LINEAR PROTON ACCELERATORS

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(presented by G. I. Batskikh)

The USSR, like many other countries, is carrying out extensive work on linear proton accelerators. Experiments are carried out and modifications are introduced at the linacs I-100 (the injector of the 76 GeV proton synchrotron at Serpukhov) and I-2 (the injector of the 7 GeV proton synchrotron at ITEP in Moscow) which are now in full operation. Theoretical and experimental studies are being conducted in connection with the projects of a 800-1000 MeV linear accelerator (injector for the cybernetic accelerator) and a 600 - 1000 MeV accelerator (meson factory), both under development at the Radiotechnical Institute. Works are carried out on the design of a 37 MeV linear accelerator to be used as an injector for the Serpukhov proton synchrotron booster.

Particular attention is paid to investigations aimed at increasing the beam intensity and also at creating systems which can give better beam parameters at a reduced cost. Computer simulation is widely used to facilitate the investigations.

Of course, in this short review I would like to cover only the main branches and results of these works, this task being easier with earlier results delivered at previous conferences.

It is a matter of convenience to begin with the work on the I-2 and I-100 accelerators which are now in operation.

I-2 Linear Accelerator

The 24.6 MeV proton accelerator[1] has been in operation since June 1966, being a reliable injector of the ITEP 7 GeV proton synchrotron.

Prof.I.M.Kapchinsky kindly informed us that the accelerator is at 24 hours operation for 3 weeks, and then one week of maintenance work follows. In 1970 the total operation time was about 5000 hours, of which 4400 hours the accelerator was used for injection purposes. The down-time per operation cycle is between 0.5 and 3 per cent.

The injector beam parameters:

Beam current	90-110 mA;
Current pulse-to-pulse stability	8-10 per cent;
Momentum spread at half maximum	± 0.6 per cent;
Normallized output emittance	0.9 cm.mrad.

I-100 Linear Accelerator

The linear accelerator-injector I-100 operates without compensation of accelerating field drops[2], and the operating conditions provide for the following basic beam parameters:

Peak beam current	70-80 mA
Beam pulse duration	12-14 μsec
Current pulse-to-pulse stability	5 per cent
Particles momentum spread at half maximum	± 0.3 per cent
Normallized total emittance (with channel acceptance of 6 mrad.cm)	1.0 mrad.cm

The maximum beam current was 150 mA at a current pulse length of about 5 μsec. Excessive drops in beam loaded cavities were the reason of the limited pulse length. To overcome this limitation additional compensating RF power may be coupled into the cavities.

The normal operation shedule for the accelerator is 3 weeks of 24 hours operation followed by one week of maintenance work. The accelerator proved to be highly reliable. For example, in 1970 the total time of operation in the injector mode was 5400 hours, down-time due to faults being less then 2.5 per cent of the total time, of which 0.85 per cent was due to the RF system.

The reliability of the accelerator was increased not only by debugging and by modifying some units, but also by a profound study of the operating conditions of the linac.

I-100 Linac RF System Modification

A three-turn injection is to be introduced at the Serpukhov proton synchrotron, so a necessity arises to bring the beam pulse length up to 36 μsec from the present value of 12 μsec.

Hence it was necessary to supply into

each of the cavities an extra RF power that should exceed the output power of a single RF amplifier by a factor of 1.5. To solve this problem additional output RF amplifiers have been installed.

The experience gained during the 2-year experimental operation of two output amplifiers with direct power superposition in the 1-st cavity of the I-100 linac proved this simple method to be effective and reliable. The requirements for the coupling with the cavity, for the driving voltage phase in each amplifier and also for the identity of the tube parameters were found to be rather loose which makes both the tuning and the running of the RF system easier. Now each of the three cavities is fed by two output amplifiers driven in phase (Fig.1).

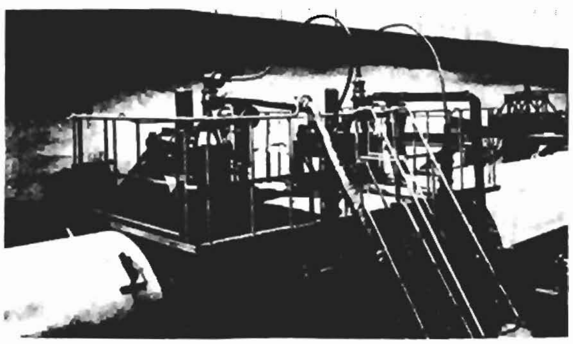

Fig.1. Two output amplifiers mounted on cavity of I-100 linac.

To stabilize the accelerating field two fast systems, controlling the plate circuits of the output amplifiers have been developed and tested. A shunting tube is used in one of the systems, and a programmed stabilization system with additional modulator is used in the other. A pulse is produced in the latter system (Fig.2) with the duration equal to the acceleration time, which is added to the main modulator pulse through a diode switch, its amplitude and time position being adjustable. Both systems allow to obtain accelerated beam current up to 100 mA at the pulse length of 36 usec.

A peculiar feature of the automatic control systems for RF field stabilization in long cavities should be noted. When an automatic control system using a shunting tube was tested at the 1-st cavity of the I-100 accelerator, the difference frequency between the first and the zeroth modes, which modulates the envelope of the RF field in the cavity, was about 70 kHz. This frequency fell within the bandwidth of the system and caused oscillations which looked like self-exited ones (Fig.3).

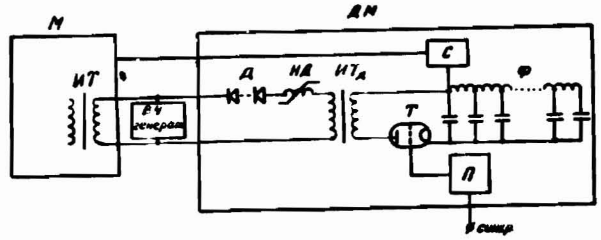

Fig.2. Simplified block-diagram of additional modulator. М - main modulator, ДМ - additional modulator, Д - diode switch, Т - thyratron, ИТ - pulse transformer, С - charging stabilizer, Ф - pulse shaping line, П - driver, НД - nonlinear choke.

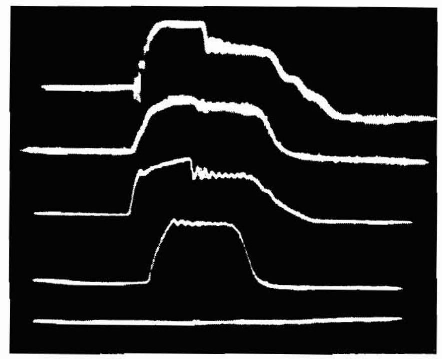

Fig.3. Typical oscillogrammes obtained at automatic control system with parallel tube at 1-st cavity of I-100 linac.
Trace I - output amplifier plate voltage.
Trace II and III - cathode and plate currents respectively.
Trace IV - top of RF envelope in the cavity (~ 24%).

The effect of the first mode has been reduced by using a sum signal from adding two envelopes of two detectors coupled with the cavity at its opposite ends. To provide for the experiments on three-turn injection the most efficient and simple method was adopted that involves simultaneous programmed control of plate voltage in the output amplifiers and in the drivers. The control system (Fig.4) ensures critical mode of operation of the output amplifiers with minimum forcing of the plate and driving voltages, thereby increasing the tube life time. A tube protection circuit is incorporated to switch off the plate voltage in case of a breakdown.

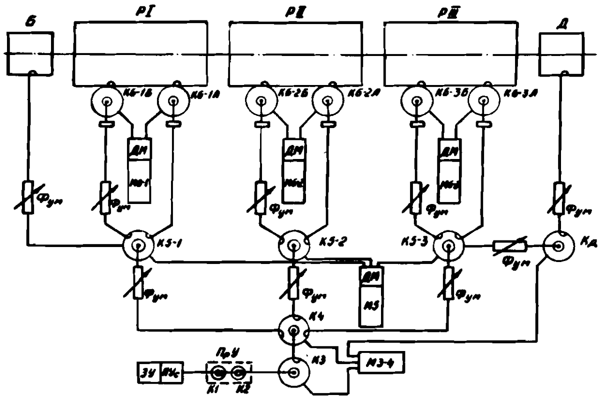

Fig.4. I-100 linac RF system block-diagram. PI, PII, PIII - accelerating cavities, Б and Д - buncher and debuncher, K6 - output amplifiers, K1 - K5 - driver stages, M - modulators, ДМ - additional modulators, $\Phi_{УМ}$ - phase shifting circuit, P_{Φ} - reflection meter, ЗУ and $ПУ_{С}$ - master oscillator, $П_{р}У$ - preamplifier.

Projects of 600-1000 MeV Linacs

Works have been carried out for a number of years at the Radiotechnical Institute on the design of a 800 MeV linear proton accelerator with a pulse current of 100 mA. This accelerator is to be used as an injector for the 1000 GeV cybernetic accelerator. The principal data of the linac and of its systems have been published elsewhere[3,4]. The following composition of the linac has been adopted: a 750 keV preinjector, then the first stage of the linac with the Alvarez type structure operating at 200 MHz, and the second stage in which 1000 MHz cavities are used. The transition energy was initially supposed to be within 100-200 MeV.

The subsequent research of new accelerating structures and also of beam dynamics to be discussed later have allowed to make some refinements. The transition energy between the Alvarez structure and the higher frequency structure has been chosen to be 100 MeV, and the cavities operating frequencies - 198.2 and 991 MHz respectively. To focus the beam quadrupole magnet lenses are used in the first stage of the linac, and magnet doublets in the second one.

The research works on the linac injector of the cybernetic accelerator have been also laid into the basis of the project of a high current linear accelerator - the meson factory now under design at the Radiotechnical Institute. There are two versions of the project, their principal data being given in Table I.

The first version is a 1000 MeV linear accelerator with an average beam current of 2.5 mA. The second version has a reduced output energy of 600 MeV and an average beam current of 0.5 mA. The beam duty factor has been also reduced to 1 per cent instead of 5 per cent.

In both versions of the meson factory the same composition as described above is used. The difference is that in the second version a beam stretching storage ring is used which allows to increase the beam duty factor to nearly 100 per cent.

Protons and negative hydrogen ions (H^-) will be simultaneously accelerated in the linac, therefore the ratio of the frequencies in the 1-st and the 2-nd stages of the accelerator was chosen to be an odd number. The accelerated H^- beam will be deflected into the storage ring stretcher and will be accumulated there through multiturn charge exchange injection with simultaneous slow extraction of the stored beam. The principal data of the storage ring stretcher are given in Table 2. The stretcher is designed to give a constant extracted current up to 200 microamps. A one-turn extraction is also possible.

Some Design Problems of Linear Accelerators for Meson Factories

Some interesting problems arise in development of high current linear accelerators for energies of hundreds MeV. Results of some investigations carried out at the Radiotechnical Institute are given below.

Beam Dynamics

The necessity to provide minimum losses of particles in the 600-1000 MeV accelerator at relatively high average current has necessitated a thorough computer-aided investigation of beam dynamics in the linac.

Fabrication tolerances and accuracy of mounting and alignment have been taken into account in the computer simulation.

One of important points of the investigations was the choice of transition energy between the first and the second stages of the linac. Longitudinal motion of particles has been simulated in the first stage for energies up to 200 MeV with usual RF field and geometry tolerances. The bunch size was found to depend slightly on energy in the energy region of 70-200 MeV (the adiabatic damping is compensated by an increase in the bunch effective size due to the random errors). Thus the transition energy was chosen to be 100 MeV, bearing in mind that the effective shunt impedances of the accelerating structures in both stages of the linac are equal.

It was also shown by computer simulation that even comparatively tight tolerances for the amplitude and phase of RF field in the cavities (of the order of

Table I Principal data of the high current linac - the meson factory

Parameter	Unit	Version I Stage 1	Version I Stage 2	Version II Stage 1	Version II Stage 2
Injection energy	MeV	0.75	100	0.75	100
Output energy	MeV	100	1000	100	600
Average beam current	mA	2.5		0.5	
Peak current	mA	50		50	
Pulse length	μsec	500		100	
Pulse repetition frequency	pps	100		100	
Beam duty factor	%	5.0		1.0	
Accelerating field frequency	MHz	198.2	991	198.2	991
Total length of accelerating system (gaps between cavities excluded)	m	67.5	750	67.5	280
Number of cavities		5	64	5	24
Total peak RF power	Mw	13.5	100	13.5	72
Total average RF power	Mw	0.9	5.5	0.4	0.85

Table II Principal data of the storage ring stretcher

Parameter	Unit	Value
Output proton energy	MeV	600
Average proton current	mA	0.2
Average stretcher radius	m	24
Stretcher length	m	150
Magnetic field in bending magnets	kgauss	6
Magnetic system lattice		FODO
Number of betatron oscillations per turn		3.75
Chamber radial aperture	cm	11
Chamber vertical aperture	cm	6

one per cent and 1° respectively) do not prevent the amplitude of coherent phase oscillations at the output of the 1-st stage to achieve more than 1/3 of the phase width of the bunch. Thus for reasonable choice of the equilibrium phase in the second stage of the accelerator it is necessary to adjust automatically the bunch center of mass to the separatrix center of the 2-nd stage and to fit the beam dimensions in the phase plane to the separatrix.

To solve the first problem, a system that damps the coherent phase oscillations is used that involves an automatic beam-controlled RF-phase control system. The description of the latter system has been given in[3,4,5].

The second problem, i.e. that of bunch transformation, is solved by an appropriate choice of parameters of the first stage output cavity, the latter being essentially a matching element. The longitudinal oscillations frequency in this cavity must be increased as compared to that in the previous one. In the linac for the meson factory there is a frequency increase of about 1.4 times obtained by increasing the synchronous phase to 60°. The operation of the matching element is illustrated in Fig.5. If the cavity length is equal to a quarter of the longitudinal oscillations wavelength then the representative ellipse A in the phase-space plane is transformed into an ellipse B. The phase compression improves the beam matching to the capture region of the 2-nd stage of the linac.

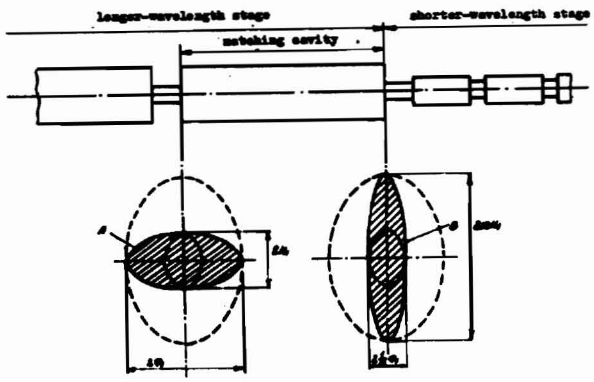

Fig.5. Matching of accelerating channels between 1-st and 2-nd stages of linac.

Accelerating Structures

We consider the post coupling structure developed at the Los Alamos Laboratory to be still the most suitable for use in our projects at energies of up to 100 MeV. A possibility is studied now to reduce the number of posts in this structure, which is of interest in designing long cavities for low energies.

For energies above 100 MeV various stabilized structures are investigated. One of them is a structure with annular coupling cavities (Fig.6) operating at a $\pi/2$ standing wave mode[6].

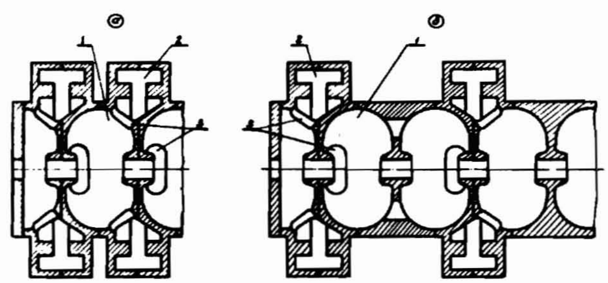

Fig.6. Accelerating structure with annular coupling cavities.

It can give higher coupling between the cells than the structure with side coupling cavities. This structure is also easier to be manufactured and heat is more uniformly distributed in the walls. The calculated effective shunt impedance of this structure at relative velocities $\beta = 0.4 - 1.0$ at 1000 MHz and the aperture of 4 cm varies between 26 and 52 Mohm/m. Experimental data for the shunt impedance at 5-10 per cent coupling between the cells are 20-25 per cent below the calculated values.

Figure 6b shows the accelerating structure with annular coupling cavities operating at a $2\pi/3$ standing wave mode. The structure design is advantageous in low energy range due to reduced number of coupling cells.

The technique of manufacturing of these cavities is now being elaborated. A possibility is considered in particular of cold stamping of all elements of the structure with subsequent brazing. The cavity design allows brazing the cavity sections during one heating cycle in a hydrogen oven. A model of this structure is shown in Fig.7, which was tested for its sealing properties and proved to have high quality seals.

Fig.7. Model of accelerating structure with annular coupling cavities.

Another structure has been investigated which is a further development of the accelerating structure with conducting washer-shaped discs operating at a π mode[3,4]. The new structure operates at a $\pi/2$ mode[7] and consists of a cylinder resonant cavity with conducting discs and drift tubes, conducting diaphragms being installed in between the drift tubes in the middle of the gaps (Fig.8). Metal rods are used to fix the discs. The rods are parallel to the cavity axis and mounted in the RF voltage nodes. The rods are also fastened to radial lugs at the diaphragm edges.

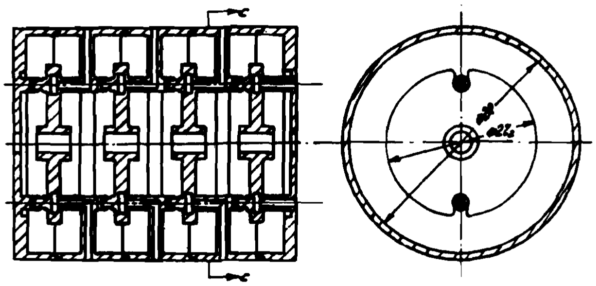

Fig.8. Accelerating structure with discs and diaphragms.

Computer calculations have been made to find the acceleration system geometry which gives minimum RF losses. For this case the effective shunt impedance at 1000 MHz was found to vary from 19 to 45 Mohm/m for respective relative velocity β=0.4–1.0 and the aperture diameter of 4 cm. In accordance with β variation in this range the cavity diameter varies from 440 mm to 360 mm and the discs diameter from 290 to 250 mm.

It was measured that the coupling factor which characterized frequency difference between 0- and π -modes is about 50 per cent in such a structure.

Beam Loading of Cavities

The influence of an intense beam on RF fields in a cavity has been a matter of extensive investigations for a number of years. Along with theoretical analysis experimental investigations were conducted on the I-100 linac and also on cavities loaded by bunched electron beam.

It was shown by the investigations that:

a) undercompensation of the accelerating field drops is tolerable if the drops are similar and simultaneous in all cavities. For example, in the three-cavity linac I-100 with initial equilibrium phase $\varphi_s = 37^\circ$ the drops may be as high as 8–10 per cent. Corresponding changes in the beam parameters and particularly the energy spread of output beam are quite tolerable.

b) any spacial inhomogeneities of the beam and of accelerating field lead to exitation of higher modes in the cavities. However, if the equilibrium phase does not vary long the length and no compensation for the field drops is provided, the distortions of the RF amplitude and phase are small enough. In the 1-st cavity of the I-100 linac they are 8% and 5° per one amp of beam respectively.

When additional power is fed to compensate for the drops field distortions may arise due to the coupling between the operational mode and the higher modes through the RF system. The distortions can reach 20% per one amp of beam current.

c) the RF field amplitude and phase variations are strongly affected by the operation conditions of the output RF amplifier and also by the parameters of the coupling system between the amplifier and the cavity. In particular, the appropriate choice of these values allows to compensate for the amplitude and phase perturbations of the RF field only by varying the operation conditions of the RF output tube.

More detailed results are given in[8-11].

Accelerating Structures with RF Beam Focusing

Studies are being made at the Radiotechnical Institute of asymmetrical alternating-phase focusing in proton linacs (AAPF). In this method both longitudinal and transverse stability is provided by the accelerating field itself due to periodic oscillations of the synchronous phase around a certain mean value[12]. In multigap cavities this is achieved by means of appropriate alternation of the drift tube lengths.

It was shown by calculations and by computer simulation that the AAPF method can give the capture region of about 50-70°, taking into account the transverse stability. Output currents of up to 100 mA can be obtained at the accelerating wavelength of 1.5 - 2 m and the injection energy of 750 keV[13]. The injection energy may be reduced to some 50 keV, however this makes the beam intensity to fall to 10 mA. The AAPF method can be effectively used at energies of up to 150 MeV. Like any other electrostatic focusing, it becomes inexpedient at higher energies because its efficiency decreases with β.

One of the advantages of the AAPF method is that the accelerating and focusing fields are axially symmetrical, therefore the method can be used both in the Alvarez structure and in any other.

Stable acceleration of protons has been achieved at an experimental accelerator with the 575 keV energy and 2 mA beam current and injection energy of 50 keV. The 340 mm diameter accelerating cavity had 10 drift tubes. The H-mode was excited at 148 MHz. The drift tubes diameter varied from 30 mm at the input to 100 mm at the output of the cavity, which made the accelerating field to increase from 1 MV/m at the input to 3 MV/m at the output.

The aperture gradually increases from 7 mm in the first tube to 15 mm in the output one.

A group headed by V.A.Teplyakov at the IHEP is working on the development of a proton linac in which RF quadrupole field is used for focusing. First successful experiments on proton acceleration in a 2.4 m long section have been carried out during this year. The protons were accelerated to 4.0 MeV from the initial energy of 0.7 MeV, making approximately one phase oscillation in the section. A double-gap structure was used which has been described in[14]. The electrodes were installed in an H-shaped cavity in which the RF voltages were equal in all the gaps.

The cavity structure and its elements are shown in Fig.9. The accelerating electrodes are mounted alternately at the opposite sides of the inner tube. The intermediate electrodes of the double gap are mounted on rods crossing the cavity at its diameter. Two double gaps fall within the length of one $\beta\lambda$. The cavity diameter is 230 mm, the aperture is 16 mm, and the accelerating gaps are 8 mm long.

The cavities were excited by 30 μsec RF pulses, while the 35 μsec beam was injected slightly earlier. A view of the experimental setup is shown in Fig.10.

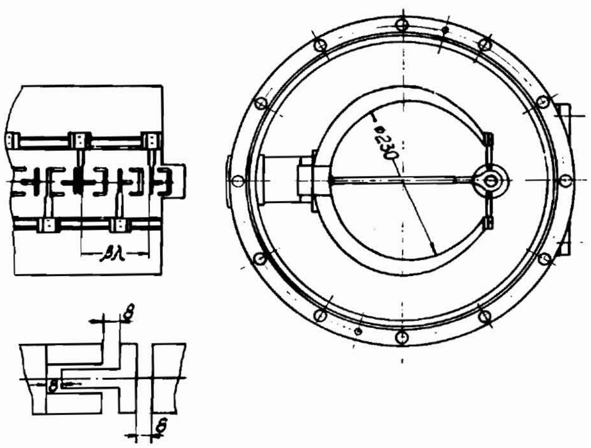

Fig.9. Schematic view of cavity with RF field focusing.

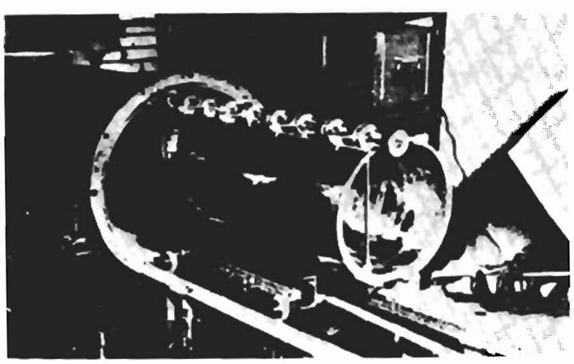

Fig.10. View of experimental setup using quadrupole RF field focusing.

The experiments have resulted in obtaining a well-focused 10 mA beam (the emittance was 0.8 mrad.cm). The obtained current value of 10 mA was much less than the limiting one for this structure, therefore no effect of the beam current has been noticed.

No breakdowns were observed when the RF power slightly exceeded the rated value. The rated voltage across the gap was 95 kV, and the total voltage per period was 190 kV.

Many laboratories in the Soviet Union are now carrying out theoretical and experimental studies of superconducting linacs. Experimental data obtained by now are not sufficient to discuss the problem in detail. However, we believe that the superconducting technique will eventually become the basis for the design of new linear accelerators.

In conclusion I should like to note that linear accelerators have been progressing rapidly for the past 5 years. New accelerators have been put into operation with output energies of up to 200 MeV and beam currents as high as 100 mA. Interesting studies were carried out which have allowed to perform the design works and to start the construction of 1000 MeV range linacs with high average beam intensity. There is no doubt that this trend in linac development will be broadening and new linacs with higher beam currents will be eventually constructed.

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DISCUSSION

P. LAPOSTOLLE: In the two-gap RF focusing test work by Teplyakov, et al., which you mentioned, was the current limited to 10 mA by the source or by the accelerating structure? In case it was the source, what is the estimated limit from the structure?

G.I. BATSKIKH: The limitation in this test work was due to the ion source. As far as I know, the theoretical limit is about 100 mA.