COMMISSIONING/OPERATION OF THE MOSCOW MESON FACTORY LINAC

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Abstract

The linear accelerator has been commissioned with a 17 mA peak current proton beam up to 423 MeV and operates mainly for two goals: isotope production by a 160 MeV beam with an average current up to 50 μA as well as for nuclear physics in the energy range 250-423 MeV. In the high intensity mode of operation the total beam loss in the linac is kept less than 0.1%. Major efforts have been directed towards a deep understanding of the high intensity beam dynamics. For studying the proton beam parameters, a wide range of beam instrumentation and tuning procedures have been developed. In order to produce a more intensive beam many accelerator systems are being improved.

Introduction

The linac consists of a 750 keV proton and H$^-$ injector, 5 Alvarez tanks at 198.2 MHz followed by 28 DAW modules at 991 MHz [1,2]. During the last two years the proton beam energy has increased from 247 to 423 MeV, being limited by the number of klystrons on hand. The linac provides a beam duty factor of 0.35% for routine operation for experiments as well as for isotope production, with an average current of 50 μA at 160 MeV. The acceleration of a proton beam with 20 mA peak current has been demonstrated, this provides an average current of 70 μA with 0.2% beam loss. This paper describes the main stages of the linac commissioning, the results of detailed studies of proton beam parameters as well as linac operation maintenance with low beam losses.

Injection system

The injection system comprises two 750 keV HV injectors for protons and H$^-$ [3] as well as two 7.7 m long LEBTs followed by a common bunching section (BS) consisting of two resonators and focusing lenses [4]. The proton source is a duoplasmatron [5] which together with a HV accelerating tube produces a proton beam with the following parameters:

Pulsed current	120 mA (including H_2^+)
Pulse duration	75 μs
Repetition rate	50 Hz.

Much effort has been directed to improve the reliability of the HV transformers and accelerating tubes. In the last production shifts, the HV breakdowns occurred loosing 6 hours' output. Due to the heating problems at the pulse amplitude stabiliser the designed 100 Hz rep.rate did not yet realised routinely although all linac RF systems can be easy transferred to 100 Hz. The LEBT comprises collimators and bending magnets therefore the pulsed current at the funnelling point is 80 mA and 45-50 mA upstream of the first drift tube tank. The injector provides higher pulsed current if it operates at a lower repetition rate. Careful emittance measurements by a slit-collector system can be done at several locations along the LEBT. Particularly, one of the emittance station (EM2) is located in the direct line of output from the funnelling magnet and it measures the emittance of the beam which drifts through the magnet when it is off. The typical rms unnormalized emittances obtained from the measurements conducted during last five years at EM2 are shown in Fig. 1. The ion source operation mode has shown small variations during these measurements. Fig. 2 shows the phase space and 80 mA peak current beam parameters at EM2 for the routine operation mode. The INR linac was designed a long time ago, and the injection system is not optimal for preventing emittance growth. It has led to emittance values in the low energy region which are almost 2.5 times bigger than is achievable in modern machines (see, for instance, [6]).

At this stage of linac routine operation just one of the two buncher resonators is used. Although the H$^-$ ion source and HV accelerator have been tested we cannot use H$^-$ beam because, for budgetary reasons, the equipment of the H$^-$LEBT is not ready.

Diagnostics

The linac incorporates various diagnostic devices to give the needed beam information for commissioning and operating the accelerator. The beam diagnostic devices are divided into three functional categories: 1. general purpose (current transformers, Faraday cups, beam loss monitors), 2. longitudinal parameter measurements, 3. transverse parameter measurements.

The longitudinal diagnostics comprise beam harmonic monitors operating on the third harmonics and located downstream of each accelerating module [1], a bunch shape monitor (BSM) [7] located in the transition region (TR) between the DTL and DAWL, a magnetic spectrometer with two slits and a high sensitivity blade scanner located at the

160 MeV intermediate beam extraction region (IBER), an absorber-collector unit located at the TR and a momentum halo measurement at the IBER.

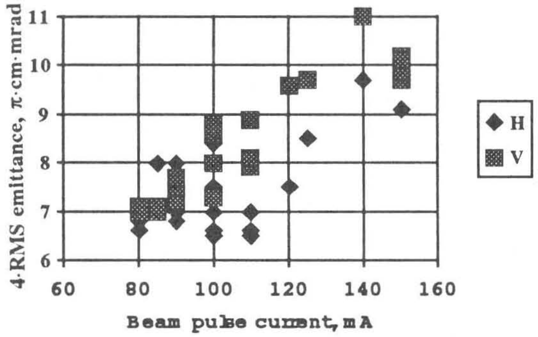

Fig. 1. The rms transverse emittances at the output of LEBT

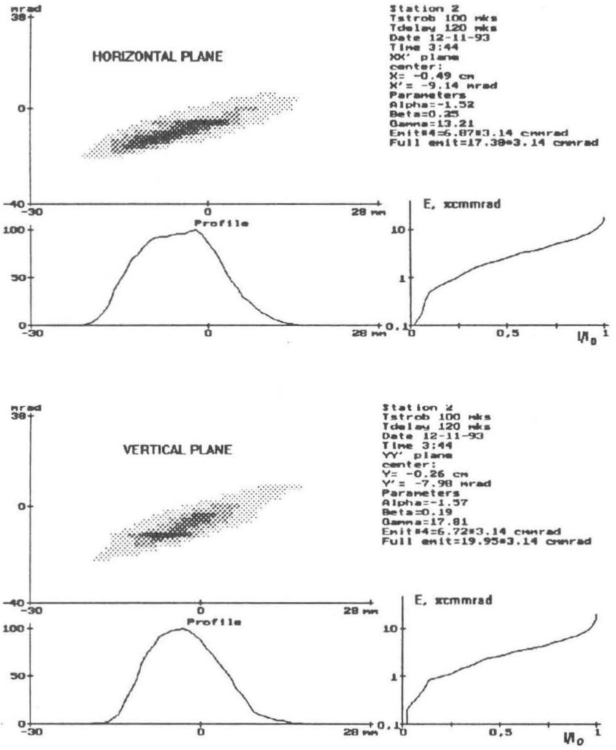

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Fig. 2. The transverse emittance plots at the output of LEBT

The transverse diagnostics comprise slit-collector type emittance measurement units, wire scanners, resonator type position monitors and harps. The wire scanners are a linked a set of 4 or 5 units located through each section of the DAW modules. Five such sets have been installed along the DAWL. The electronics of the WS comprises a preamplifier covering 5 orders of signal amplification; this feature allows the study of output signals produced by the beam halo.

The beam loss monitor system includes 120 detectors consisting of NaJ scintillators and photomultypliers. The detectors are placed in the middle between adjacent DAW sections 1 m away from the beam line. Two thirds of the detectors have been calibrated with a precision of ±50% for absolute beam loss measurements.

In addition to the standard set of diagnostics, a set of special diagnostics has been developed and is used for detailed beam information. This includes a device to measure a density distribution in the transverse cross section of the beam by analysing the secondary electrons produced by the proton beam interaction with a thin wire, a device to measure the transverse profile distribution along the beam pulse with fast electronics, a wide aperture strip line located in the IBER and a wall current monitor to measure the longitudinal structure of a chopped beam.

Beam Commissioning

Longitudinal tuning

To accurately set the RF power, phase and amplitude in the first four tanks of the DTL, the phase-scan method with an absorber-collector has been used [8]. The absorber-collector unit, which enables the separation of the beam output energies from each tank, is located at the TR. Thereby the design phase and amplitude can be found comparing experimental data with the beam dynamics simulation.

A detailed description of the application of the ΔT-procedure at the DAWL is given elsewhere [9]. It is well known that for the higher energy modules (above 247 MeV at our linac) the slope of the variable phase curves in the Δ T-plane becomes insensitive to the RF field amplitude. Originally, to set the RF field amplitude for energies higher than 247 MeV, the phase has been scanned and a peak in the change of time-of-flight is determined and compared with theory [9]. The ΔT-procedure is carried out only to find the phases as the amplitudes in the DAWL have remained unchanged for the last two years. We introduced an additional instrument to measure the beam energy at the outputs of each accelerating module; the absolute energy is compared with the design value. The time-of-flight equipment to measure the beam velocity is shown in Fig. 3. Two BHMs placed one or two modules apart are calibrated on-line using a sinphase excitation by a 594.6 MHz pulsed generator (PG). The signal induced by a bunched beam is mixed with the master oscillator (OS) signal and is measured with the aid of an electronic phase meter circuit (PMC). A preliminary longitudinal tuning is accurate enough to be within the energy uncertainty range of the device. Induced periodic signals, together with the long distance between the detectors, contribute to this uncertainty. Five velocity detectors are distributed along the DAWL in order to measure absolute beam energy. The error of energy measurements is 0.1% - 0.2%.

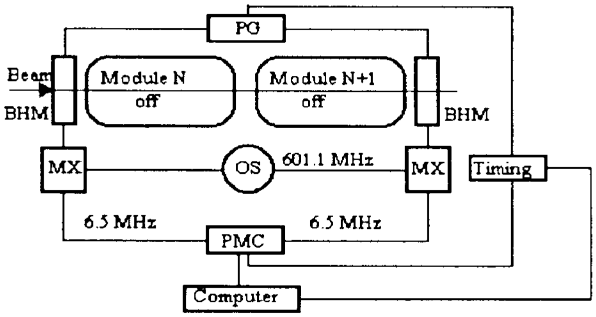

Fig. 3. Block-schematic of the time-of-flight measurements for the determination of absolute energy.

Recently a detailed study of the longitudinal halo of the 100 MeV beam has been carried out using the BSM. As an example, in Fig. 4 the beam fraction versus bunch width is presented. For this particular acceleration mode the bunchers were off and the peak current was 12.5 mA. From this figure it follows that (0.35±0.1)% of the total number of particles is located outside the separatrix of the DAWL. We plan more detailed studies of the longitudinal beam halo for the various modes of acceleration.

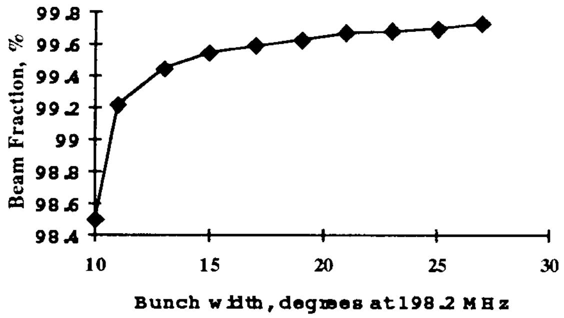

Fig. 4. Beam fraction versus bunch width at the TR.

Transverse tuning

Quadrupole gradients along the linac correspond to design values except for the TR and IBER. Initially, the matching gradients in the last two regions have been set using standard beam matching techniques knowing the rms ellipse parameters. The ellipse parameters in the transverse phase space are determined from profile measurements using the least square method. To get a higher precision of emittance reconstruction we use more than three beam profiles, either with an appropriate number of wire scanners or by taking profiles for several gradient settings in the focusing lenses [10]. In Fig. 5 the rms emittances are shown in the 4 locations along the linac. The emittances at the output of the linac have been measured for a 247 MeV beam transported to an experimental area. The rms emittance growth is essentially above the 160 MeV area to the end of machine. At this time we ignore this emittance growth because the beam loss is within its design value and we believe that the emittance growth occurs due to the beam mismatching. Therefore more carefully matching of the beam parameters above the 160 MeV part of the linac is required.

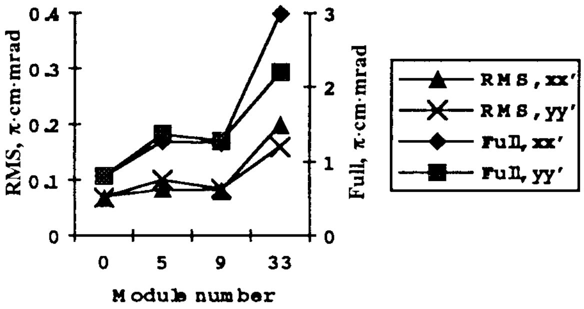

Fig. 5. Normalised emittance growth in the linac.

During the final tuning of the linac using the beam loss information we found that the fine experimental tuning of matching quadrupoles in the TR as well as IBER is required in order to minimise the losses. After such tuning we took beam profiles for the emittance reconstruction at the TR. First, the beam profiles have been measured in the usual way to determine rms beam sizes and to calculate the rms emittances. Increasing the amplifier gain by known values enables us to determine beam profiles with higher signals near the beam halo (Fig. 6). It allows us to determine the beam sizes containing almost all particles. Full emittances can be reconstructed supposing the elliptical symmetry of the density distribution in the phase space. A detailed consideration shows that ~99.8% of the total number of particles is within the "full" emittance determined in this way. In the Fig. 7 we present the rms and full emittances in comparison with the acceptance at the entrance of the DAWL. In Table 1 the mismatch factor is presented.

There are two important conclusions: (i) the large mismatch factor for rms emittance in the horizontal plane indicates some disagreement between the simulation and measurements, (ii) the full emittance is 2.5 times less than the acceptance.

TABLE 1
Transverse Mismatch Factor in the entrance of DAWL

Emittance	xx′	yy′
RMS	0.70	0.06
Full	0.31	0.50

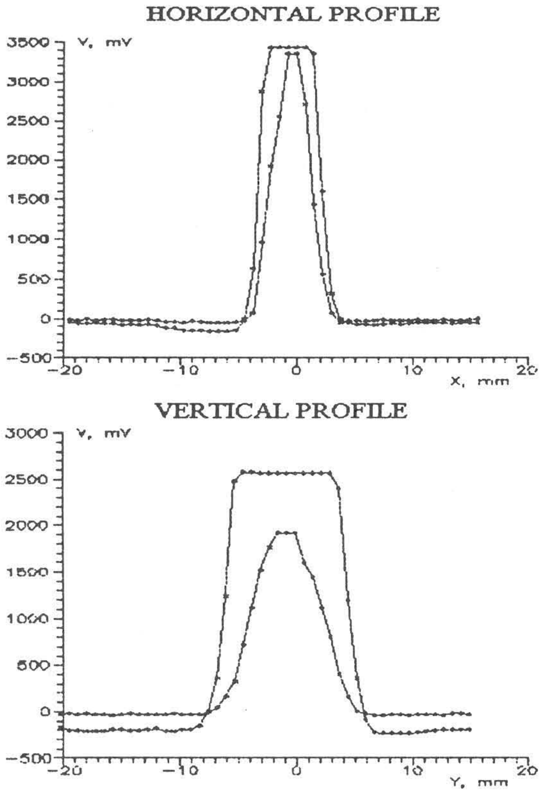

Fig. 6. An example of transverse beam profiles at the first DAW module obtained for two amplifier gains.

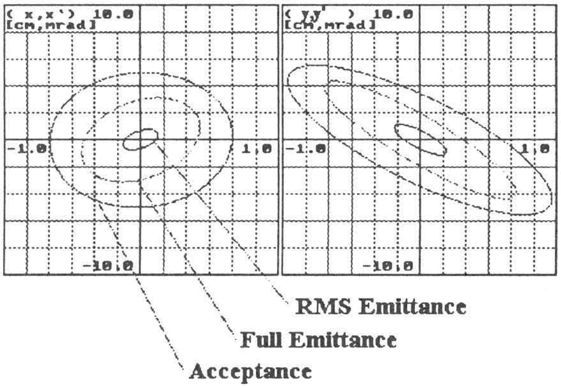

Fig. 7. The rms and full emittances in comparison with the transverse acceptance of the DAWL (normalised values).

Beam production

Operational regimes of the linac

A typical operation schedule of the linac consists of four six to eight weeks production shifts per year. With many improvements in the RF power supply, beam diagnostics, and control systems, together with the new procedures for beam tuning, the linac in 1993 and the first half of 1994 provided 4640 hours of operation. The beam availability for experiments and studies was ~55%. 50% of this time was devoted to nuclear physics at beam energies between 247 and 423 MeV, and another 35% was spent on isotope production at 160 MeV. The rest was used for machine studies and beam quality improvements. With the main experimental hall for the storage ring and secondary beams not complete, a small experimental area was constructed at the exit of accelerator tunnel.

In the beginning of this year a fast beam chopper was installed in the LEBT. The chopper comprises an 80 cm travelling wave stripline with a voltage of 3.5 kV and a ground plate. The chopper produces a special longitudinal beam structure with a pulse length from 0.1 to 1.0 μs in order to make time-of-flight measurements for neutron experiments.

The physics program at the linac includes several experiments with pion beams as well as the neutron experiments with short beam pulses.

Linac tuning for beam production

When delivering beam to experimental installations, beam losses should be reduced to less than 0.2 % at a pulse current of 20 mA. This is realised usually in several steps [11]:

- Preliminary tuning. The phases and amplitudes of the fields in all of the DTL and DAWL modules are adjusted following settings taken from the previous production shift. The integral loss level after such data restoration is equal to 4-6 % at a beam pulse current of 5-7 mA.
- The next step is the reduction of the relative losses to the level of $(1.0\text{-}0.5)\cdot 10^{-3}$ at a beam peak current of 5-7 mA. Our experience shows that the main fraction of the losses occurs due to imperfect restoration of the field amplitudes and phases in both DTL and DAWL modules. Due to the significant length of the drift space between a bunch phase probe and the DAWL (~1.0 m) even the small energy deviation at the output of the DTL, say 0.2%, leads to the beam mismatching in the longitudinal phase space at the input of the DAWL. For that reason the fine tuning of the accelerator is executed as follows:

1. The bunch shape measurement at the output of the DTL. Only if, at the beam peak current of 5 mA, the length of the bunch exceeds 13° (rare case) is the phase scanning procedure necessary in order to set the phase and amplitude in the DTL.

2. The beam energy is adjusted at the exit of DTL to its design value; the measurements are carried out in two ways:

a) Absolute energy measurement using the time-of-flight method.

b) Relative energy measurement using the ΔT-procedure. By means of the phase variation in the last DTL cavity the beam energy at the input of the DAWL is set to (100.1±0.1) MeV.

3. The ΔT-procedure is carried out along the whole DAWL. In the course of this step the beam's absolute energy is measured in the three regions: IBER, 247 MeV (downstream of the 9th regular DAW module), 380 MeV (downstream of the 16th regular module).

4. Fine tuning of the quadrupole gradients and steering magnets in the TR as well as in the IBER is carried out.

The sequence of the steps 3 and 4 is fairly arbitrary and may be repeated.

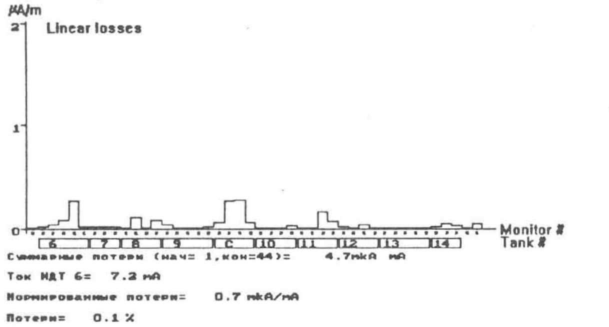

Fig. 8. Pulsed beam loss histogram at sector 3 of the linac after completion of the ΔT-procedure.

Fig. 8 shows the beam loss histogram along the 3rd sector of the linac (250 MeV) after steps 3 and 4 are fulfilled. The dots along the abscissa represent 44 beam monitors. The numbers of accelerating cavities from #6 to #14 are also shown. Similar results are obtained for the 4th sector (423 MeV). The losses shown here slightly exceed the real value due to a noise signal corresponding to ~1 μA of total losses.

Increasing the beam peak current whilst leaving the accelerator parameters unchanged leads to an increase of the relative beam losses. For instance, with a 20 mA beam peak current the losses are 0.2%. In order to accelerate a beam with higher peak current the RF power for the DTL must be increased. A tuning work of the beam loading compensation system, together with the power upgrade of the 198.2 MHz RF generators is under progress.

Conclusion

The linear accelerator of the Moscow Meson Factory produces a 17 mA peak current proton beam with energies up to 423 MeV at a 0.35% duty factor. An average current of 70 μA with 0.2% of total beam losses has been demonstrated. Deep understanding of the high intensity beam behaviour along the linac has been achieved. It allows good control of the beam parameters along linac and enables the induced radioactivity to be kept to a very low level.

References

[1] "Ion Linear Accelerators", vol.1,2, ed. by B.P.Murin, Moscow, Atomisdat, 1978. (In Russian)

[2] V.D.Burlakov et al, "Status of the Constriction of the INR Meson Factory", Proc. 1984 Linear Accel. Conf., Seeheim, (GSI-84-11), p. 9.

[3] A.M.Anikeichik et al. "Injectors for High-Intensity Linear Accelerators of the Moscow Meson Factory", Proc. of the 1988 Linac Conf., Newport News, Virginia, USA, CEBAF-report-89-001, p.55.

[4] O.S.Kuzmin, A.N.Mirzojan and P.N.Ostroumov, "Commissioning of LEBT of the INR Linac", Pribory i Technika Experimenta, No.3, p. 52 (1990).

[5] A.S.Belov et al, "Ion Sources for Linac of Moscow Institute for Nuclear Research", Rev.Sci.Instr., v.63, No.4, part II, p. 2622, (1992).

[6] K.F .Johnson et al, "Characterization of a Ramped Gradient DTL: Experiment and Theory", Proc of the 1991 Particle Accel. Conf., San-Fransico, USA, p. 3017.

[7] A.V.Feschenko and P.N.Ostroumov, "Bunch Shape Measuring Technique and Its Application for an Ion Linac Tuning", Proc. 1986 Linear Accel. Conf., Stanford, p. 323.

[8] G.I.Batskich et al, "Proton Beam Acceleration up to 160 MeV at the Moscow Meson Factory Linac" , Proc. of the 1991 Particle Accel. Conf., San-Francisco, USA, p. 3067.

[9] Yu.V.Bylinsky et al. "Setting of RF Phase and Amplitude in Multi-Tank Ion Linac", ibid., p. 805.

[10] I.N.Birukov et al. "Transverse Beam Parameter Measurements at the INR Proton Linac", Proc. of the EPAC-92, Berlin, p. 1109.

[11] S.K.Esin et al, "Beam Loss Study at High Intensity Proton Linac". To be published in the Proc. of EPAC-94, London, June 1994.