a high-pass differentiator (roll-off frequency 0.5 kHz at –3 dB). Higher harmonics of rotational frequency 183.7–202.0 kHz are naturally filtered out by the 2 low-pass integrators themselves.

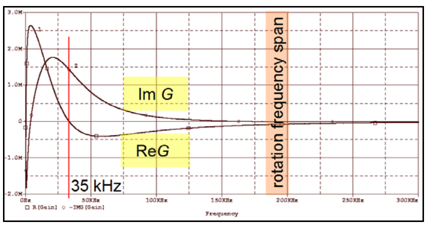

Figure 6: In-out transfer function *G* of the low-level signal processing electronics.

The resultant transfer function *G* is plotted in Fig. 6. Horizontal and vertical channels are identical. There is no need to vary system parameters during cycle: even in the hardest case of horizontal oscillations phase deviation of correction stays within safe ±π/4 w. r. t. the π/2-optimum.

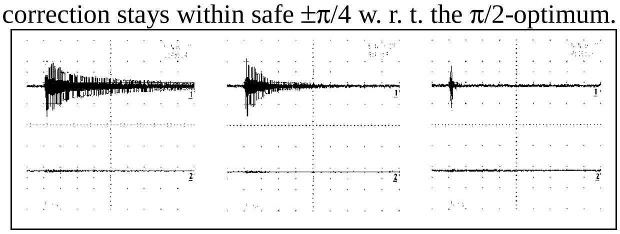

Figure 7: Damping of horizontal oscillations. Feedback gain increases from left to right, starting from 0.

Closing the feedback loop resulted in a fast decay of transverse oscillations, see Fig. 7. Extra damping factor observed is around 100 w. r. t. a natural decay time due to de-coherence of betatron motion.

In a routine operation of the U70, patterns of orbit filling with bunches are commonly non-symmetric. Bunch-to-bunch eigenmodes for such a beam are not necessarily orthogonal to the 10th azimuthal harmonic of coherent perturbation. Therefore, the narrow-band low-pass feedback in question sees and dampens a wide scope of coupled-bunch modes. In other words, its stabilizing effect observed has definitely exceeded design expectations.

Extraction

First, feasibility tests for an advanced slow stochastic extraction (SSE) scheme at the U70 were performed in 2004 [3]. In those SSE tests, the so-called natural stochastic spills were obtained and recorded, being imposed by RF noises with their power spectra kept invariant through time of extraction. Such spills had inherently no flat-top in their DC content and, therefore, were yet unfit to be supplied to beam consumers.

Efforts were continued in 2005–6 towards approaching an operational grade of the SSE scheme. A dedicated circuitry has been developed and beam-tested [4]. The core of the system constitutes a feedback loop that modulates amplitude of the operational noise in response to spill current signal monitored with a beam loss monitor located downstream of the electrostatic septum deflector. Being a DC-coupled feedback with a finite base-band bandwidth, the system developed deemed to both, flatten and smoothen the stochastic spills.

This activity succeeded in a well prescribed operation of the SSE setup. The primary design goal to obtain low-ripple flat-toped spills lasting 2–3 s was achieved as shown in Fig. 8. A noticeable progress in quality of slow spills has been recorded. The persistent AC ripple observed in extracted current now shows up as a random signal. It was found to be insuppressible via the feedback control employed due to a limited base-band bandwidth of the 3rd order transverse resonance transfer function involved in the overall closed-loop gain product.

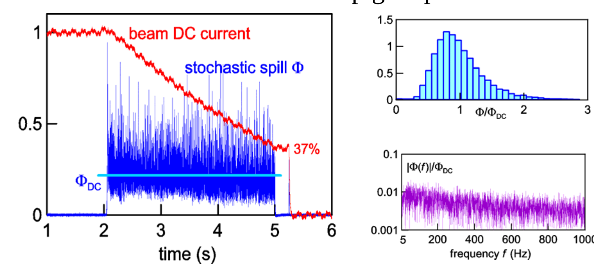

Figure 8: Beam DC current and spill current Φ. 63% of waiting beam is extracted in 2.9 s (left). Histogram of spill ripple magnitude distribution about the average value of spill current Φ_{DC}, recorded at a 50 kS/s rate. Its σ = 0.40 and spill duty factor $\langle\Phi\rangle^2/\langle\Phi^2\rangle = 0.86$ (top right). Amplitude Fourier spectrum of the spill ripple. It is rather continuous and free of discrete lines due to the mains harmonics (bottom right).

The entire run of the U70 in 2006 was routinely serviced by the SSE setup in question yielding 1.1 s long slow spills. The scheme exhibited a robust and reliable behavior compliant to the design fore-thoughts.

Further elaborating of the SSE setup at the U70 is planned and promises a better machine functionality for external fixed-target experiments in the future.

DEUTERON BEAM

The goal to accelerate light-ion beams in the U70 complex is being pursued step-by-step.

To this end, first, the existing Alvarez DTL I100 is being revitalized. By now, its 3rd tank is no longer fed with RF power. Instead, it is employed in a beam-transport mode with the DT-lenses powered. In such a layout, the facility can yield either 72.7 MeV protons (at a 2π-mode), or 16.7 MeV/nucleon light ions with q/A = 0.5 (a 4π-mode) [5]. The first option is treated as a backup proton injector supplying a test proton (p) beam with magnetic rigidity 1.26 T·m that is close to $B\rho$ = 1.19–1.18 T·m of the reference ions $_2H^{1+}$ (d) and $_{12}C^{6+}$.

It was found experimentally [5] that d-beam (q/A = 0.5) is safely captured to the I100 starting from the 5th gap, on having passed through a 570 keV electrostatic fore-injector. Since the top feasible value of HV is 750 kV, ion species with $q/A \geq 0.4$ can only be accepted. This restraint on the charge-to-mass ratio complies with a +20% safety margin available to force up the DT-lenses. Therefore, the design goal is set to accelerate ions with q/A = 0.4–0.5 ca.

Many efforts are spent for a routine maintenance of technological subsystems of the aged I100, its beam diagnostic and control equipment is being gradually renewed. A fast chopper with 10 ns fronts was integrated into ion gun. A 3 m long base available between the gun and a Faraday cup allowed for TOF spectrometry to monitor technical status of duoplasmatron judging by amount of heavier ion species in the beam. As a pay-off, in the 1st run of 2008, the facility yielded a 16.7 MeV per nucleon beam of d with pulsed current 15 мA in 5 μs long pulses.

By 2006, the 43 m long beam transfer line from I100 to U1.5 was installed, see Fig. 9, left. It crosses the basement wall between two buildings, comprises 4 bends, 8 lenses, 3 H/V correctors, and a set of beam diagnostic devices (mostly, scintillation screens and current transformers). The BTL was commissioned with protons (72.7 MeV, 17.11.06) and deuterons (16.7 MeV/nucleon, 01.12.06).

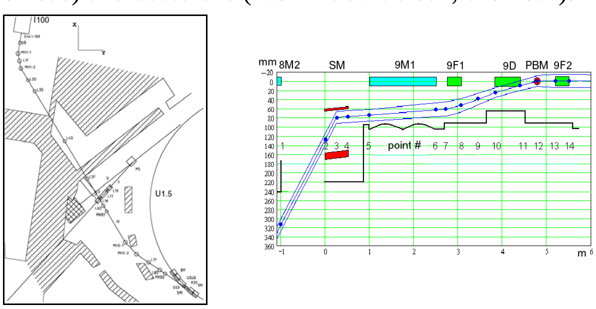

Figure 9: Beam transfer line I100/U1.5 (left). Injection into period #9 of the U1.5 lattice (right).

Significant efforts were directed to reassemble period #9 of the U1.5 lattice (Fig. 9, right) and update other equipment of the machine. To this end, a wider-aperture dipole 9M1 with a new vacuum chamber was installed. To free the room, one RF cavity of 9 was taken away and is now stored as a spare unit. 177 mrad septum magnet SM followed by 23 mrad pulsed bump magnet PBM with their power supply units were mounted. A new DDS RF master oscillator and extra capacitive loads to 8 remaining RF cavities were installed to accommodate to the RF lowered from 0.75 to 0.56 MHz. Sensitivity of beam diagnostics was raised, though partially as yet. Consequently, the following major milestones were accomplished:

1. 10–12.12.07; p; 72.7–1320 MeV; $3{\cdot}10^{10}$ ppb; 35% transmission through the U1.5.
2. 29–30.03.08; d; 16.7–455 MeV/nucleon; $3{\cdot}10^{10}$ ppb; 34% transmission through the U1.5, see Fig. 10.

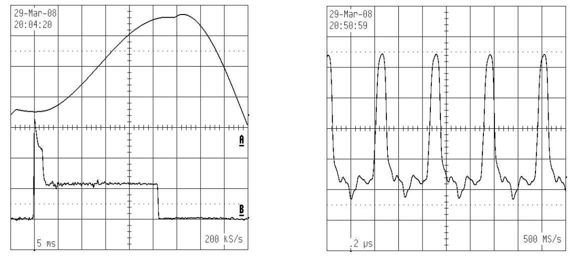

Figure 10: Magnetic guide field (ray A) and signal of deuteron beam from DCCT in the U1.5 (ray B) (left). Deuteron bunch at 1.18 T and RF 2.212 MHz (right).

Overall data of the first successful attempt to accelerate deuterons through I100 and U1.5 is compiled in Table 4.

Proton beam from I100 has to be conditioned. Deuteron beam exhibits an acceptable quality, its intensity being close to the design value. Beam capture efficiency is low due to an excessive $\Delta p/p$ of beam injected. A possibility to install a debuncher cavity will be considered. A two-turn injection from I100 to U1.5 is to be assessed as well.

CONCLUSION

Accelerator complex U70 of IHEP-Protvino readily ensures running the fixed-target physics program, has noticeably improved quality of proton beam, and is on a way towards accelerating light-ions to 34 GeV per nucleon.

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Table 4: Overall status of I100, BTL I100/U1.5 and U1.5 in the 1st MD run of 2008

@	Exit from I100	Exit from BTL	1st turn	Circulation	Start of ramp	Extraction
p, 72.7–1320 MeV	48 mA	20 mA	15 mA	$8.2{\cdot}10^{10}$	$6.7{\cdot}10^{10}$	$1.5{\cdot}10^{10}$
TOTAL:	$3.0{\cdot}10^{8}$ $p_{U1.5}/mA_{I100}$, IN–OUT$_{U1.5}$ = 18%					
d, 16.7–455 MeV/u	15 mA	9.6 mA	8 mA	$8.8{\cdot}10^{10}$	$8.1{\cdot}10^{10}$	$3.0{\cdot}10^{10}$
TOTAL:	$2.0{\cdot}10^{9}$ $d_{U1.5}/mA_{I100}$, IN–OUT$_{U1.5}$ = 34%					