STATUS OF U-70 OPERATION AND UNK PROJECT

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1. U-70 operation, improvement and problems.

IHEP 70 GeV Proton Synchrotron (U-70) was put into operation on 14-th of October 1967 [1,2,3]. Its present configuration is shown in Fig. 1.

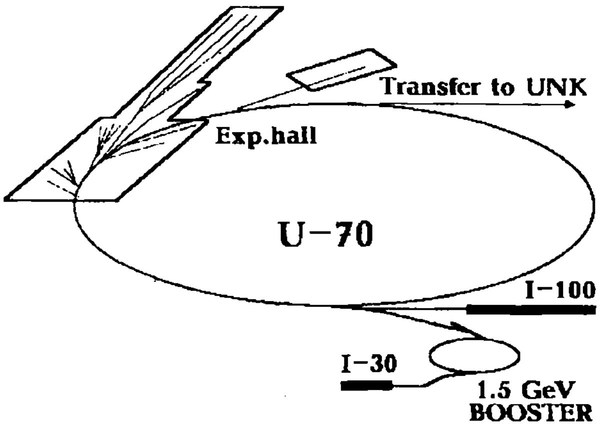

Fig. 1. Layout of U-70 Proton Synchrotron.

Accelerator complex includes 70 GeV proton synchrotron and 1.5 GeV fast cycling booster with injection from 30 MeV RFQ linac I-30. The 100 MeV linac I-100 has served as injector before 1985, now it is used only in application tasks.
Main parameters of U-70 and the booster are shown in Tables 1 and 2.
The accelerator improvement during 30 years of U-70 operation is illustrated by the most important events:

1968. First experiments started using secondary particles generated on internal targets. Project value of beam intensity (1.10^{12} ppp) was achieved by October.
1970. 2 s flat top is introduced in the magnetic cycle.
1971. Intensity 2.10^{12} is achieved using single turn injection.
1972. Fast extraction system was installed in the frame of the collaboration with CERN and put into the operation.
1973-76. 5 turn injection was realized resulting in max. intensity 5.10^{12} ppp. Up to 5 experiments were carried out simultaneously.
1974-80. Creating and investigation of stopband correction system.
1975. Start of construction of the 1.5 GeV booster.
1979. Slow extraction system was put in the operation.
1981. The intensity was raised to record level with 100 MeV injection ($5.6.10^{12}$ ppp). Acceleration system was replaced by new one to prepare for operation with the booster.
1983. Acceleration of beam at the booster.
1984. First 70 GeV beam at U-70 with injection from booster.
1988. U-70 max. intensity $1.75.10^{13}$, not overcome yet.
1989. The U-70 upgrading program was developed.
1992. First extraction of U-70 beam by bent crystal.

Fig.2 shows variation of U-70 maximum operational intensity, shut-down percentage and annual scheduled time. Before 1992 the typical annual schedule foresaw 5 accelerator runs, each of ~900 hours. About 180 hours of each run was usually spent for switching the accelerator on and for its development.
Starting from 1992 the annual operational time was shortened to 2000 hours or even less due to high cost of electricity.

Table 1. U-70 main parameters.	
Maximum energy	70 GeV
Orbit length	1483.699 m
Maximum field	12 000 Gs
Injection field / energy	353 Gs / 1.32 GeV
Focusing type	comb.funct. FODO
Number of magnets	120
RF harmonic number	30
RF frequency	5.51-6.06 MHz
RF voltage	max. 400 kV
Betatron frequencies h/v	~ 9.8 / 9.85
Transition energy	8.89 GeV
Repetition rate	1/9.3 s
Injection filling time	1.8 s
Acceleration time	3 s
Flat top	2 s
Power consumption	15 MWt mean

Table 2. Booster main parameters.	
Maximum / operational energy	1.5 /1.32 GeV
Orbit length	99.16 m
Maximum field, design/operat	13.1 /12 k Gs
Injection field / energy	1.39 kGs / 30 MeV
Focusing type	sep.func. B-FDF-B
Number of periods	12
RF harmonic number	1
RF frequency	0.75-2.8 MHz
RF voltage	max. 60 kV
Betatron frequencies h/v	~ 3.92 /3.73 (inj.)
Transition energy	3.6 GeV
Repetition rate	16.6 Hz, 29 booster pulses per one U-70 cycle
Injection	multiturn
Acceleration time	30 ms

Intensity limitations. Typical accelerator run can be characterized by such figures:
Linac beam current 40-70 mA at 6 μs pulse duration; efficiency of booster 4 turn injection - 70% ; capture and acceleration efficiency at the booster - 70%, efficiency of beam transfer to U-70 95%; efficiency of

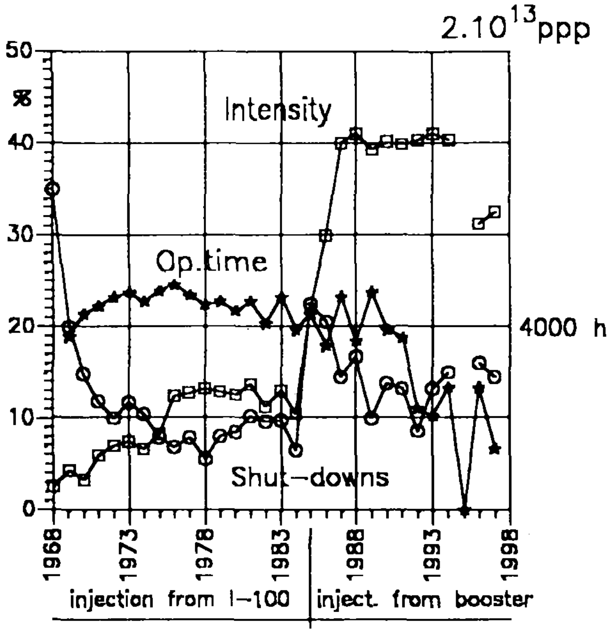

Fig. 2. Statistics of U-70 operation.

storage of 29 booster pulses at U-70 injection flat porch- 85 %; efficiency of acceleration at U-70 - 95 %. The booster acceleration efficiency strongly depends on the Linac beam momentum spread which has to be periodically measured and tuned. Efficiency of multiturn injection and capture at the booster is restricted by dynamical acceptance (about 250 mm. mrad) which is much smaller than geometrical one (450 mm.mrad) determined by vacuum chamber geometry and closed orbit distortion (±10 mm). That is why significant increase of booster beam intensity requires improvements of injection system.
Booster magnetic field quality is quite good and only closed orbit and half-integer stopband have to be corrected during high intensity operation.
Neither transversal nor longitudinal instabilities are observed at intensity level achieved up to now (9.10^{11} proton/booster cycle).
85-90% of beam injected into U-70 are accelerated up to the maximum energy. One of the reason to loss particles during accumulation is bad quality of the pulse of injection kicker (too long rise time and large ripples during the pulse).
Best results for U-70 intensity ($1.75.10^{13}$ ppp) were achieved in 1988 . This intensity limit was determined by two reasons: 1) the lack of intensity supplied by booster; 2) several longitudinal effects before transition. One of them was dipole coupled bunch instability (often accompanied by quadrupole oscillations). The impedance causing this instability was impedance of accelerating cavities which had the frequency dependent feedback and hence asymmetric resonance curve. Switching the feedback off made acceleration much more stable (though it was a temporary solution). Injection with phase mismatch helped to stabilize the beam as well. Another important effect was ~6 GHz microwave instability near transition due to interaction of the beam with corrugated vacuum chamber. The instability led to increasing the longitudinal emittance by factor 3-4. This case aperture limitations could cause the beam losses. However the programming of RF amplitude to match the beam during γ_{tr}-jump, correction of closed orbit and tuning the chromaticity allowed to cross transition with no loss at this level of intensity.

Technical state of accelerator.
During 30 years of operation about 45.10^6 magnetic cycles were generated. Large mechanical strengths and irradiation (especially in extraction region) led sometimes to damage of accelerator components. The most unreliable elements are correcting pole face winding with epoxy insulation. 20 "pancakes" were damaged. Now significant amount of such coils is manufactured and mounted on the magnet.
Motor-generators of main power supply system are suffered from cycling mechanical stress resulting in appearance of chinks in the rotor body. Repair was made and smooth switching of main rectifiers was introduced to dump shocks. As a result no new damages were observed last 10 years.
Booster synchrotron after 13 years of operation is quit stable and reliable machine, though some systems need to be modified.
Taken into account the requirements of physical experiments and the future operation of U-70 as injector for UNK the program of U-70 improvement was developed. The goal of the program is to increase the U-70 intensity by 5.10^{13} ppp and to improve reliability.
Main point of the program and its status up to now is as follows.
1. Charge exchange injection into the booster.
Prototype of H^- source is tested. Injection magnetic system is manufacturing.
2. Creation of new 60 MeV injector (30 MeV-first stage).
1-st (of 4) section (1.8 MeV RFQ) is ready and provides 120 mA beam. 2-nd section (7 MeV RFQ) is under testing.
3. Modifying the booster magnet power supply in order to avoid spikes in magnetic cycles and improve the reliability. The modifying needs some additional equipment (transformers, new condenser battery etc.)

All thyristor switches are now replaced by new based on modern components.
4. Modifying the booster - U70 beam transfer kicker magnets. At the present is under consideration.
5. Replacement of U70 corrugated vacuum chamber by smooth one.
Finished in 1996. In 1998 year all old rough pumping stations were replaced by oil free pumps.
6. Creation of new closed orbit measurement system.
Created at collaboration with CERN. In operation since 1996.
7. Decreasing the coupling impedance of accelerating system.
First stage - increasing the gap capacitance - was realized and tested. Needs some changes. Will be satisfied up to intensity 3.10^{13} ppp. Some measures must be taken to prevent parasitic bunching at 70 GeV flat top (RF feedback or instability damping system).
8. Improvement of electronics.
New equipment for radial and phase servo-control is near to be completed.
9. Improvement of accelerator control system (in collaboration with CERN). Top level is close to be finished. All booster systems are now controlled by new system. Other systems are in preparation stage.
10. Modifying of U70 magnet power supply (elimination motor - generators and replacement them by direct supply from mains)
The main problem is to buy transformers for power supply system.

The replacement of vacuum chamber led to significant change in beam behavior. Bunch width near transition becomes 1.5 times shorter and no indications on microwave instability were observed. Instead of them a strong quadrupole in-phase oscillations appeared starting at ~ 150 ms before transition and living by the end of cycle. Result of the instability was beam losses. The most likely reason for the instability is parasitic sensitivity of PLL phase probe for bunch shape. We hope to avoid the instability with new PLL electronics which is now under construction. As a temporary solution the bunch dilution was used with the help of 200 MHz active cavity (RF amplitude ~100 kV) switched on ~200 ms before transition (fig. 3). Dilution was achieved as a result of some tens of resonant interactions of beam and RF field when the ratio [200 MHz/(revolution frequency)] crosses integer values. Longitudinal emittance increase by factor 3 was achieved with this method providing stable operation at intensity more than $1.3.10^{13}$ ppp.

Operation of ejection systems. The following systems are now used at U-70 for beam ejection:
1.System for single turn fast ejection of arbitrary number of bunches (from 1 to 29).

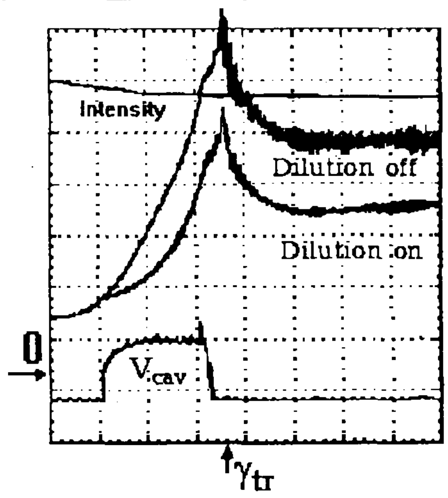

Fig. 3. Example of bunch dilution by 200 MHz cavity. Horizontal scale-100 ms/div. Vcav-cavity voltage. Peak detector curves illustrate max. bunch density with and without dilution. γ_{tr}-transition energy. "0" indicates zero level for peak and intensity curves.

2. Slow resonant extraction with extraction time up to 1.7 s.
3. Extraction of secondary particles generated on internal targets.
4. Slow extraction of protons elastically scattered by internal targets (diffractive extraction)
5.Slow extraction of protons by means of bent monocrystal.

Typical modes of extraction systems operation are shown in Fig. 4. In mode A the fast extraction operates in the beginning of flat top followed by targeting in parallel with diffractive and crystal extraction. In mode B the flat top is been divided between slow extraction and targeting, fast extraction can be used as well.
Existing extraction systems allow to carry out up to 7 experiments simultaneously.
Consumed intensity is typically $1.3\text{-}1.5.10^{13}$ for fast extraction, no more than 8.10^{12} for slow extraction and 2.10^{12} for targeting.

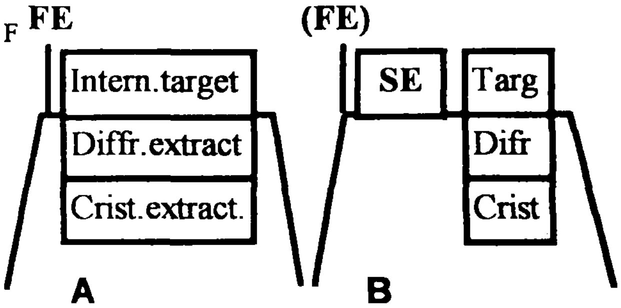

Fig.4. Typical modes of extraction systems operation.

Diffractive extraction covers the intensity range 10^6-10^{10} ppp. Main advantage of this method is very good quality of time structure owing to use the thin carbon film as a scattering target.
Efficiency of slow extraction is now about 85%. Time structure is good at small intensity but becomes dramatically worse with increase of its value. This effect is caused by "selfgrouping" of debunched beam due to its interaction with accelerating cavities. Significant improvement in time structure was achieved when the method of phase displacement was introduced [4]. The method includes two stages: 1) widening the beam momentum spread by means of 200 MHz cavity driving by frequency modulated generator; 2) pushing the beam trough empty 200 MHz buckets. In experiments this method showed good results by the intensity 10^{13}, in real operation only half of this figure is reliable limit.
Beam extraction by bent crystal is in operation at U-70 since 1982. Extraction efficiency is of the order of 10^{-4}. Now new approach is investigated which allows to rise the efficiency to 50% or even more [5].

2.Status of UNK project.

Original project of accelerating - storage complex (UNK) intended the construction of 3000 GeV superconducting accelerator with slow and fast extraction of the beam to external targets [6]. 400 GeV accelerator with conventional ("warm") magnets had to serve as a booster. Both accelerators had to be placed in common tunnel of 5 m diameter and 21 km long. Colliding of 3000 and 400 GeV beams would be possible with this configuration. The tunnel has room enough for installing in future another superconducting ring to realize colliding mode at 3000x3000 GeV. In 1993 due to significant shortening of finance the Committee on scientific policy of the State program on high energy physics decided to concentrate efforts on the construction of the first stage of UNK. New project had been issued [7] where 400 GeV booster was transformed to 600 GeV accelerator (U-600) with internal polarized jet target for "NEPTUN" experiment (first goal) and possible extraction of the beam in the experimental area. Now this variant is under realization [8].
Fig. 5 schematically shows the layout of U-600. Main parameters of the accelerator are given in Table 3.
At the U-600 project the synchrotron U-70 is used as an injector. Its beam is transferred to U-600 by long (2. 7 km) injection line. Median plane of U-600 is 6m lower than that of U70, so the injection line has bends in both planes. Horizontal bend is 64° towards tangent direction of U-600. Magnetic optics provides the matching of betatron functions and dispersion of U-70 and U-600. Aperture of channel is sufficient to accept beam emittance 2 π mm.mrad and momentum spread

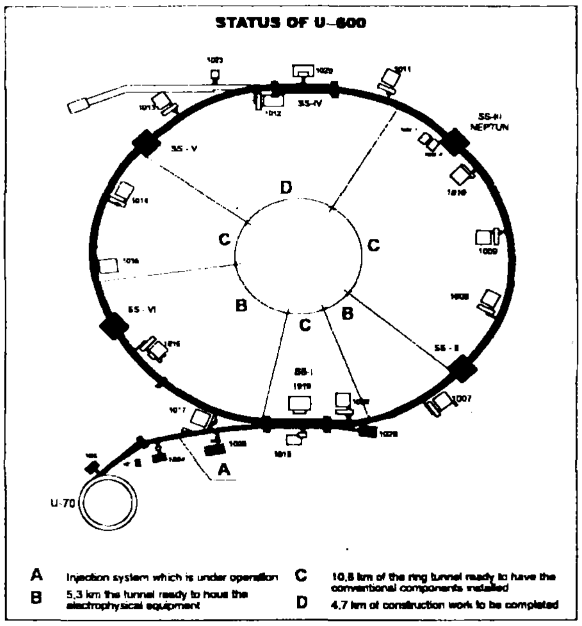

Fig. 5. Layout of UNK

$\pm 2.10^{-3}$. Injection channel consists of 88 quadruples, 52 dipoles and 56 correctors. Diagnostic system allows to measure beam position in 46 points, profile (26 points), beam current, beam halo and beam losses. In 1994 the channel was put into operation. U-70 beam was accelerated to the energy 65 GeV, after that it was recaptured from U-70 RF frequency 6 MHz to UNK frequency 200 MHz and extracted . The beam was observed at the beam dump placed in 2 km from U-70 at the end of horizontal bend. Measured beam dimensions were in good agreement with calculations, stability of beam position was quite good. Prototype of UNK control system developed in collaboration with CERN was successfully tested during the launching the channel.

Ring Tunnel. Tunneling has been fully completed. 5.3 km of the tunnel are ready for installation the electrophysical equipment. Water pipelines,

Table 3. U-600 parameters	
Max energy, GeV	600
Injection energy, GeV	65
Orbit length, m	20771.9
Max. magnetic field, T	1
Field at injection, T	0.108
Duration of magnetic cycle, s	120
Time of acceleration, s	20
Harmonic number	13860
RF frequency, MHz	200
Total RF amplitude, MV	8
Transition energy, GeV	42
Mean beam current, A	1.4

illumination, cables, bar to supply the magnets, supports for the magnet and vacuum equipment are installed there. The assembling technique of the ring electromagnet has been fixed and the test placing of the dipole magnet performed. Three surface buildings are now near to be completed housing powerfull equipment, ventilation and heating systems. Long time measurements of stability of the tunnel geometry are performing.

Another part of the tunnel (10.8 km long) is completed for installation of conventional equipment. Underground experimental hall (60x 15x11 m^3) in the straight section 3 where " NEPTUN" experiment has to be located is ready as well.

Today only the north part of tunnel 4.7 km long needs the completion of construction work.

Equipment of U-600. Table 4 shows status of manufacturing the U-600 equipment. One can see that about 70% of the total amount is already delivered to IHEP. Magnetic field measurements made at the production plant shows satisfactory quality of dipoles and quadrupoles.

Table 4. U-600 equipment

Equipment	Project	Available
Dipoles	2196	1550
Quadrupoles	503	473
Correctors	1180	1180
Magnet power supply sources	25	13
Accelerating cavities	16	8
RF generators	8	3
Vacuum chamber	23.7 km	17 km
Beam position monitors	550	150

Mean square deviation of effective lengths does not exceed 1.10^{-3} at injection field level and becomes much smaller at high field level. Contents of the field harmonics within the working aperture ±35 mm satisfy the requirements. 280 magnets were tested at IHEP before installation. Results of the testing are in good agreement with those made in plant.

We have 17 km of vacuum chamber for all arcs of accelerator. Parts of vacuum system for straight sections are not manufactured yet. Each chamber before delivery to IHEP was baked at 400 °C during 6 hours. Before installation the surface of chambers was treated by discharge in argon. The 100 m chain of vacuum chambers was assembled and tested. Vacuum 10^{-9} torr was achieved without heating and after 2000 hours of pumping it has been raised up to 3.10^{-10} torr. 240 chambers were installed in dipoles.

RF acceleration system of U-600 consists of 8 modules. Each module contains two accelerating cavities feeding by high power amplifier. Amplifiers and their power supplies are located at the surface building and connected with cavities by 50 m wave guide feeder. Each amplifier has 800 kWt CW output power being the sum of 4 parallel stages. Specialized 250 kWt tetrods were developed for the amplifier. All power supplies and three power amplifiers were delivered from industry and tested. Cavities and wave guides are producing at IHEP. One of acceleration module is installed in U-70 ring and used for various tasks.

A half of main magnet power supply sources is available. One of them was tested and now is used to supply bending section of injection channel.

New high power electric substation is under commissioning.

Conclusion.

Present economic situation in Russia led to dramatic shortening of financing the UNK construction. The manufacturing of UNK components is now stopped. Some activity is been continued now to complete the ring tunnel and provide the safe conditions at she technical site. Under reduced circumstances we have to concentrate our efforts on supporting the U-70 accelerator. Though it suffers from the same problems it remains still reliable machine providing physical experiments with beams of high quality.

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