THE FIRST CW ACCELERATOR IN USSR AND A BIRTH OF ACCELERATING FIELD FOCUSSING

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ACCELERATORS IN THE INSTITUTE OF CHEMICAL PHYSICS

In 1947 I joined the Institute of Chemical Physics in Moscow. Its director was Nikolai Semyonov, the future Nobel Prize winner. My first job there was a lab technician in the laboratory of Boris Shembel. He explained to me: "the charged particles in the linear accelerator are accelerated by a high-frequency electric field. This field is created in the volume resonator. The ions are accelerated in the gap between drift tubes. When the field becomes decelerating the ions drift inside the tube. We shall develop such an accelerator".

My personal assignment was to study the frequency shift dependence in a short resonator from the drift tubes size. I managed to establish a strange dependence: relative frequency shift or $\Delta\lambda/\lambda$ depends on parameter (2d + h), where d is the diameter of the drift tube, h is the length of the resonator. As a consequence, my first article in a magazine [1] was published.

As it turned out, our accelerator research was not an isolated project. It was required to provide a powerful stream of neutrons. Neutrons enable processing of thorium into uranium or uranium into plutonium. The same kind of accelerator was being developed in Livermore in the USA.

While we were working hard to develop the accelerator ourselves, the geologists found enough uranium sources and physicists learned to turn it into the plutonium.

In 1955 Boris Shembel was going to a conference on accelerators in Geneva. And I became obsessed with an idea: "The accelerator should not be designed like in Livermore - in the form of a tank of 20 m in diameter and 26 m in length. It should work in two frequencies. And the initial part of the accelerator should be different from the main part. The task of the Initial part is to prepare a beam of ions for a regular acceleration in the main part. The initial part should utilise the quarter wave coaxial resonators". Even prior to the beginning of the Geneva conference it became known that the Americans were going to report on the A-48 accelerator project. It appeared that my invention was too late. However Boris Shembel was requested to continue to work on our project which, to my surprise, resembled the American A-48 more and more.

An Initial Part is particularly useful in the cw accelerator with a powerful beam. It is important to increase the factor of capture and to lower the injection energy. Thus I was charged with the task of improving the one gap buncher and developing a buncher with several high-frequency gaps and, possibly, with acceleration as well.

In the beginning I considered a "two-gaps buncher". It turned out that in the first gap, the thin beam is modulated by speed, and in the second gap the modulation must be removed. Consequently it was possible to achieve both the bunching of clots and their focusing. However, my suggestion was contradicting Earnshaw's Theorem and my colleagues refused to treat it seriously. They considered me a dreamer. But in my own eyes I was an inventor - though my inventions were usually a bit late. Quite often I was asked: "Why this is not done abroad?" And I was at a loss: " Why can't we do it such way?" My superiors suggested: "It is better to wait and see. If an idea is valid – it will surface somewhere else for sure." I was trained not to publish "raw" ideas.

Soon the necessity of an CW accelerator for manufacturing the plutonium disappeared. It was suggested to use the accelerator for producing electric power. Vigorous deuterons produce many neutrons. They are absolutely necessary to support the nuclear reaction in uranium. Now we had to think about increasing the efficiency of the accelerator, about its high reliability.

Focusing of ions by magnetic solenoids imply very high consumption of energy, so it was necessary to find a better way. It was necessary to get rid of mercury vacuum pumps and find more economical vacuum generating devices. And I had the desire to invent in all these directions.

For sure, soon the opponents of the electronuclear method appeared. They argued that it would not be possible to boost the efficiency of the accelerator up to 20%. And nobody will operate it with the help of robots.

ACCELERATORS IN THE URALS

So, we had to re-orient ourselves and to start developing the accelerator for the needs of thermonuclear synthesis. In 1958 we were transferred from Moscow to the base in the Urals. A fantastic land, and not so densely populated as it seemed from Moscow.

Forty five years ago I with Gennady Anisimov [3] put forward the idea of FAF - focusing by the accelerating field. At first this idea was published in our book [2].

The principle of alternating-sign focusing is well known from optics: for example, telescopes and microscopes are made from a sequence of focusing and defocusing lenses. Cylindrical lenses are known as well.

The idea of FUF was implemented for the first time in the electronic model of the proton accelerator by Anatoly Maltsev [4]. Drift tubes with channels of rectangular section were placed in a cylindrical resonator. Focusing was carried out by the edge effect of the field alternatively vertically and horizontally. We intended to publish this version of focusing at the conferences of 1963 in Dubna. However we found out that F. Fer, P.

Lapostolle, etc. had also submitted a report with a similar idea.

In 1963 my article [5] appeared. I showed there that focusing by high-frequency quadrupoles may be quite effective. The thing is that if on one gap both quadrupole and axial components of the field are produced; the voltage at the quadrupole is limited by the danger of breakdowns. The rate of acceleration appears low, and the focusing insufficient. During the period of acceleration it is necessary to have not less than four gaps with the voltage admissible at one quadrupole.

To distribute potentials at the accelerator electrodes properly, I, together with Victor Stepanov had to invent a new type of cavity - the H-cavity [6]. It exited on the H-wave, at the lowest (critical) frequency (TE-mode). While investigating this resonator we understood it as a quarter wave or half wave resonator with larger length in the cross-section direction.

Our H-resonator loaded with electrodes of quadrupole focusing turned to be a rather simple and easy to manufacture. Its external diameter was almost four times less than the diameter of the cylindrical resonator.

When Boris Shembel reported our invention of this new type of accelerator to one of the heads of our Institute he was advised "not to stick out": let others judge us.

Nevertheless we managed to build a small proton accelerator with FUF effect and tested it successfully. The PT-500 cw accelerator was launched into operation. It accelerated protons of 150 mA current from 70 up 500 keV.

In 1966 the ideas of thermonuclear synthesis went out of favour. It was decided to disband Boris Shembel’s group. I moved to Protvino near Moscow, to the Institute for High Energy Physics.

I-100 INJECTOR IN IHEP

In IHEP, I, together with some other colleagues was engaged in operating the I-100 accelerator.

The assembly of I-100 was performed by the employees of the Radio-Technical Institute. The general management from our side was carried out by the Engineer-in-chief Sergey Iljevsky, and the scientific supervision by Ilya Kapchinsky from ITEP. They were competent and skilled managers. My own task was troubleshooting.

The first thing that I had to do was to get rid of the oil-vapour pump traps with liquid nitrogen. In those times there were no other types of vacuum pumps with such speed of degassing. So we had to invent pulse injection of hydrogen into the proton source. We already had a proton source with small vacuum chamber volume. With the pulse hydrogen injection per second the consumption decreased sharply. Thus it became possible to use titanium magnetic discharge pumps like for the accelerator cavities.

While working with the booster in the packet-pulse mode the volume of the source had to be reduced still more. Great ingenuity and hard work of Vitaly Nizhegorodtsev ensured the proper functioning of the ion gun.

Finding out and eliminating the reasons of failures, breakdowns and instability of I-100 we managed, basically, to finish these works by November 1967, by the launch time of the U-70 ring accelerator.

Having provided reliable operation of I-100 we had an opportunity to continue the development of the accelerator with focusing by the accelerating field.

URAL IN PROTVINO

In the beginning we checked the working ability of URAL-4 (Accelerator Resonant Autofocusing Linear for the 4 MeV proton energy) on a mock-up model. Focusing worked with the current of the accelerated protons up to 20 mA. Under such a current resonances of the intermediate electrodes stems occurred.

For quite some time I did not manage to realize how to organize the work of a buncher with several drift tubes. And suddenly (after fifteen years of searches) it came to me: in the Initial Part of Accelerator (IPA) it is necessary to form clots of particles with constant density of the charge! By this time I already knew that it was possible and I knew how to do it. An elementary theory for the particle dynamics was ready by the next day. Ilya Kapchinsky very actively contributed to the development of a more comprehensive theory of dynamics of particles in IPA. As a theorist, he was able to work quickly and energetically. On my part I still could not for a long time find the necessary manufacturing know-how for the electrodes and resonator. It was clear to me that a four-chamber resonator (like in magnetrons) suited IPA. Ilya Kapchinsky liked this idea very much. So, in two evenings in Protvino he sketched the theory of the four-chamber resonator. But to me it was still not clear how to make it.

My mental tortures resulted in the design of a 2H-resonator. Now IPA became an adiabatic buncher, with acceleration and focusing of the beam by a high-frequency field homogeneous on length, with quadrupole symmetry [7]. Now it was possible to make it in hard metal. (Fig. 1)

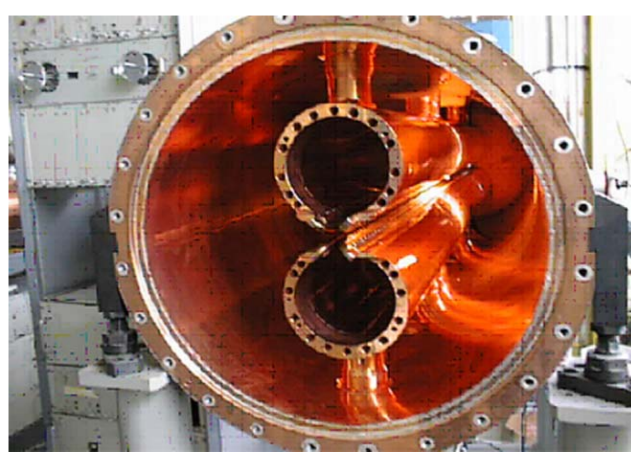

Figure 1: 2-H resonator.

In 1972, initial testing was accomplished, and accelerated beam was obtained in the first RFQ at IHEP in Protvino. Later I. Kapchinsky's dream – RFQ on the basis of a four chamber resonator was realized, at ITEP in Moscow.

I was lucky that in our collective there were not only remarkable designers and engineers but also skilled men who always found ways how to make things.

In a small-sized H- or 2H- resonator the accumulated energy is about an order of magnitude less than in the DTL. Due to the huge energy in the resonator of the Livermore accelerator, during breakdowns it was the copper of the drift tubes that cracked. Because of the low accumulated energy in the URAL-30 resonators the field drops down fast when the proton beam is switched on. In order to damp the non-stationary processes in the generator-resonator system, it was necessary to invent the AD system – Auto Damping system [8]. AD is not a system of stabilization of the field - it plays the role of a ferrite circulator. It brings into the system active losses at a mismatch of the generator and the resonator. Ivan Maltsev and his group had to work hard to develop a powerful system of high-frequency supply of the accelerator URAL-30 with an AD system.

We were carried away by enthusiasm developing a proton accelerator with the 30 MeV energy. At that time the ideas of setting up a booster in the accelerator complex of the Institute for High Energies Physics were discussed.

At the VII Yerevan Conference on Accelerators Kapchinsky, Maltsev and myself reported on the development of the 30 MeV proton energy accelerator with quadrupole focusing [9]. However, very few people took this project seriously.

With Anatoly Logunov's support and Alexey Naumov's participation we managed to build URAL-30 using only the facilities of the Institute for High Energy Physics.

RFQ IN LOS ALAMOS

It was there that the RFQ abbreviation was born.

The first experimental test of the RFQ principle, outside of the USSR, was performed early in 1980. This test was so successful that the RFQ was adopted as an essential part of several Los Alamos accelerator projects. These include the Fusion Materials Irradiation Test (FMIT) accelerator, the Pion Generator for Medical Irradiations (PIGMI), and the experimental program on directed energy beam technology. In addition, the RFQ may have important applications in the radio-frequency linac approach to heavy ion fusion.

Several CW RFQ's were commissioned, the first being the 80 MHz FMIT prototype at LANL. In Chalk River an ~ 1 MeV RFQ was launched. Then in Los Alamos LEDA project started to work - a demonstration accelerator of low energy up to 6,7 MeV with the proton current up to 100 mA

The barrier which existed in the beginning of continuous wave acceleration was overcome!

Still, till now nobody dared to use high frequency quadrupole focusing as we did in URAL-30 (RFQ DTL)! Such an accelerator for the 20-30 MeV has no rivals as yet.

The linear accelerator remains interesting. It is still possible and necessary to improve it.

REFERENCES

[1] V.A. Teplyakov and B.K. Shembel, Radioelectronics, vol. 1, issue 4, 1956.

[2] D.V. Karetnikov et al, Linear Accelerators of Ions, Gosatomizdat, 1962.

[3] G.M. Anisimov and V.A. Teplyakov, PTE, vol. 1, 1963.

[4] A.P. Maltsev et al, PTE, vol. 4, p. 29 (1965); vol. 6, p. 17 (1966)

[5] V.A. Teplyakov, PTE, vol. 6, 1964.

[6] V.A. Teplyakov and V.B. Stepanov, Radioelectronics, vol. 13, issue 11, 1968.

[7] V.A. Teplyakov et al, Proc. of the 6-th Int. r Conference, 1967.

[8] V.A. Teplyakov and I.G. Maltsev, Preprint IHEP. 74–112, 1974.

[9] I.M. Kapchinsky, A.P. Maltsev and V.A. Teplyakov. Proc. of the 7th Int. Particle Accelerator Conference, 1969.

Figure 2: Right-to-left, Profs. Teplyakov, Andreev, Kapchinsky; around 1980.

Figure 3: Prof. Dr. V.A. Teplyakov views the BEAR RFQ (Beam Experiment Aboard Rocket)

I-100

PROTON AND/OR H- LINAC

Name of Linac : *I-100*
Function : *Fixed target*
Institution and address : *IHEP, 142284, Protvino, Moscow Region, Russia*
Person in charge : *V.A. Teplyakov*
Name of person supplying these data : *Maltsev A.P.*
e-mail : *zherebtsov@vx.olu.decnet.ihep.su*
tel. : fax : *+95 230 23 37*

HISTORY AND STATUS

Const. started : *1961* ; first beam : *11/1966*
Present status : *Operational*
Cost of facility :
Present linac staff : *8 man-years*
Present yearly operat. time : *1000 (1994)* h

LINAC PARAMETERS

Ion Source
Type : *Plasma accelerator*
Output : *300* mA at *700* keV
Pulse length : *300* µs; rep. rate : *1* Hz
Normalized emittance (1σ) : *0.2* π mm-mrad

Pre-accelerator
Types : *Pulse transf.* ; lengths : *2.2* m
Output : *300* mA at *700* keV
Pulse length: *300* µs; rep. rate : *1* Hz
Normalized emittance (1σ) : *0.2* π mm-mrad

Longitudinal Matching
Type : *One buncher system*
Mod. *25.4* keV; drift *995* mm at *148.5* MHz
keV; drift mm at MHz

Accelerating System
Total linac length : *80* m; No. of tanks : *3*
Tank diameters : *1.32; 1.22; 1.08* m
Number of drift-tubes : *(1)*
Drift-tube lengths : *(2)* mm
Drift-tube diam (range): *232 - 100* mm
Gap/cell length (range): *0.185 - 0.277*
Aperture diameter : *20* mm to *40* mm
RF frequency(ies) : *148.5* MHz
Field modes : *E010*
Eff. shunt impedance : *25 - 15* MΩ/m
Q : *72000; 50000; 36000*
Filling time : *< 100* µs
Equilibrium phases : *-37° to 50°*
RF rep. rate : *1* Hz; pulse : *400* µs
Beam rate : *1* Hz; pulse : *100* µs
RF power peak : *10* MW; mean : *0.004* MW

Focusing System
No. elements : *163*
type : *Pulsed* order : *FODO*
Gradients : *60* to *4* T/m
Other : *Pulsed flat top (250 µs)*

LINAC PERFORMANCE

	Normal Operation	Max, or Design	
Energy :	*38;74;103*		MeV
Mean acc. rate :	*1.25*		MeV/m
ΔE/E (FWHM) :	*0.45*		%
Beam current :	*≤ 100*		mA peak
Norm. emit. (1σ) :	*2*		π mm-mrad

OTHER RELEVANT INFORMATION

(1) 93+2 (1/2); 41+2 (1/2); 26+2 (1/2)
(2) 62 - 413; 456 - 537; 586 - 624

Alvarez linac structure.

Proton injector for IHEP Acclerator complex in 1967-1983.

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URAL-30

PROTON AND/OR H- LINAC

Name of Linac : *URAL-30*
Function : *Proton Injector for IHEP Accelerator Complex*
Institution and address : *IHEP, 142284, Protvino, Moscow region, Russia*
Person in charge : *V.A. Teplyakov*
Name of person supplying these data : *A.P. Maltsev*
e-mail : *ZKEREBTSOV@VX.OLU.DECNET.IHEP.SU*
tel. : fax : *+7 095 230 23 37*

HISTORY AND STATUS

Const. started : *07/1973* ; first beam : *11/1983*
Present status : *Operational*
Cost of facility :
Present linac staff : *7 man-years*
Present yearly operat. time : *1080 (1995)* h

LINAC PARAMETERS

Ion Source
Type : *Plasma accelerator*
Output : *200-250* mA at *100* keV
Pulse length : *5-10* µs; rep. rate : *16.6* Hz
Normalized emittance (1σ) : *0.1 - 0.15* π mm-mrad

Pre-accelerator (including RFQ)
Types : *2H RFQ* ; lengths : *4.1* m
Output : *100* mA at *1980* keV
Pulse length: *5-10* µs; rep. rate : *16.6* Hz
Normalized emittance (1σ) : *0.8* π mm-mrad

Longitudinal Matching
Type :
Mod. keV; drift mm at MHz
keV; drift mm at MHz

Accelerating System
Total linac length : *21.3* m; No. of tanks : *2*
Tank diameters : *0.42 ; 0.42* m
Number of drift-tubes : *65 ; 57*
Drift-tube lengths : *9.7 - 97.5 ; 50.8 - 89.6* mm
Drift-tube diam (range): *34.4 ; 37.4* mm
Gap/cell length (range):
Aperture diameter : *19* mm to *22* mm
RF frequency(ies) : *148.5* MHz
Field modes : *Longitudinal magnetic field*
Eff. shunt impedance : *120 - 10* MΩ/m
Q : *15000*
Filling time : *< 30* µs
Equilibrium phases : *-30° ; -30°*
RF rep. rate : *16.6* Hz; pulse : *5-10* µs
Beam rate : *16.6* Hz; pulse : *5-10* µs
RF power peak : *10* MW; mean : *0.004* MW

Focusing System
No. elements : *122*
type : *RFQ* order : *FFDD*
Gradients : *337 kV/cm²* to T/m
Other : *Space-periodic RFQ focusing system*

LINAC PERFORMANCE

	Normal Operation	Max, or Design	
Energy :	*30*		MeV
Mean acc. rate :	*1.3*		MeV/m
ΔE/E (FWHM) :	*± 0.35*		%
Beam current :	*50 - 70*	*100*	mA peak
Norm. emit. (1σ) :	*2.5*		π mm-mrad

OTHER RELEVANT INFORMATION

Space-periodic radio-frequency quadrupole focusing system.

H←resonator; RFQ : 2H←resonator.

Linac parameters described at EPAC 1988.